Moisture content and drying defects in kiln-dried *Eucalyptus grandis* poles

By

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Declaration

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ………………………… Date: ……………………………

Summary

There has been a reported reduction in the durability of creosote treated, wooden utility poles in South Africa in recent years. Several factors could have been responsible for this. In this study, *Eucalyptus grandis* pole drying schedules currently used, methods of measurement of moisture content (MC) after drying and drying defects were investigated. Relationships involving drying defects and MC gradient before treatment which may help in the development of simple non-destructive methods of assessing defects such as surface checking, honeycomb and collapse, and MC gradient were also explored. The long term goal of this study was to increase the durability of treated poles by avoiding unacceptable drying defects and MC values before treatment. The results of this investigation are presented in the following chapters:

- an introduction motivating the aims of the investigations (Chapter 1);
- a review of literature relevant to MC and drying defects in sawn or round wood (Chapter 2);
- ready for press manuscripts on MC and drying defects in kiln-dried *E. grandis* poles (Chapters 3 to 7) and
- a general conclusion that links up chapters 3 to 7, and recommendations (Chapter 8).

The auger drill method gave reliable MC values when samples in increments of 25 mm depths into the pole were taken. However, when single samples of 50 mm and 75 mm depths were considered, the auger drill MC measurements were unreliable. It was concluded that SABS SM 983 (2000), which specifies taking single radial auger drill samples of depth 70±5 mm at pole mid length, is not a reliable method of measuring MC in a kiln-dried *E. grandis* pole.

Correlation results indicated that tree growth factors such as sapwood depth, green MC and heartwood percentage were related to final drying defects and may be used as criteria for pole sorting before kiln drying. Also, the number of valleys per unit length (VPUL) of the circumference at the theoretical ground line (TGL) was positively correlated with honeycomb and closed surface checks, implying that VPUL as a parameter of the pole circumference profile can be used to assess invisible, internal defects.

The dry bulb temperature (T_{db}) of 80^{o}C, used to dry poles in industry, was too high and resulted into unacceptable levels of drying defects in kiln dried *E. grandis* poles. In addition, the drying period of 8 days was too short to attain an acceptable MC gradient in poles.

It is, therefore, recommended that:

- To use the auger drill method to reliably determine the moisture content of a pole, samples in increments of 25 mm should be taken.
- MC measurements should be made at the most critical zones of a pole such as the TGL and not higher up since there is normally considerable MC variation in the longitudinal direction. It is also important to consider sampling more than one position on the pole circumference to cater for the MC variation in the tangential direction.
- For poles with large sapwood depths i.e. >15mm, mild drying conditions at the beginning of a drying run should be used, since such poles may be more susceptible to surface checking. Poles with large heartwood percentages should also be dried with suitable kiln schedules, i.e. with low T_{db} to minimise honeycomb and collapse. In general, T_{db} lower than 80^{o}C should be considered in order to reduce the defects to acceptable levels.
- Poles should be dried for longer than 8 days even at T_{db} as high as 80^{o}C to reduce the MC to acceptable values and gradients.
- Since only three schedules were tested, more drying schedules should be investigated to make reliable conclusions about the effect of schedule on drying defects. In addition, more poles per schedule should be considered in order to obtain statistically reliable results.
- The relationship of pole diameter and drying defects also requires further investigation.
- Since a limited sample was used to test for the effect of source of poles and drying schedules on defect correlations, further studies should be done on sufficient samples to come up with more reliable conclusions. It is also necessary to further investigate the possible variation in correlation of VPUL and internal defects on a large sample of poles from specific sources and drying schedules.

Opsomming

Die afgelope paar jaar is waargeneem dat kreosootbehandelde transmissiepale ‘n afname in duursaamheid toon. Verskeie faktore kan hiervoor verantwoordelik wees. In hierdie studie is huidige *Eucalyptus grandis* oonddrogingskedules en voggehalte- (VG) bepalingsmetodes vóór en na droging asook drogingsdefekte ondersoek. Verwantskappe tussen drogingsdefekte en VG-gradiënt vóór behandeling wat kan meehelp om nie-destruktiewe metodes te ontwikkel om defekte soos oppervlaktekrake, interne barste en instorting en VG-gradiënt te bepaal, is ook bestudeer. Die langtermyn doelwit van hierdie studie is om die duursaamheid van behandelde pale te verbeter deur onaanvaarbare drogingsdefekte en voggehaltes vóór behandeling te vermy. Die resultate van hierdie ondersoek word in die volgende hoofstukke bespreek:

- ‘n inleiding waarin die doelwitte van die onderskeie ondersoeke motiveer word (Hoofstuk 1);
- ‘n oorsig van die literatuur relevant tot VG en drogingsdefekte in gesaagde en rondehout (Hoofstuk 2);
- persklaar manuskripte oor VG en drogingsdefekte in oondgedroogde *E. grandis* pale (Hoofstukke 3 tot 7) en
- ‘n algemene gevolgtrekking wat bevindings uit hoofstukke 3 tot 7 saamvat gevolg deur aanbevelings (Hoofstuk 8).

Die augerboor-metode kon betroubare VG-waardes lewer indien monsters van 25mm diepte-inkremente in die paal geneem is. Augerboor-voggehaltemetings met enkel 50mm en 75mm monsters was egter onbetroubaar. Daar is bevind dat SABS SM 983 (2000), wat ‘n enkel radiale augerboormonster tot op ‘n diepte van 70±5 mm in die middel van die lengte van die paal spesifiseer, nie ‘n betroubare VG-bepalingsmetode vir oondgedroogde *E. grandis* pale is nie.

Die resultate het aangetoon dat boomgroeifaktore soos spinthoutdiepte, groen voggehalte en die persentasie kernhout aan drogingsdefekte verwant is en as basis vir sortering van pale vóór oonddroging gebruik kan word. Ook kon die aantal valleie per eenheidslengte (e. VPUL) van die omtrek by die teoretiese grondlyn (TGL) positief met interne barste en geslote oppervlaktekrake korreleer word wat impliseer dat VPUL as parameter van die omtrekprofiel van die paal gebruik kan word om onsigbare, interne defekte mee vas te stel.

Die droëbaltemperatuur (T_{db}) van 80°C wat in die industrie gebruik word, was te hoog omdat dit onaanvaarbare vlakke van drogingsdefekte in oondgedroogde *E. grandis* veroorsaak het. Daarbenewens was die drogingsperiode van 8 dae by 'n T_{db} van 80°C te kort om 'n aanvaarbare VG-gradiënt te lewer.

Die volgende word derhalwe aanbeveel:

- Om betroubare VG-resultate d.m.v. die augerboormetode te verkry, behoort monsters in inkremente van 25mm geneem te word.
- VG-metings behoort in die mees kritiese dele van 'n paal gedoen te word byv. by TGL en nie hoër nie omdat daar normaalweg beduidende VG-variasie in die longitudinale rigting is. Dis ook belangrik om op meer as een posisie op die omtrek te meet om vir die variasie in die tangensiale rigting voorsiening te maak.
- Ligte drogingstoestande behoort aan die begin van die drogingsproses by pale met groot spinthoutdieptes, byv. > 15mm, gebruik te word omdat sulke pale meer geneigd tot oppervlaktekrake is. Pale met hoë kernhoutpersentasies moet ook met geskikte drogingskedules, byv. met lae T_{db}, gedroog word om interne barste en ineenstorting te verminder. Oor die algemeen behoort T_{db} laer as 80°C oorweeg te word om die omvang van defekte by aanvaarbare vlakke te hou.
- Selfs by T_{db} so hoog as 80°C behoort pale langer as 8 dae te droog om die VG tot by aanvaarbare waardes en 'n gradiënt te bring.
- Omdat slegs drie skedules evalueer is, behoort meer skedules ondersoek word om betroubare gevolgtrekkings oor die effek van skedule op drogingsdefekte te verskaf. Addisioneel behoort meer pale per skedule oorweeg word om statisties betroubare resultate te verkry.
- Die verwantskap tussen paaldeursnee en drogingsdefekte benodig ook verdere ondersoek.
- Aangesien 'n beperkte aantal pale gebruik is om die herkoms en drogingskedule met defekte te korreleer, behoort verdere studie op genoeg pale gedoen te word om meer betroubare gevolgtrekkings te kry. Dit is ook noodsaaklik om die moontlike variasie in die korrelasie tussen VPUL en interne defekte op 'n groot aantal pale van spesifieke herkoms en drogingskedules vas te stel.

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Chapter 1: General introduction

The importance of wooden poles in telephone and electricity reticulation systems cannot be overlooked. In South Africa alone, the electricity parastatal, Eskom, has an estimated 2 million wooden poles in the field, while the telecommunications parastatal, Telkom, owns an estimated 10 to 12 million poles (ESI Africa, 2000). Both pine and Eucalypts are used to produce utility poles, but there is a continued reduction in the production of treated pine poles mainly because of the reduction in supply of pine raw material (SAWPA, 2007), making *Eucalyptus* poles increasingly important. For instance, the estimated total volume of wood utility pole sales in South Africa for the year 2006, was 584 m^3, of which 511 m^3 was Eucalypts and only 73 m^3 was pine (SAWPA, 2007). One of the major *Eucalyptus* species grown for the production of utility poles is *Eucalyptus grandis.*

Depending on the in-service environment, a properly treated wooden pole is expected to have a useful life of about 40 years. It is reported that premature failures have recently increased (ESI Africa, 2000). According to this report, negligence claims associated with premature failures of wooden poles that are made against Eskom and Telkom can amount to R30 million per year. In fact, this could be an Africa wide problem, since treated wood poles are exported to several African countries including Nigeria, Senegal and Eritrea (Woodline, 2007), and plans to cover even more countries are already underway (SAUPA, 2007).

Causes of decreased durability may be inherent in the wood material itself such as, species, hybrids, age, and source of poles, but the drying, treatment process, utilisation and maintenance are also possible sources of the problem. The present large use of high temperature kiln drying might result in the production of poles with too steep moisture content (MC) gradients and more extensive drying defects. MC at the time of treatment and drying defects can be decisive as far as the in-service life of utility poles is concerned, because they affect the penetration, distribution and retention of preservative chemicals. Ninety percent of pole failures worldwide can be attributed to treating poles when they are still too wet (ESI Africa 2000). It is specified that the average MC measured at pole mid length should not exceed 25%, with no individual pole allowed to have an MC value exceeding 28% (SANS 754, 1994). Considering the test methods used (Hill *et al*., 2006; SABS SM 983, 2000), it cannot be guaranteed that critical parts for example, around the theoretical ground line (TGL) of all the poles meet the required MC values. Rypstra *et al*. (2004) reported that MC was higher at TGL than mid length in a study done on 9 m long, kiln-dried *Eucalyptus* poles at a drying and treatment plant in Kwazulu-

Natal. It is because of this, and the relationships between MC and drying defects (Chapter 2), that all measurements in this study were done at TGL.

In addition, drying defect specifications for only end checks and surface checks are given (SANS 754, 1994), leaving out potentially serious internal drying defects such as honeycomb and collapse. As non-destructive methods are used in grading poles, internal drying defects are in practice accepted to be almost impossible to detect and quantify.

Thus, this thesis presents the following:

1. a general review of literature relevant to MC and drying defects in sawn or round wood (Chapter 2);

2. relationships between drying defect parameters and some growth characteristics in kiln-dried *E. grandis* poles (Chapter 3);

3. suitability of auger drill sampling for measurement of moisture content gradients of kiln-dried *E. grandis* poles (Chapter 4);

4. correlation of drying defect parameters in kiln-dried *E. grandis* poles (Chapter 5);

5. surface profilometry and internal drying defects in kiln-dried *E. grandis* poles (Chapter 6);

6. effect of kiln drying schedule on the quality of *E. grandis* poles (Chapter 7) and

7. a general conclusion that links up all the chapters from 3 to 7, and recommendations (Chapter 8).

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Chapter 2: Literature review

2.1 Surface checking in logs/poles and boards

2.1.1 General

A check is a lengthwise separation of wood that usually extends across the rings of annual growth and parallel to wood rays (Boone, 1997). Panshin *et al*. (1964) refers to surface checks as seasoning checks that develop on the surface and extend into the wood for varying distances. A check does not however, extend from one face of timber to another (Desch and Dinwoodie, 1981). Such separations or ruptures of the wood tissues in the longitudinal plane that extend from face to face are regarded as splits (Figure 2.1a). Surface checking is a major problem in wood drying, and all possible precautions are necessary to avoid this form of drying degrade. It occurs in boards, debarked poles as well as logs with bark, of both hardwoods and softwoods.

According to Mackay and Oliveira (1989), surface checks are caused by surface layers drying and shrinking faster than the core. During kiln and air seasoning, moisture evaporates from the surfaces of boards and if this evaporation is in excess of the rate of moisture movement from the core, a moisture content (MC) gradient is induced with the board surfaces at lower MC than the core (Pratt, 1974). If this gradient becomes too steep (Rice, 1994; Pratt, 1974), the outer parts of the wood will tend to shrink excessively on to the inner, and severe stresses will develop. When the stresses exceed the maximum tensile strength of the wood perpendicular to the grain, checks occur (Brown, 1989; Hildebrand, 1970). Similarly, the major cause of checking in poles is circumferential stress build up in or near the pole surface during drying that exceeds the tensile strength of the wood (Evans *et al*., 1997).

Apart from uneven core and surface drying (Koehler and Thelen, 1926), checking can develop due to tangential shrinkage being greater than radial. According to Pentoney (1953) and Dinwoodie (2000), greater tangential shrinkage than radial can partly be explained by the fact that the radially oriented rays prevent radial shrinkage because lengthwise shrinkage of individual ray cells is minimal, and, therefore, restricts the latewood from shrinking in this direction. In addition, Pentoney (1953) and Beckwith (1994) indicated that radial shrinkage is the average of the high shrinkage in the relatively high-density latewood and the low shrinkage in the relatively low-density earlywood, while tangential shrinkage is dominated by the high shrinkage of the latewood that forces the earlywood to shrink with it in the process.

Consequently, checking is most likely to occur on the faces of tangentially cut boards and on the edges of quarter-sawn material (Pratt, 1974). According to Koehler and Thelen (1926), timbers containing the pith centre will check more or less in drying because of the differential shrinkage and also because the central portion dries more slowly. Checks, whether in lumber or timbers, nearly always extend across the rings radially because, in addition to differential shrinkage, a weak plane is produced where the rays and fibres cross (Koehler and Thelen, 1926).

In a board, checks appear as longitudinal slit-like openings on the surfaces when observed with the naked eye (Figure 2.1a).

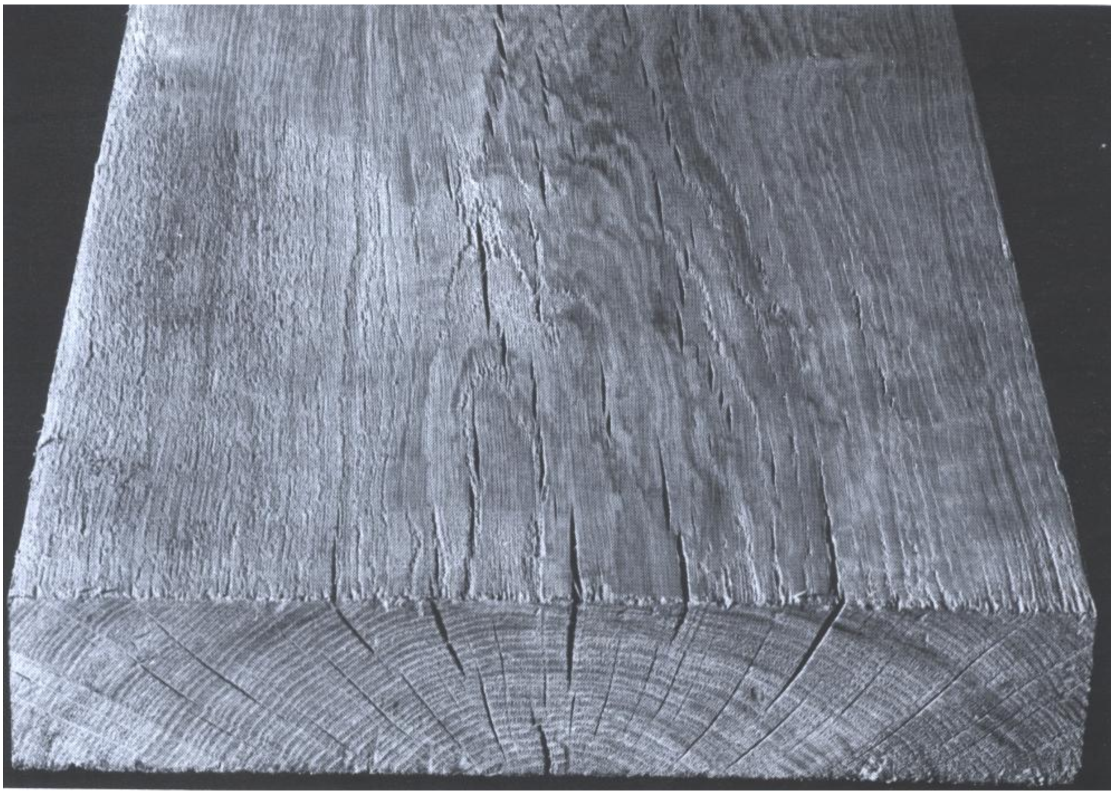

Figure 2.1a: Surface checking, end splitting and end checking in plank of Oak (Pratt, 1974).

The checks seem to spread from surface to the interior of the board irrespective of whether the board consists of either sapwood or heartwood, or both. It can also be seen that surface checks follow along the ray tissue (Figure 2.1b) due to the line of weakness created by the latter (Figure 2.1c) especially in timbers with large rays such as oak.

Figure 2.1b: Cross-section of an oak timber showing how surface checks follow rays (Koehler and Thelen, 1926)

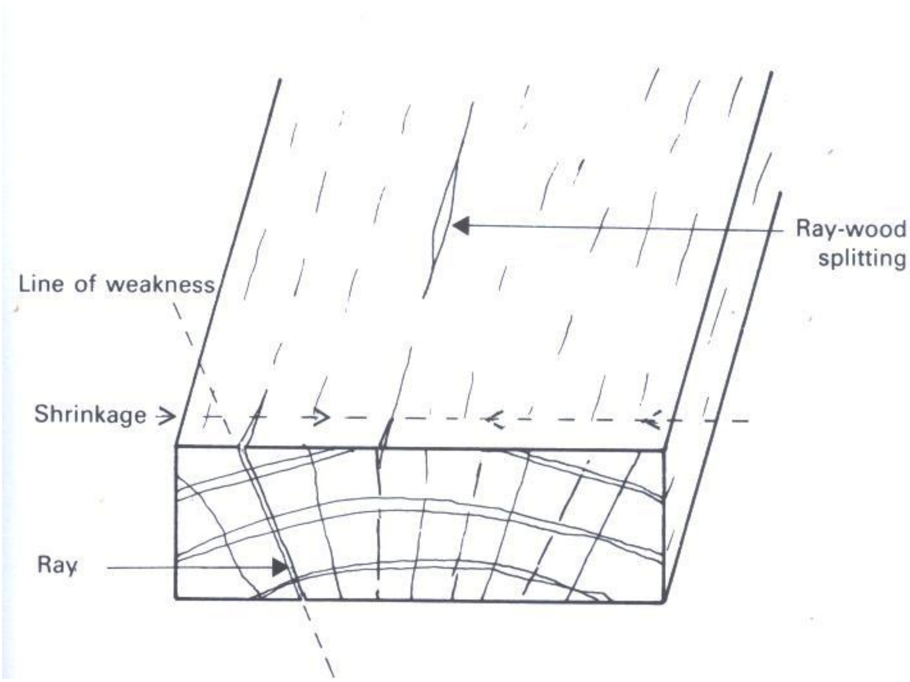

Figure 2.1c: Rays as lines of weakness (Brown, 1989).

It might not be evident by looking at the surface of the board that latewood checks more than earlywood but based on the findings of Perré (2003) that checking initiates in the latewood, this trend is expected. This also implies that the possibility of surface checks occurring on the tangential face might be higher when a board has more latewood parts compared to earlywood.

In logs or poles, surface checks appear as openings along the grain on the pole surface. Checks can better be observed on the surface of debarked poles (Figure 2.1d) than when the bark is on, as it may tend to conceal thinner checks (Figure 2.1e).

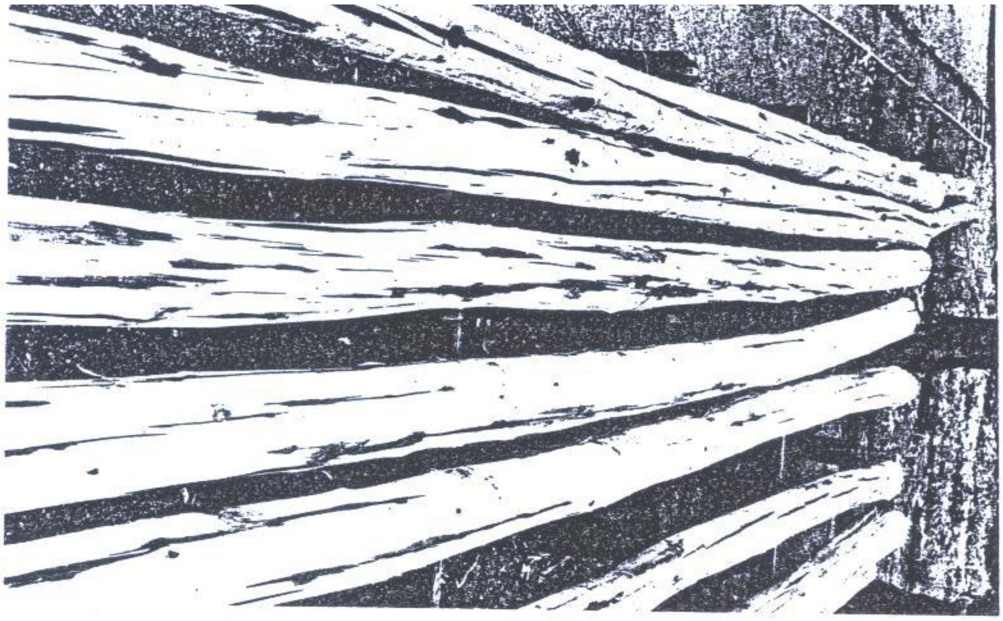

Figure 2.1d: Surface checking in debarked air-seasoned poles (Stöhr, 1982).

From pole cross-sections surface checks can better be seen originating from the surface radially through the sapwood and heartwood, and sometimes deeper towards the pith (Figure 2.1e). The cross-sections also reveal the closed checks and their depth can best be analysed. Sometimes the checks may be so deep that they meet at the pith, but this still might not be evident by just observing the pole surface until cross-cutting. Checks cross through different growth rings and again follow the ray tissue. One could say the whole circumferential pole surface initially free of defects, would be equally susceptible to checking, since it is tangential to the growth rings when exposed to the drying conditions.

Figure 2.1e: Surface checks as seen on cross-section of a log with bark (Koehler and Thelen, 1926).

2.1.2 Factors that determine surface checking

Surface checking can be caused by inherent wood factors or as a result of unsuitable physical processing methods. The wood factors may be unique to tree species or groups of species, and may determine how particular species behave during drying in terms of extent of checking under given conditions. The wood factors also interact with the process factors and as a result surface checking may be severe.

2.1.2.1 Wood factors

(a) Tensile strength perpendicular to the grain

Checks form when the tensile drying stresses perpendicular to the grain exceed the tensile strength perpendicular to the grain (Rice, 1994; Brown, 1989; Hildebrand, 1970). Therefore, it would be expected that drying stresses, not strong enough to overcome the tensile strength of wood perpendicular to the grain, would not cause surface checking. This may probably partly explain why some species are able to withstand severe drying conditions while others check excessively under the same drying conditions.

(b) Green MC

One would expect less or minimal checking in a board composed of heartwood only and that has very low MC when green. Bowyer *et al.* (2003) indicated the heartwood MC range of many hardwood and softwood species to be 33-98% as compared to that of sapwood of 44-249%. Also, Mcginnes and Dingeldein (1969) reported the heartwood of Eastern Red cedar to have an MC range of 19-25%. Due to such low MC, a less steep MC gradient between the shell and core and, therefore, less stress would develop during drying resulting into minimal checking.

(c) Fibre saturation point

USDA (1974) defines fibre saturation point as the stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities contain no free water. Drying beyond this point removes bound water from the cell walls, which causes shrinking (Suchsland, 2004). Different species may reach this stage at different MC values. For example, the fibre saturation point of Sitka spruce is about 28% while that of rosewood is only 15% (Bowyer et al, 2003). Since the amount of shrinkage that occurs is proportional to the amount of water removed from the cell wall, Sitka spruce would lose more water and shrink more than rosewood when both species are dried to 0% (oven dry). Greater shrinkage values would be expected to cause more checking in Sitka spruce than rosewood dried under the same conditions if their other wood factors were approximately the same.

(d) Ray size and grain orientation

Wood species with large rays and fairly straight grain (Brown, 1989) are the most susceptible to surface checking. One such species is oak, which normally develops checks along the rays during drying. Surface checks follow rays because of the relatively lower magnitude of tensile strength values of rays compared to prosenchyma in the tangential direction (Schniewind, 1963). The ray cell walls, therefore, separate along the ray tissue or at the ray-prosenchyma boundary in the radial direction of the board.

(e) Density

Morén (1989) indicated that high-density wood is more sensitive to checking than wood of low density. This is probably because the magnitude of shrinkage is higher with higher density

(Suchsland, 2004; Tsoumis, 1991), due to greater cell wall thickness and, therefore, larger amount of wood substance in woods of higher density. Thus, at growth ring level one would expect more checking in the thick-walled late wood as Perré (2003) reported, but Panshin *et al.* (1964) indicated that checks result from the separation of the thinner-walled early wood cells. However, according to Perré (2003), surface checks usually initiate in the latewood due to the greater shrinkage of the latewood and finally spread in the earlywood zone. In fact, the same author shows that due to the difference in shrinkage between earlywood and latewood some small checks persist in latewood even at the end of drying.

2.1.2.2 Process factors

(a) Drying stresses

Depending on the drying conditions, stresses of different magnitude develop in wood and a reaction by the wood in form of strain results. Rice (1994) identified the three types of strain that occur during drying as: the elastic strain; viscoelastic strain and the mechanosorptive or set strain. He reported that it is the elastic strain, which increases very quickly in the surface layers under severe drying conditions that often leads to checks. Schniewind (1963) suggested that even at room temperature surface checks can develop within the rays when, as a result of dimensional changes caused by drying, the tensile stresses within the rays exceed the compressive stresses in the adjacent longitudinal tissues (prosenchyma). The rest of the process factors affect surface checking through the influence they may have on the magnitude of the stresses.

(b) Temperature

Although it may not be possible to control temperature in air-drying, this is possible in kiln drying by setting the required dry bulb temperature values. The higher the temperature used during drying, the higher the rate of moisture loss from the surface of wood (Stöhr, 1977) and, therefore, the higher the MC gradient that would be set up between the shell and core. This means that excessive stresses will occur in the shell since it will start shrinking when the core is still very wet, causing severe checking. Panshin *et al* (1964) indicated that at high temperature, there are also additional stresses resulting from thermal expansion.

(c) Relative humidity

Relative humidity determines the amount of moisture that the air can absorb from the drying wood (Rice *et al*., 1988) and the rate of absorption, since it is basically the amount of water that is already in the air. In kiln drying it is controlled by the difference between the set dry-bulb and wet-bulb temperature values i.e. the wet bulb depression. Use of low humidity during drying leads to faster moisture loss from the wood surface (Stöhr, 1977; Pratt, 1974), setting up stresses that cause surface checking.

(e) Air velocity (speed)

When moisture evaporates from wood, it is usually carried away by air, thus maintaining a gradient than ensures continued moisture loss from wood. Air is, therefore, the transfer medium in kilns, supplying heat to the wood and removing evaporated moisture from it (Walker, 1993; Anon., 1991). Rice *et al.* (1988) stated that the air velocity controls the rate at which evaporation from the surface occurs. The higher the air velocity, the higher the rate at which energy is brought the wood and the higher will be the rate at which moisture is carried away from near the wood surface. In low humidity conditions, air speed can be critical in determining the extent of surface checking during air-drying. In kiln drying, unnecessarily high air velocity can also cause loss of money in terms of the extra energy to run fans (Anon., 1991)

(f) Thickness of timber or log diameter

The thicker the timber being dried the steeper the MC gradient (Tsoumis, 1991; Brown, 1965; Wangaard, 1950). This is because of the increased distance between the shell and the core. Greater stresses and more surface checking is, therefore, expected in thicker timber during drying. When kiln drying green Eucalypt timber of thickness greater than 25 mm, dry bulb temperatures should not exceed 45^{o}C during the early stages, otherwise surface checking might develop (Campbell and Hartley, 1978 quoted by Vermaas and Neville, 1988). In the same way, the log or pole diameter is important. Small diameter poles are expected to experience smaller MC gradients between the shell and core, and consequently less surface checking than large diameter ones during drying.

2.1.3 Measurement of surface checks

In assessing surface checking, qualitative or quantitative methods may be used. By putting checking extents into classes, different samples or drying schedules can be compared (Stöhr, 1982). Surface checking can also be evaluated by taking counts of individual checks, as was done by Gaby (1963). Other parameters such as check length and width (SANS 754, 1994), as well as check depth and volume (Evans *et al*., 1997) may be used to quantify the surface checking. In relatively small (in dimension) timber samples, exposing closed checks and later on measuring them, can be done according to the procedure and guidelines given in the ZA Dry-Q Kiln Drying Management System (Perold, 2006). This involves submerging the kiln dried boards in water for about 10 seconds and placing them in the sun to dry out the surfaces again, then measuring the checks after they have re-opened. This may, however, not be possible when handling larger timber or even logs. After counting the checks, a steel ruler can be used to measure the length, and maximum width, and with the help of feeler gauges the maximum check depth can be measured as well (Evans *et al*., 1997).

2.1.4 Effect of surface checking on wood properties and utilization

Depending on its severity, surface checking may limit wood to only specific uses. The influence of checks depends not only on the frequency and depth, but also on the orientation relative to the applied load (Desch and Dinwoodie, 1981). Deep checks considerably reduce the strength of wood, particularly in shear (Panshin *et al*., 1964), due to reduction in the area of the surface that can offer resistance to shear.

Boyd (1963) indicated that seasoning checks reduce pole bending strength, the severity of which is species dependent. To a lesser extent checks also reduce compression strength parallel to the grain (Desch and Dinwoodie, 1981). Due to reduced strength in products such as structural members and athletic equipment, surface checks can increase the tendency of wood to split during use (Ward and Simpson, 1991). Also as USDA (1974) noted, even with no visible signs of degrade some loss of strength may occur when wood is dried at excessively high temperatures (temperature effect).

Panshin *et al*. (1964) reported that surface checking affects the finishing characteristics of the wood. Timber that has checked during drying requires deeper planing for example before it can be used to make furniture. With deep checking, the timber may be ripped and utilized for purposes that require thinner members. Surface checking also affects wood preservation. If poles are treated before shrinkage is complete, for example at 30% MC, further drying to equilibrium MC lower than this value may occur, leading to more checks (Han, 1985). The author indicated that these checks, that may even go deeper than sapwood after treatment, create openings for fungi and insects into the untreated heartwood.

Although large checks are detrimental, fine checking may be beneficial as far as preservative treatment of certain wood species is concerned (Rudman, 1965). In an experiment on penetration of eucalypt sapwoods, the author reported that access to some vessels in *Eucalyptus regnans* and *E. obliqua* 3 feet long pole slabs was achieved through fine checks, and suggested that in full size poles of such species, fine checking should be encouraged to achieve better preservative retention and distribution.

2.1.5 Control of surface checking

Successful drying resulting in wood free of surface checks requires control of the rate of drying (Mackay and Oliveira, 1989) to minimize MC differences between shell and core. Use of low temperature and high relative humidity in the early stages of drying is, therefore, important (Pratt, 1974). This will result in a low drying rate, which should be maintained until the fibre saturation in the shell is reached when more rapid drying conditions are appropriate (Walker, 1993). How low the minimum, or how high the maximum temperature and humidity should be, also depends on the size of material and species being dried among other factors.

If the surfaces of an unseasoned piece of wood are coated with a substance that sufficiently restricts moisture loss, then the moisture movement through the wood will be slowed, regardless of the MC of the lumber or the ambient conditions (Rice *et al*., 1988). Based on this, the authors experimented with polyvinyl acetate on red oak lumber and concluded that a coating that reduces surface moisture loss can be a potentially effective method of preventing surface checking under somewhat severe drying conditions.

Moisture pallets that consist of two parallel sheets of plywood separated by stickers were used by Hart and Gilmore (1985) to restrict moisture loss from lumber. Green lumber is stacked on the moisture pallets rather than on conventional stickers for drying, thus sandwiching the boards between plywood sheets. The pallets were effective in reducing surface checking in oak lumber (Hart and Gilmore, 1985).

Under the same conditions of drying, Leny (1964) studied checking susceptibility of planed and rough red oak lumber. He reported that the rough surfaces (i.e damaged fibres) checked more than the smooth surfaces. The rough surfaces may present points of weakness that result in localized failures when stresses develop during drying. The method of processing of the boards can have an effect on the checking as well. In a study to determine the effect of log sawing and lumber surfacing methods on the subsequent development of surface checks, Gaby (1963) indicated that circular sawn boards checked considerably more than either band sawn or green surfaced boards. The author suggested that sawing stresses and tears the wall tissue, and the surface thereby loses some of its original strength and continuity of cell bonds of wood elements. Circular saws create rough surfaces due to fewer teeth and wider cutting edge. The rough surfaces have a large proportion of loose and torn fibres, which may cause the development of many small checks due to accelerated drying and shrinkage stresses in local areas beneath them (Gaby, 1963).

Since surface checking results from shrinkage related stresses, dimensional stabilization of wood can help in control. Stamm (1956) stabilised the dimensions of small cross sections of wood with carbowaxes to virtually eliminate shrinkage. The stabilisation was due to bulking of fibres by deposition of materials within the cell walls. This means that even after drying minimal shrinkage would take place thus avoiding stress build up and surface checking.

In slash pine poles, a number of physical treatments proved effective in reducing surface checking (Evans *et al*., 1997). These treatments included boring a centrally located 32-mm-diameter hole along the entire length of the post, incising, and single and double radial saw kerfs. The authors indicated that single and double kerfing, and to a lesser extent centre boring, were effective in reducing surface checking. In a related study on pine posts, Evans *et al.* (2000) confirmed the effectiveness of kerfing in reducing surface checking. Centre boring was able to prevent checks from increasing in depth and width, but not in number. An earlier study by Helsing and Graham (1976) indicated that a saw kerf made to the centre from the butt to about 1.5 meters above the ground line of Douglas-fir poles is an effective means of controlling checking and preventing internal decay in this critical zone. These physical treatments reduce drying stresses that develop when wood shrinks thus preventing checking.

2.2 Honeycombing in logs/poles and boards

2.2.1 General

Boone (1997) and USDA (1974) defined honeycombing as checks, often not visible at the surface, that occur in the interior of a piece of wood, usually along the wood rays. Sometimes the terms hollowhorning and internal checking are used when referring to honeycombing. Occasionally honeycombing occurs only in the earlywood between two latewood rings (Bariska *et al*., 1987).

The checks usually extend along the rays because, as is the case with surface checking, the tangential shrinkage is greater than the radial and there is a weak plane where the rays cross the fibres (Koehler and Thelen, 1926). Honeycomb arises from internal tension stresses that develop during drying (Simpson, 1984). As drying progresses beyond the initial stages from the surface inwards, the core eventually dries below fibre saturation point and tends to shrink (Mackay and Oliveira, 1989). Shrinkage of the core is restricted however, by the outer zone which was forced to dry in a stretched condition (Pratt, 1974). According to the same author, a tension stress, therefore, is set up in the core and, if this stress is greater than the strength of the wood, wood cells will tear apart and internal checks will result.

Honeycombing is rather deceptive since its development is often not suspected from superficial examination (Pratt, 1974). It should not be confused with surface checks that usually penetrate deeply into the interior of wood during early stages of drying (Pratt, 1974; Wangaard, 1950), but tend to close as the surface layers fall under compression in the final stages of drying. Ward and Simpson (1997) reported that a corrugated appearance on the lumber surface might indicate severe honeycombing, which is often associated with severe collapse. Internal checking can only be ascertained by cross cutting and observing the internal cross sections of dried wood material (Vermaas, 2006, pers. comm; Desch and Dinwoodie, 1981). Figure 2.2a shows the surface appearance and internal cross section of a board with honeycomb after machining.

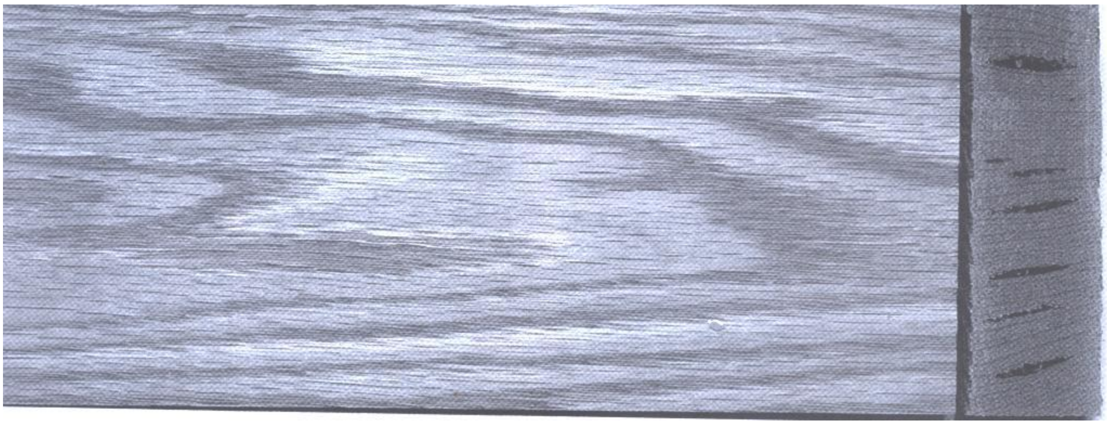

Figure 2.2a: Honeycomb not appearing on the surface of a planed red oak board but seen on the internal cross section when the board is cross-cut (Ward and Simpson, 1997).

In a board the orientation and severity of honeycomb checks depends on the sawing method. Quarter (radially) sawn boards may tend to show less severe internal checking than back (tangentially) sawn material (Chafe *et al*., 1992). In quarter-sawn boards, honeycomb fractures are usually oriented parallel to the wide face, yet in back-sawn boards, the fractures are oriented perpendicular to the wide face (Figure 2.2b). This demonstrates the association of honeycomb with the rays. Simpson (1984) reported that honeycomb fractures usually occur in ray tissue or at the interface of the ray tissue and the surrounding tissue.

In logs internal checking also appears as lentil-shaped, radially oriented cracks of varying width and length on the internal cross-sections (Figure 2.2c). During the drying of big *Eucalyptus* poles, the stresses developed are far higher than in thinner members, and collapse is accompanied by severe checking and splitting (Chudnoff, 1955) as seen in Figure 2.2c.

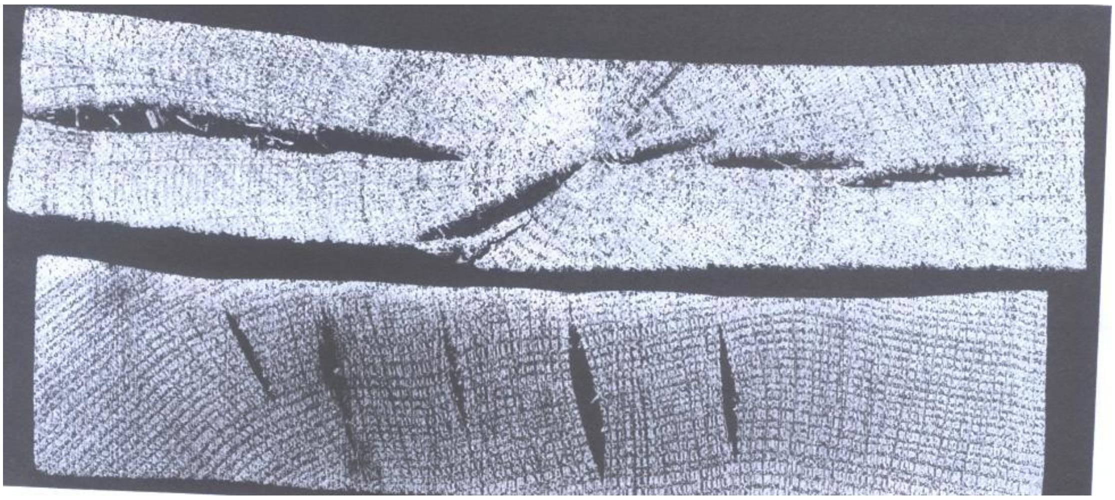

Figure 2.2b: Cross-section of quarter-sawn and back-sawn red oak boards showing honeycomb and slight collapse (Simpson, 1984).

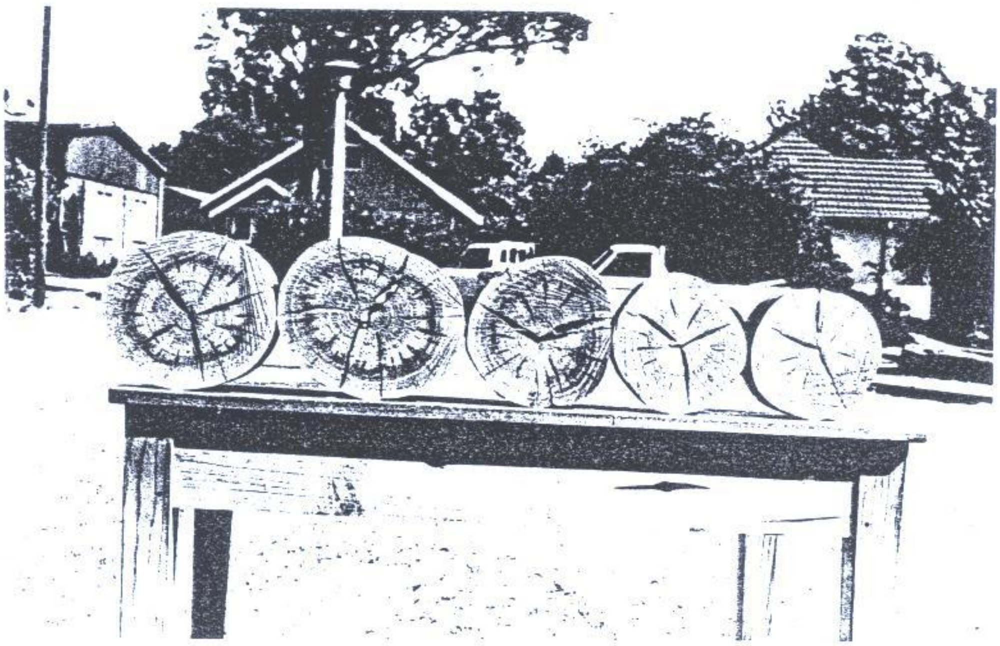

Figure 2.2c: Honeycombing in *E. grandis* poles dried at temperatures between 80 and 90°C (Stöhr, 1982)

Honeycombing seems to occur more in heartwood than sapwood, and at growth ring level it is more common in the earlywood than latewood, in association with collapse (Figure 2.2d).

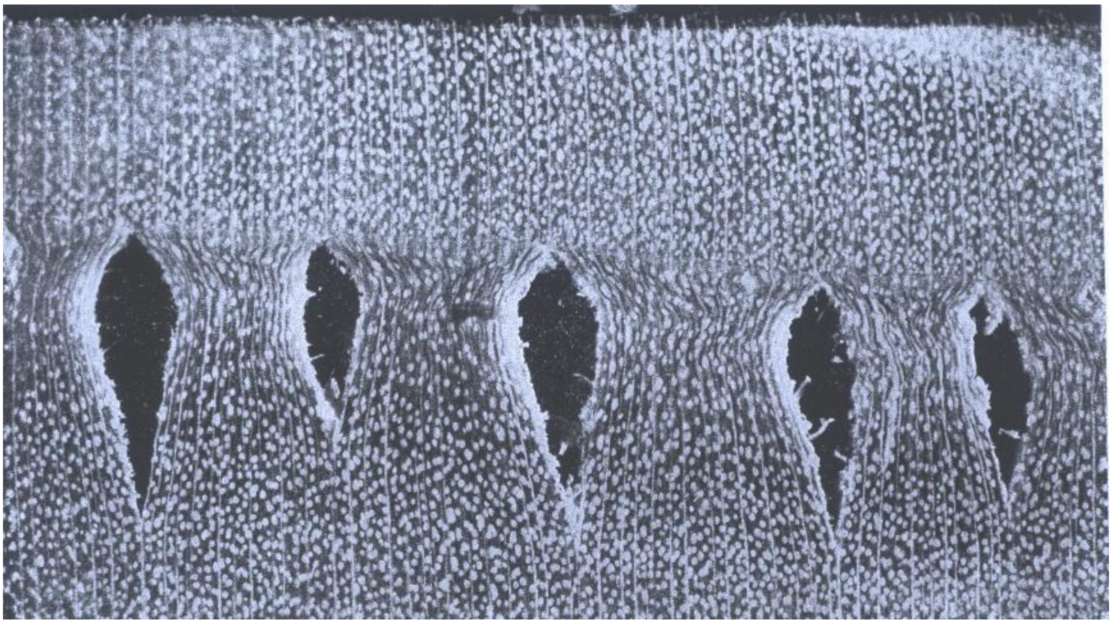

Figure 2.2d: Honeycombs and collapsed fibres as discovered in a single ring in a dry board of yellow poplar (Tiemann, 1941).

2.2.2 Factors that determine honeycombing

Most of the factors that determine the occurrence of surface checking are also responsible for the occurrence of honeycomb. However, while surface checking takes place early during drying, honeycomb takes place later when the core starts shrinking and stresses are reversed.

2.2.2.1 Wood factors

Wood factors such as tensile strength perpendicular to the grain, original MC, fibre saturation point and ray size, all affect the occurrence of honeycombing in a similar way as was discussed in surface checking. Other factors include the following:

(a) Density

Density is another major wood factor that determines the occurrence of honeycomb. In a study on red oak lumber, Harris and Araman (1995) and Harris *et al*. (1988) stated that a positive correlation existed between the green density and occurrence of honeycomb during kiln drying. Stöhr (1982) indicated that honeycomb was more severe in the butt as compared to top portions of *Eucalyptus grandis* poles. In many species, butt logs tend to have a higher density than logs cut from higher up in the main stem (Bowyer *et al*., 2003). The high shrinkage associated with higher density (Tsoumis, 1991), could, therefore, explain severe honeycombing in the pole butt portions. However, a single factor may not always cause honeycombing in isolation but rather in combination with others. For instance at growth ring level, internal checking may be confined to lower density earlywood and absent in the higher density latewood (Chafe *et al*., 1992), due to greater strength of the latewood.

(b) Thickness of wood material

Chafe *et al*. (1992) indicated that 50mm *E. regnans* regrowth boards were more prone to honeycombing than 25mm material, which showed less evidence of internal checks. Chudnoff (1955) also reported that severe internal checking is expected in thick *Eucalyptus* poles as compared to thinner material. Thicker material develops a steeper MC gradient during drying and greater stresses are set up.

2.2.2.2 Process factors

(a) Internal tension drying stresses

The permanent stretch called the mechanosorptive or set strain is an attempt by wood to reduce the amount of stress at the surface by stretching. It is the largest of the other strains and is the basis for honeycomb formation in wood (Rice, 1994). After the stresses have reversed, the amount of set strain in the surface determines to a large extent how much tension occurs inside the wood. If large amounts of set occurred as the surface dried, the tension inside the wood will be high because the surface stress is much larger than it would be if no strain occurred early in drying (Rice, 1994).

(b) Temperature, humidity and air velocity

Use of high drying temperature, low humidity and high air velocity all cause wood surface layers to dry and shrink too quickly when the core is still wet. The rapid and early attempt to shrink in the shell is opposed by the very wet core, causing a large amount of set strain in the shell. The shell that dried in a largely extended size causes high internal tension stress when the core begins to dry and shrink, resulting into severe honeycombing.

(c) Collapse

Honeycombing may be associated with collapse where large aggregates of cells collapse and cause internal fractures (Brown, 1989). The same author added that this type of honeycombing occurs above fibre saturation point and may normally be distinguished from the internal checking occurring below fibre saturation point by the associated collapsed surfaces (Figure 2.2d). While not mutually exclusive, there is also a tendency for externally manifested collapse to occur at the expense of internal checking and vice versa (Rozsa, unpublished data quoted by Chafe *et al.*, 1992).

2.2.3 Measurement of honeycombing

If images of cross-sections of boards or poles are produced using a scanner or digital camera, honeycomb can be measured by image analysis. In addition, in the case of a pole, a disc can be cut at a specified length and scanned or photographed. On the cross section image of the disc, the radius is divided into intervals of 1cm from the pith outwards. The sum of tangential widths of all the internal checks is then expressed as a percentage of the circumference at that radius (Bariska *et al.*, 1987). The length and maximum width of the checks can also be measured.

Internal check counts can also be used as a measure of the extent honeycombing. Simpson (1984) evaluated honeycomb in boards by cross cutting each board into equal lengths and counting the number of individual honeycombs at each internal cross section.

2.2.4 Effect of honeycombing on wood properties and utilization

Honeycombing may seriously reduce the resistance of wood to longitudinal shear (Wangaard, 1950; Garratt, 1931). Using wooden members with honeycomb for applications where longitudinal shear strength is critical may have serious consequences. The fact that honeycomb is not visible on the surface may lead to assuming strength of wooden material higher than the actual value, hence using it for an inappropriate application. As long as further machining does not take place the appearance of wood with honeycomb is not affected. During machining the defect is exposed (Ward and Simpson, 1997; Pratt, 1974) and this has a positive side since at this stage a decision may be taken not to use the board for its previous intended purpose. In utility poles where there may not be further machining, honeycomb may go undetected causing unpredicted premature failures in the field.

Honeycomb may affect preservative penetration and distribution. In a well treated utility pole a complete penetration of the sapwood band is expected. The honeycomb fractures may, however, create pockets where preservative chemical can settle giving high retention values but poor distribution. Johanson (1971) noted that although the average retention in the sapwood of the pole may be high, uneven penetration of preservative in a pole could result in areas of inadequate treatment, permitting an early entry of wood destroying organisms.

2.2.5 Control of honeycombing

Honeycombing which is already formed can no longer be eliminated (Hildebrand, 1970) and, in most cases the timber cannot be used. It is, therefore, important that preventive measures be put in place before the actual drying is done to avoid the formation of this defect. The prevention of internal checking is based upon not creating too great initial MC gradients between the shell and the core for susceptible species (Mackay and Oliveira, 1989). This will require that the use of high temperature and low humidity be avoided, especially during early stages of drying, to maintain appropriate drying rates.

Chafe (1993a) demonstrated that pre-heating green mountain ash wood in water could assist in reducing internal checking. This probably relates to what Henderson (1936) reported about intermittent steaming which relieves the stresses and prevents honeycombing by plasticising the surface.

In an experiment done on quarter-sawn and back-sawn red oak boards, Simpson (1984) reported that press drying using optimum platen pressure considerably reduced honeycombing in quarter-sawn boards while it persisted in back-sawn boards. However, the author noted that there was increased thickness shrinkage in quarter-sawn boards because the tangential direction coincides with that of the platen pressure.

2.3 Collapse in logs/poles and boards

2.3.1 General

Mackay and Oliveira (1989) defined collapse as an abnormal type of shrinkage, which distorts, flattens or crushes wood cells. This type of shrinkage occurs above the fibre saturation point during the early stages of drying, when the free water leaves the cells (Chafe *et al*., 1992; Pratt, 1974; Tiemann, 1941). It is brought about by surface tension forces, which free water exerts upon the cell walls, causing them to be pulled inwards and flattening the lumens (Chafe *et al*., 1992; Pratt, 1974; Tiemann, 1941).

If air is already present in the cells (Garratt, 1931; Koehler and Thelen, 1926), as in partially seasoned lumber or in many green species, collapse does not take place because the air expands and reduces the area over which the force of the retreating moisture becomes effective in drawing the cell walls together when the water leaves. Collapse may also be caused by compressive drying stresses (Ward and Simpson, 1997) during early drying stages in interior parts of a wood piece that exceed the compression strength of wood.

At pole or even board level, slight amounts of collapse may not be noticed (Ward and Simpson, 1997). The same author indicated that in severe cases, collapse usually shows up as grooves or corrugations, a ‘washboarding’ effect at thin places in a board (Figure 2.3a) but sometimes collapse shows as up as excessive shrinkage rather than distinct grooves or corrugations. Chafe *et al*. (1992) reported that the manifestation of collapse as corrugations or ‘wash board’ is seen in quarter-sawn boards. Under a microscope (Figure 2.3b), evidence of collapsed wood cells can clearly be observed (Ward and Simpson, 1997).

Figure 2.3a: Severe collapse in a western red cedar board (Ward and Simpson, 1997)

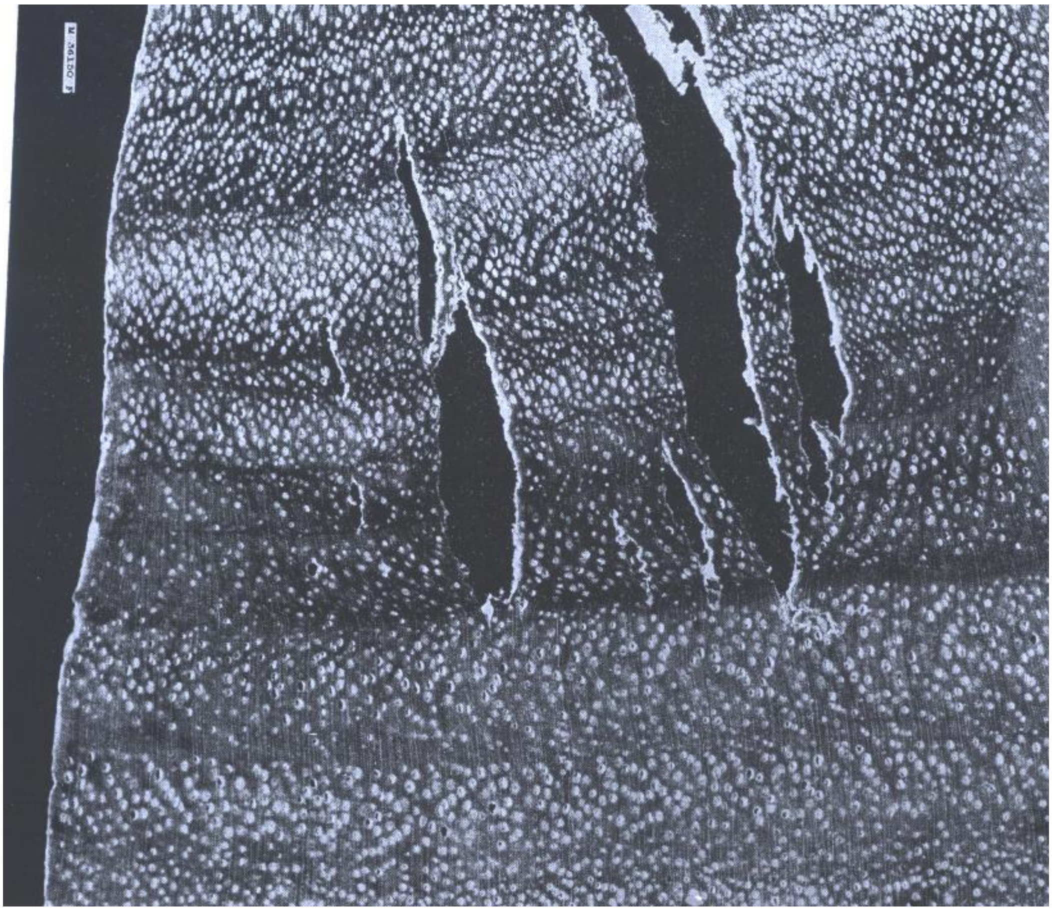

Figure 2.3b: Distinction between collapse in heartwood (upper portion) and sapwood (lower portion) (Tiemann, 1941).

2.3.2 Factors that determine collapse occurrence

2.3.2.1 Wood factors

(a) Compressive strength perpendicular to the grain

It is possible for collapse to occur when the capillary tension inside the cells exceeds the compressive strength perpendicular to the grain (Siau, 1995). In the case of susceptible species such as redwood (*Sequoia sempervirens*), the Wood Handbook (USDA, 1974) gives a compressive strength of 2.9×10^6 Pa for old-growth wood in green state. Under conditions of kiln drying at elevated temperature this would be reduced to approximately half or 1.5×10^6 Pa. Collapse is thought to occur in material with low strength and many micropores (Bariska, 1992).

(b) Air permeability

Wood in which air can easily enter is less susceptible to collapse. For this reason collapse does not occur at the ends or near the surface of boards, or in sapwood, as in these parts air enters readily (Koehler and Thelen, 1926). The same authors indicated that kiln dried oak and red gum often show plump sapwood while the adjacent heartwood is shrunken and wrinkled because of the uneven collapse of the cells. Chafe (1985) indicated that *E. regnans* samples containing sapwood showed lower values of collapse than heartwood samples (Figure 2.3b). In western red cedar collapse has been found to occur more often in the butt logs than in logs from higher up the tree (Brown, 1965; Henderson, 1936). In this case the butt logs are expected to have more heartwood, which has poor permeability resulting in collapse susceptibility (Yang, 1998). According to Wilkins and Wilkes (1987), in some timbers deposition of extractives in heartwood may reduce pore size and so increase the extent of collapse. Permeability is dependent on the size of pits, the smaller the pit openings the lower the permeability. Small pit openings increase the susceptibility of wood to collapse because of the resulting high capillary tensions during drying from cells completely full of water (Siau, 1995).

(c) Green MC

According to Chafe (1985) the severity of collapse increases with higher MC values. He indicated that if newly sawn green material shows high MC, there is a very good chance that in

Eucalyptus regnans severe collapse will occur during drying. It is also thus expected that wood material kiln dried from green might develop more collapse than if the MC was lower, hence the standard recommendation to pre-dry Eucalypts before final kiln drying.

(d) Wood density

Wood of lower density is more susceptible to collapse than higher density wood (Siau, 1995; Chafe *et al*., 1992; Chafe, 1985). The corrugated surface or 'wash board' effect often observed in quarter-sawn boards occurs where lower density earlywood may collapse but higher density latewood is sufficiently strong to resist liquid tension forces (Chafe *et al*., 1992). The higher density, therefore, increases the potential of the material to resist the surface tension forces tending to pull cell walls together.

(e) Thickness of wood material

Chafe *et al*. (1992) reported that when dried under most commercial regimes, 25mm material from *E. regnans* regrowth showed little evidence of collapse, while 50mm boards were prone to collapse degrade. Thicker material develops greater drying stresses that may result in greater compressive forces and hence collapse more.

2.3.2.2 Process factors

(a) Drying stresses

Drying stresses are a significant factor because the shell of the board being dried shrinks more than the core initially, exerting a compressive stress on the core (Kauman, 1958). The more severe the drying conditions, the more the extent of collapse. Severe drying conditions create greater drying stresses due to steeper MC gradients (Bariska, 1992) resulting in severe collapse. Low humidity and high air velocities contribute positively to the drying stresses, worsening the extent of collapse.

(b) Temperature

Ellwood and Ecklund (1963) reported increasing collapse with increasing temperature in black oak samples. Collapse occurs due to use of excessively high dry-bulb temperatures early in kiln drying (Yang, 1998; Ward and Simpson, 1997). According to Mackay and Oliveira (1989) and Tiemann (1941), heating susceptible wet wood at high kiln drying temperatures makes cell walls soft and plastic and more liable to collapse.

2.3.3 Measurement of collapse

Small dimension timber samples (Choong, *et al*., 1973; Mackay, 1972; Kauman, 1958; Chudnoff, 1955) or increment cores taken at specific tree heights (Chafe, 1990; Chafe, 1985) have been used to determine collapse. In this case, the total percentage shrinkage in drying to specified MC in collapsed samples (S_a), and true percentage shrinkage to specified MC in collapse free samples can be obtained (S_t). The amount of collapse can, therefore, be obtained by subtracting the latter from the former (S_t –S_a) (Mackay, 1972). In larger dimension timber or poles collapse can be estimated based on visual comparison (Vermaas, 2006, pers. comm.) of samples and categorizing the extent on some scale.

2.3.4 Effect of collapse on wood properties and utilization

Collapse substantially affects the strength properties of wood, especially the cross-grain tension strength and the shear strength, it increases the costs related to timber drying, and lowers the exploitable volume of wood (Bariska, 1992).

2.3.5 Control of collapse

Certain wood species such as Eucalypts are very prone to collapse (Brown, 1989) to the extent that their seasoning methods have been specially formulated to control the problem. Mackay and Oliviera (1989) indicated that for such species, lumber is usually air dried first before kiln drying, and if all of the drying is done in a kiln, then low temperatures not exceeding 120^{o}F (67^{o}C) dry bulb are used until the MC has dropped to fibre saturation point and the danger of collapse is over.

Collapse can be reduced by reducing the surface tension (Chafe *et al*., 1992). The author noted, therefore, that impregnation of wood by wetting agents or replacement of water by other liquids for very long immersion times can reduce collapse. By pre-freezing at a temperature of -20^{o}C, Ilic (1993) reported reduction in collapse in regrowth *Eucalyptus regnans* boards. In fact, complete prevention of collapse in Eucalypt wood can be achieved by pre-freezing (Choong *et* *al*., 1973). According to Ilic (1995), pre-freezing produces a marked reduction in shrinkage of wood, thereby reducing associated defects. The author suggested that the main mechanism responsible for reduced shrinkage is due to the migration of moisture from the cell wall onto frozen lumen water. The moisture loss from the cell wall produces what Ilic (1995) referred to as a cold shrinkage. Water to ice transformation leads to expansion of liquid water in the lumen, thus imparting a compressive stress to the cell wall. This and the moisture loss make the cell more rigid and, therefore, less likely to shrink.

Chemical treatments by zinc chloride solutions (Chudnoff, 1955) and very dilute hydrochloric acid (Pankevicius, 1962) have been effective in reducing collapse because of pit membrane hydrolysis and the increase in capillary radius (Kauman, 1964 quoted by Chafe *et al*., 1992). More concentrated solutions cause weakening of the cell wall and increase collapse (Kauman, 1964 quoted by Chafe *et al*., 1992).

In a study on green mountain ash wood, Chafe (1993a) reported that pre-heating of green material could assist in increasing collapse recovery. The author heated increment core samples in water at various temperatures and reported an increase in collapse recovery with increasing temperature. By proper selection of pre-heating times, collapse recovery can be increased by more than 30% (Chafe, 1993b). In already collapsed wood, it has been found that in many instances, much of the collapse and consequent distortion may be removed by means of a high temperature steaming treatment (Chafe *et al*., 1992; Pratt, 1974; Tiemann, 1941). According to Chafe *et al*. (1992), during this process, MC should not be allowed to rise to such an extent that cell lumens become saturated, otherwise collapse would re-occur during subsequent redrying. Apart of steam, anhydrous ammonia has also been used in collapse recovery (Mackay, 1972).

2.4 MC gradient

2.4.1 General

MC is defined as the mass of the water expressed as a percentage of moisture-free or oven-dry wood mass (Bowyer *et al*., 2003). MC gradient expresses the variation of MC from the surface of a board or pole to the centre. In poles or logs the MC gradient is the radial MC variation. It is important to consider the MC gradient of a dried pole or board rather than a single MC value because single values do not indicate the MC distribution. In addition, it is the MC gradient between the shell and core of the material that is largely responsible for the formation or enlargement of defects such as surface checks and honeycomb.

2.4.2 Factors that determine MC gradient

(a) Size of material

When dried under the same conditions, thinner material often develops a less steep MC gradient as compared to thicker sized material of the same species. In an experiment on Douglas-fir pole sections, Graham and Womack (1972) reported that while MC gradients were similar in the outer 3 inches of large (14.8 inches in diameter) and small sections (11.4 inches in diameter) dried at 260^{o}F, at greater depths the small sections were about 7 percent lower in MC.

(b) Temperature, humidity and air velocity

High temperature (Graham and Wanock, 1972), high air velocity and low humidity (Koch, 1972) all lead to faster drying in the surface layers of wood material, creating steep MC gradients. In most cases these are the major factors that wood driers alter to shorten drying times, yet the resultant MC gradient of the material relies a lot on them.

(c) Duration of drying

When drying poles, especially those with large diameter, drying time is as important as the drying conditions. Graham and Womack (1972) indicated that irrespective of the drying temperature there are small reductions in the MC of the inner heartwood of large pole sections. The authors noted that even at elevated temperature long drying times would, therefore, be necessary to effect an appreciable reduction in MC of the inner portion of poles.

2.4.3 Measurement of MC gradient

MC gradient in a pole can be estimated by cutting a disc, from which blocks of a particular thickness are cut along the radius, and used to determine MC by oven drying (Taylor, 1991). Sample blocks are also usually used when determining MC gradients in boards yet Feng and Suchsland (1993) noted that kerf losses (saw dust) as well as moisture losses between slicing and weighing may be potential sources of errors. However, Gorvad and Arganbright (1980) studied the effect of sawing and slicing on MC of Douglas-fir wood sections and concluded that readily available metal slitting saws can actually be used to cut MC sections without unduly lowering of MC of the machined sections.

By taking core samples, subdividing them into segments and determining the MC of the segments by the oven drying method (Keating and Gilfedder, 1963; Taylor, 1991), the MC gradient in poles can also be determined. Although this is a common method, some authors have reported various sources of errors that may lead to incorrect readings. Purslow (1968) noted that a cylindrical boring is not a representative geometrical sample for a circular pole. The author also indicated that water could be lost during boring by compression and, probably to a minor extent, by evaporation caused by heating. Taylor (1991) noted that on average increment core estimates were 10 percent lower than block MC estimates.

Another method of measuring MC of a pole and sawn or laminated timber is taking drillings (SABS SM 983, 2000) and oven drying. This method is commonly used to determine an average MC of a pole or sawn timber, but if the drillings are taken at particular successive depths, the MC gradient can be determined. However, care has to be taken to avoid loss of moisture during drilling and colleting the samples. The drill should be sharp enough and all drillings should be collected from the drilled hole. The samples should be collected in containers that are then sealed immediately with airtight lids.

2.4.4 Effect of MC gradient on wood properties and utilisation

Wood preservation is to a large extent affected by the MC gradient of the material. To achieve the purpose of preservation, moisture has to be removed from wood to create room for preservatives. Some specifications require an MC value of 25% in the outer zone (SANS 754, 1994) and Han (1985) indicated that for preservation with water-borne preservatives, the MC must be below the fibre saturation point. If only the surface layers have sufficiently dried and the core is still wet, the preservative will only penetrate and be retained in the surface zone, when such wood is treated. This means that the wood may continue to dry after treatment thus redistributing the preservative, and enlargement of initially small surface checks may occur, exposing the untreated core. In other cases drying of the core may cease after treatment. For instance, in a study on Eucalypt poles, Gilfedder and Keating (1973) reported that creosote retarded drying of the heartwood. The authors indicated that the centres of such poles might even remain above fibre saturation point indefinitely.

MC is known to affect physical and mechanical wood properties, and biological deterioration (Bowyer *et al*., 2003). A wooden pole with a steep moisture gradient, i.e. having dry surface layers and a wet core will have low strength due to overall high MC irrespective of how low the MC in the surface layers might be. In practice the most important single factor governing whether wood rots is its MC (Wilkinson, 1979). When wood MC is above 20%, then fungal decay is possible. If access to the wet core is, therefore, created via deepened surface checks, the fungal deterioration in treated poles with steep MC gradients is likely to occur.

2.4.5 MC gradient control

In order to prevent steep MC gradients in kiln-dried timber or poles, reasonable drying conditions as well as drying times need to be employed. Even at very high temperature it takes a long time before moisture is lost from the centre of thick material (Graham and Womack, 1972).

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Chapter 3: Relationships between drying defect parameters and some growth characteristics in kiln-dried *Eucalyptus grandis* poles

3.1 Abstract

Eucalyptus grandis wood is susceptible to serious drying defects and all possible measures before and during kiln drying need to be taken to minimize the defects. In order to identify factors that may affect drying quality, the goal of this study was to assess relationships between drying defect parameters and some growth characteristics of poles. The specific objectives were to assess relationships between: (i) surface check total length and depth; (ii) MC gradient; (iii) honeycomb percentage of pole cross section area and (iv) extent of collapse and sapwood depth, heartwood percentage of pole cross section area, green MC, and pole diameter. The defects were measured on 3 loads of 10 kiln-dried *E. grandis* poles each (load). After measuring surface check length using a measuring tape, poles were cross cut at the theoretical ground line (TGL), 1.5 m from the butt end, to measure the MC gradient between the shell and core of poles. Digital image analysis of cross sections of discs cut at TGL was used to measure sapwood depth, and the areas of honeycomb, heartwood and disc cross section. Collapse was assessed using qualitative methods. Surface check total length was positively correlated with sapwood depth, and the average depth of surface checks was greater than the average sapwood depth. MC gradient between the shell and core was positively correlated with green MC while the transformed honeycomb percentage (HC*) and collapse class were both positively correlated with heartwood percentage. It was concluded that sapwood depth, green MC and heartwood percentage are related to pole drying defects, and if pre-sorting of poles by these characteristics is done and appropriate kiln schedules are used, drying defects can be minimised.

3.2 Introduction

Eucalyptus grandis wood is susceptible to defects such as collapse (Brown, 1989), honeycombing and surface checking (Stöhr, 1982). Furthermore, surface checking (Panshin *et al*., 1964), honeycombing (Wangaard, 1950; Garratt, 1931) and collapse (Bariska, 1992), and moisture content (MC) (Bowyer *et al*., 2003), have all been found to affect strength properties of wood. According to Han (1985), a steep MC gradient also affects penetration of preservatives during timber treatment. Growth related characteristics of *E. grandis* poles may determine the occurrence and extent of drying defects. For example, in a study on *Eucalyptus* *regnans*, Chafe (1985) reported that high green MC values increased the possibility of collapse occurrence during drying of timber. In addition, Morén (1989) noted that high-density wood is more prone to checking than wood of low density. Therefore, it is possible that growth factors, which influence density and pole strength properties, may also affect the extent of defect formation during drying. Once these important growth characteristics are identified and assessed, proper sorting of poles before drying, and selection of appropriate schedules can be done, hence minimising defects. The goal of this study was, therefore, to assess relationships between drying defect parameters and some growth characteristics of poles. The specific objectives were to assess relationships between:

(i) surface check total length and average depth;

(ii) MC gradient between the shell and core;

(iii) honeycomb percentage of pole cross-sectional area and

(iv) collapse class,

and sapwood depth, heartwood percentage of pole cross section area, green MC, and pole diameter at TGL.

3.3 Materials and methods

3.3.1 Timber

A total of 30, debarked *E. grandis* poles from Coetzenburg, Stellenbosch was investigated. For all the poles, the diameter at the theoretical ground line (TGL), 1.5 m from the butt end, ranged between 175-230 mm. Due to the length limitation of the research kiln, only poles 2.1 m in length could be used. Full length utility poles were, therefore, simulated by sealing and putting end plates at the top ends. As done in practice, end plates were also put on the butt ends of freshly cut poles to minimise end splitting.

Immediately after cutting the 2.1 m pole, a 25 mm thick disc (disc 1) was cut from the remaining part of the tree (Figure 3.1). A 20 mm wide radial strip was taken from this disc. The average MC of the strip was then determined by oven drying (see section 3.3.3.2).

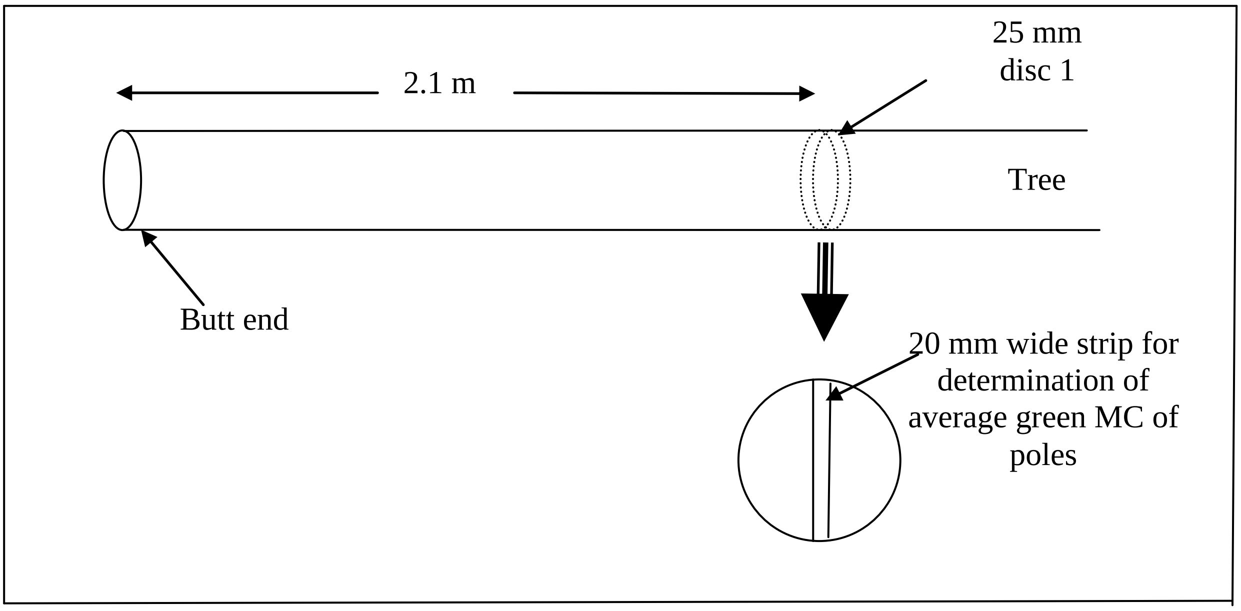

Figure 3.1: Sampling for green MC measurement of poles from freshly felled *E. grandis* trees

3.3.2 Drying

Different drying schedules were used to simulate what is normally found at preservation plants in South Africa. Pole drying was done in a Kiefer kiln, with capacity limited to 10 poles per load. Three loads of 10 poles each were dried using the following schedules:

1. $80^{o}C$ dry bulb (T_{db}) and $59^{o}C$ wet bulb temperature (T_{wb}) for 8 days;

2. $80^{o}C$ T_{db} and $69^{o}C$ T_{wb} for 10 days and

3. $70^{o}C$ T_{db} and $59^{o}C$ T_{wb} for 12 days.

The air velocity of 4-5 ms^{-1} was maintained for all three schedules.

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3.3.3 Evaluation of defects and growth characteristics

3.3.3.1 Surface checking

Immediately after unloading the poles from the kiln, the lengths of all visible surface checks ≥1 mm in width were measured using a measuring tape. The total surface check length was then computed for each pole. Surface check depth was measured using a ruler and an improvised depth gauge. The depth gauge comprised of two 170 mm long, 1 mm thick wires fixed in a cork handle on one end, with a separation distance of 20 mm between them at the opposite end.

3.3.3.2 MC gradient

A second 25 mm thick disc (disc 2) was cut at the TGL and three, 25 mm wide, radial strips were then cut from 3 positions approximately 120^{o} apart on this disc (Figure 3.2). From each strip, 12.5 mm thick samples were cut as shown in Figure 3.2. The samples were weighed, dried until constant mass in a laboratory oven at 102^{o}C, and reweighed. The MC of each sample was calculated according to the following standard formula:

$$MC = \left[\frac{Wet\ mass\ of\ wood\ (g) - Ovendry\ mass\ of\ wood\ (g)}{Ovendry\ mass\ of\ wood\ (g)} \right] \times 100\ (\%)$$

The MC gradient was then computed by subtracting the average MC of the 0-25 mm depth (shell) from the MC in the centre of the pole (core) at the same radius. The 0-25 mm depth represents more or less the sapwood depth where MC is critical in order to achieve complete preservative penetration during impregnation. Of the three radial strips (Figure 3.2), only the one with the steepest gradient rather than the average of all three strips was considered because microbial degradation may begin from any position of the pole which happens to be insufficiently treated (a too high MC in a particular position leads to insufficient preservative penetration), thus creating a localised problem. If average radial MC gradients are considered, the one too steep gradient (out of 3) may go unnoticed, especially if the remaining 2 are low enough to generate an acceptable average.

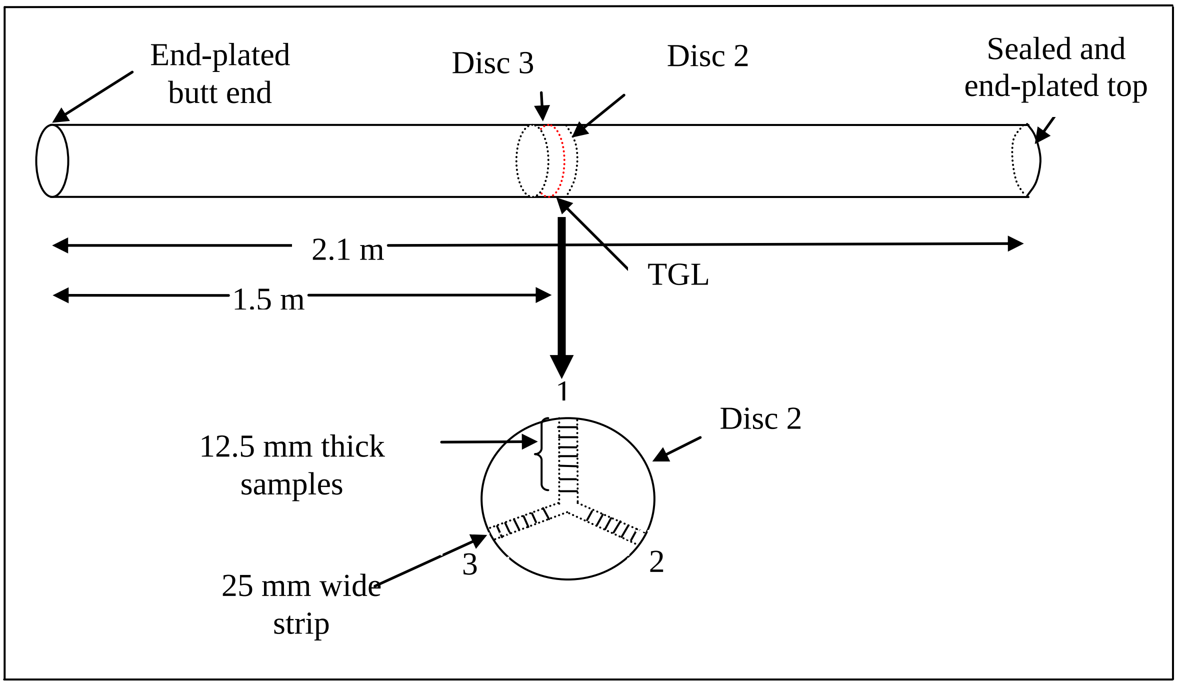

Figure 3.2: Pole sampling for moisture content gradient (disc 2) and honeycombing measurement (disc 3) after drying.

3.3.3.3 Honeycombing, sapwood depth and heartwood percentage

A third disc (disc 3) was cut just adjacent to disc 2 (Figure 3.2). The exposed cross-section on the TGL side was sprayed with a solution of 0.1 g dimethyl yellow dye in 100 ml of ethanol (95% v/v) to enhance the contrast of heartwood and sapwood, and scanned using a scanner (BRISA 620P VUEGO SCAN) to obtain digital images. Images were analysed using ImageJ software (http://rsb.info.nih.gov/ij) to measure the area of honeycomb checks and sapwood depth, cross-sectional area of the disc and heartwood percentage. It was important to include both sapwood depth and heartwood percentage to be able to make meaningful comparisons with surface check depth and honeycomb percentage respectively.

3.3.3.4 Collapse

Collapse was measured by assessing the outer surface of disc 3 (Figure 3.2) for corrugations (Figure 3.3) developed during drying. The disc cross-sectional surfaces were also observed for evidence of collapse. The pole was then qualitatively classified as belonging to one of the categories 1, 2 or 3, category 3 being one with the worst and 1 the least affected by collapse.

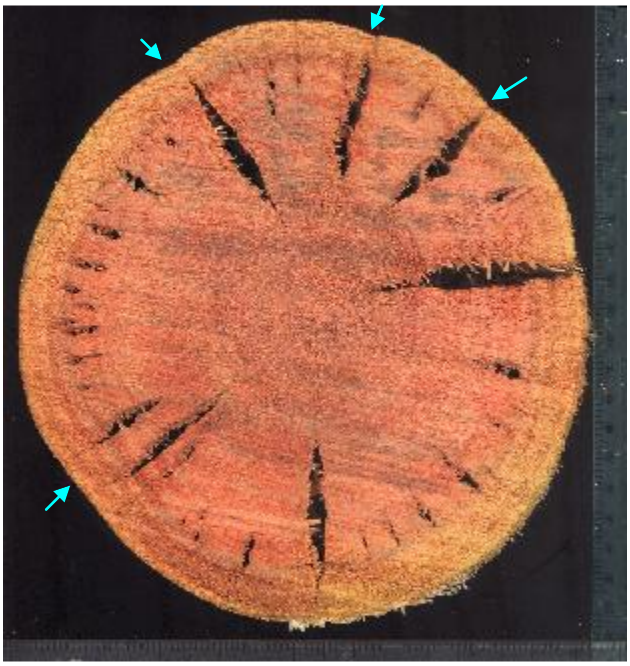

Figure 3.3 Corrugations (grooves) indicated with arrows on the outer surface of the disc at TGL

3.3.4 Data analysis

Since data was not normally distributed, Spearman non-parametric correlations were used. General regression models were also used. All tests were carried out at 5% level of significance.

3.4 Results

Growth characteristics and drying defects of poles are presented in Table 3.1. To indicate ranges of growth characteristics and drying defects in poles, maximum and minimum values are presented in colour (Table 3.1). Apart from the expected strong negative correlation of sapwood depth with heartwood percentage (Table 3.2), there were no other significant ($p<0.05$) correlations between growth factors (Table 3.2).

Table 3.1: Growth characteristics and drying defects in poles

		Pole characteristics					Drying defects				
Schedule	Pole No.	Green MC (%)	TGL diameter (mm)	Cross-sectional area (cm^2)	Av. sapwood depth (mm)	Heartwood percentage	Av. surface check depth (mm)	Surface check total length (m)	MC gradient	Honeycomb percentage	Collapse class
1	1	67.47	197	305.44	24.04	58.30	63.33	1.11	50.76	0.27	2
	2	77.61	173	235.01	19.65	58.87	37.50	0.29	52.89	0.43	1
	3	80.77	190	288.55	23.60	57.02	37.07	1.83	50.10	1.16	2
	4	89.93	205	332.71	17.28	68.66	0.00	0.00	64.92	1.14	1
	5	93.42	179	245.89	18.68	61.25	59.00	1.96	50.76	1.29	2
	6	65.21	180	251.35	20.66	60.03	55.79	3.72	38.29	0.77	2
	7	84.38	185	259.07	15.88	71.70	54.63	2.65	52.35	1.98	3
	8	71.39	196	314.80	16.14	69.65	69.67	0.52	47.56	1.00	2
	9	75.73	210	334.71	20.61	66.35	49.13	2.21	50.01	1.61	2
	10	79.98	180	266.42	14.39	72.67	65.11	0.52	45.75	2.08	2
2	11	77.79	182	253.18	8.07	82.23	0.00	0.00	44.92	2.86	2
	12	84.27	211	346.95	25.09	59.66	21.00	0.09	58.21	0.92	1
	13	81.78	204	324.02	20.35	62.36	0.00	0.00	51.37	0.83	2
	14	91.28	181	250.90	22.24	56.33	50.67	0.62	73.69	1.02	1
	15	75.67	205	333.86	21.40	63.44	14.00	0.07	67.30	0.81	2
	16	105.99	191	282.20	20.35	60.98	51.00	0.44	103.29	0.55	1
	17	75.30	182	263.38	13.77	73.38	112.00	0.30	60.39	3.08	3
	18	73.45	179	249.73	19.47	60.34	20.00	0.14	49.38	1.25	2
	19	74.90	227	402.87	24.08	61.65	75.67	1.34	50.05	0.41	2
	20	77.79	181	247.69	14.04	71.90	11.00	0.12	61.66	4.18	3
3	21	85.54	185	283.92	23.16	56.43	40.93	2.72	58.98	0.97	2
	22	81.81	175	254.87	23.51	54.06	62.61	3.05	63.25	0.78	2
	23	87.84	156	205.19	25.53	46.92	47.36	3.93	46.33	1.26	1
	24	81.74	178	265.70	14.15	69.73	24.00	0.23	69.19	1.18	1
	25	80.81	180	270.27	22.19	59.58	40.60	1.46	59.69	1.27	1
	26	79.57	188	290.81	21.40	59.83	51.59	4.20	48.83	0.71	1
	27	85.32	196	321.19	23.33	58.92	56.86	1.31	76.09	0.73	1
	28	82.54	177	259.82	10.96	75.22	0.00	0.00	95.08	1.03	1
	29	75.29	195	321.22	21.75	60.99	41.28	2.78	58.51	0.15	1
	30	81.74	181	270.44	16.49	67.04	53.20	1.08	73.41	1.01	2
	Average	**85.60**	**192**	**304.03**	**16.80**	**64.58**	**56.00**	**2.1**	**70.79**	**2.17**	**2**

Key: Red =Maximum, Blue = Minimum

Table 3.2: Correlations between growth factors of poles

Variable	Sapwood depth	Heartwood percentage	Green MC	Pole diameter
Sapwood depth	-	-0.926 (0.000)	0.066 (0.728)	0.261 (0.164)
Heartwood percentage	-0.926 (0.000)	-	-0.163 (0.389)	0.083 (0.661)
Av. green MC	0.066 (0.728)	-0.163 (0.389)	-	-0.142 (0.453)
Pole diameter	0.261 (0.164)	0.084 (0.661)	-0.142 (0.453)	-

Key: Figures in brackets = probability of accepting or rejecting the null hypotheses (p-values)
Red = Significant correlations ($p<0.05$)

3.4.1 Surface check total length and depth

The average depth of surface checks was greater than the average of 3 sapwood depth measurements at TGL, in most poles (Figure 3.4). From Table 3.1, considering measurements on all 30 poles, the average surface check depth (56 mm) was considerably deeper than the average sapwood depth (16.8 mm). Note that in pole number 4, 11, 13 and 28, there were no visible surface checks ≥1 mm in width and, therefore no values of surface check depth are indicated (Figure 3.4).

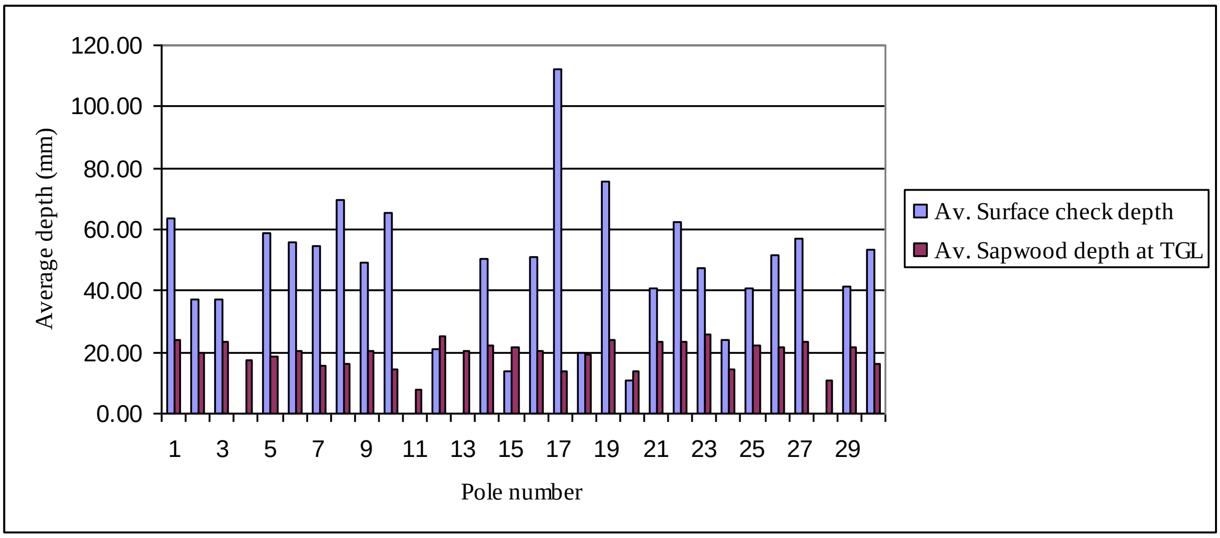

Figure 3.4: Average sapwood depth at TGL, and average surface check depth for each pole

When sapwood depth (x_1), heartwood percentage (x_2), green MC (x_3) and pole diameter (x_4) were fitted as predictors in various regression models, with surface check depth being the dependent variable (Table 3.3), the best predictor was sapwood depth, with the lowest Mallows' Cp of 1.911 (Table 3.3).

Table 3.3: All-subsets, multiple regression analysis of surface check depth versus x_1, x_2, x_3 and x_4, Mallows' Cp selection criterion and standardized regression coefficients for each model

Model No.	Mallows' Cp	No. of effects	Sapwood depth (x_1)	Heartwood percentage (x_2)	Green MC (x_3)	Pole diameter (x_4)
1	1.911	1	0.227			
2	2.301	1		-0.196		
3	2.975	1			-0.124	
4	3.204	3	1.946	1.663		-0.686
5	3.341	2	0.236		-0.140	
6	3.380	1				-0.040
7	3.568	2		-0.222	-0.160	
8	3.603	2	0.255			-0.106
9	3.867	2	0.321	0.102		
10	4.285	2		-0.194		-0.024

On the basis of a small Mallows' Cp, x_2, x_3 and x_4 were dropped leaving the following regression equation:

$$y = 16.1 + 1.34x_1 \quad \text{……….} \ (1)$$

Where: y = surface check depth (mm)

x_1 = sapwood depth (mm)

The relationship (Equation 1) was, however, not significant (p>0.05), suggesting that this is not a good model i.e. sapwood depth (x_1) does not really explain the variation in surface check depth (y). In addition, surface check depth did not have significant correlations with any of the growth characteristics of poles.

By fitting sapwood depth (x_1), heartwood percentage (x_2), green MC (x_3) and pole diameter (x_4) as predictors in a regression model, with total surface check length being the dependent variable, Mallows' Cp was 5.000 (Table 3.4). The best two predictors were sapwood depth and pole diameter, with the lowest Mallows' Cp of 3.148 (Table 3.4).

Table 3.4: All-subsets, multiple regression analysis of surface check total length versus x_1, x_2, x_3 and x_4, Mallows' Cp selection criterion and standardized regression coefficients for each model

Model No.	Mallows' Cp	No. of effects	Sapwood depth (x_1)	Heartwood percentage (x_2)	Green MC (x_3)	Pole diameter (x_4)
1	3.148	2	0.567			-0.380
2	3.584	3	1.710	1.125		-0.772
3	3.988	3	0.586		-0.169	-0.409
4	4.480	1		-0.523		
5	4.980	2		-0.508		-0.190
6	5.000	4	1.525	0.929	-0.125	-0.725
7	5.412	2		-0.550	-0.162	
8	5.528	3		-0.537	-0.190	-0.214
9	6.397	2	-0.118	-0.633		
10	6.794	1	0.468			

On the basis of a small Mallows' Cp, x_2 and x_3 were dropped leaving the following regression equation:

$$y = 4.61 + 0.17x_1 - 0.04x_4 \quad \ldots\ldots\ldots (2)$$

Where: y = surface check total length (m)

x_1 = sapwood depth (mm)

x_4 = pole diameter (mm)

The associated analysis of variance (ANOVA) is shown in Table 3.5.

Table 3.5: ANOVA for the multiple regression analysis of surface check total length (y) versus sapwood depth (x_1) and pole diameter (x_4)

Source	SS	df	MS	F	p
Sapwood depth	14.978	1	14.978	12.500	0.0015
Pole diameter	6.727	1	6.727	5.615	0.0252
Error	32.352	27	1.198		
Total	54.057	29	22.903	18.115	0.0267

Thus, sapwood depth (x_1) contributed significantly to the variation in surface check total length ($F(1, 27) = 12.50$, $p = 0.0015$). Similarly, pole diameter (x_4) contributed significantly ($F(1, 27) = 5.61$, $p = 0.0252$).

The relationship in Equation 2, between surface check total length (y) and sapwood depth (x_1) was confirmed by a positive correlation as shown in Figure 3.5. The correlation of surface check total length (y) with pole diameter (x_4) was negative and not significant ($p>0.05$).

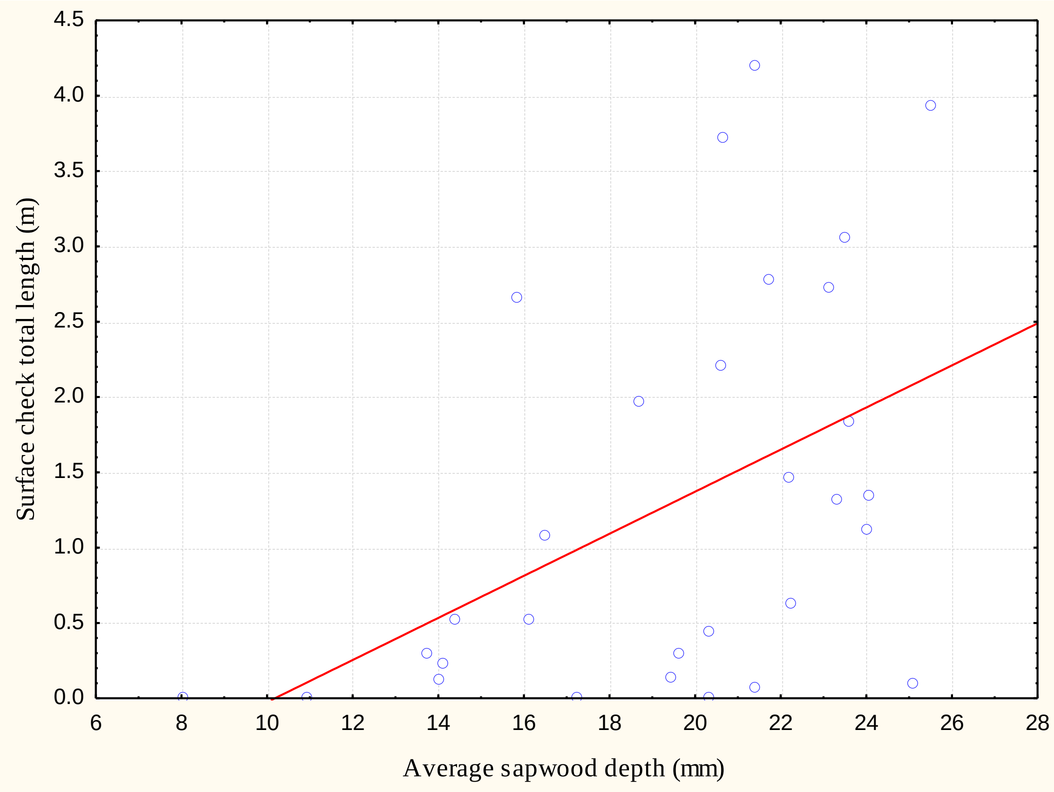

Figure 3.5: Plot of surface check total length and sapwood depth with Spearman correlation coefficient: r = 0.50 (p = 0.00)

3.4.2 MC gradient

When all the four variables, sapwood depth (x_1), heartwood percentage (x_2), green MC (x_3) and pole diameter (x_4) were fitted in a regression model, MC gradient being the dependent variable, adjusted R^2 was 0.304 (Table 3.6). The two best predictors were heartwood percentage and green MC, with an adjusted R^2 of 0.349 (Table 3.6). Thus x_1 and x_4 were dropped from the regression model (Equation 3).

$$y = 0.36x_2 + 1.14x_3 - 55.68 \quad \text{.........} \quad (3)$$

Where: y = MC gradient (%)

x_2 = heartwood percentage

x_3 = green MC (%)

The associated ANOVA showed that heartwood percentage (x_2) did not contribute significantly to the variation in MC gradient (F (1, 27) = 1.492, p = 0.232), while green MC (x_3) contributed significantly (F (1, 27) = 17.206, p = 0.0003).

Table 3.6: All-subsets, multiple regression analysis of MC gradient versus x_1, x_2, x_3 and x_4, Adjusted R^2 selection criterion and standardized regression coefficients for each model

Model no.	Adjusted R^2	No. of effects	Sapwood depth (x_1)	Heartwood percentage (x_2)	Green MC (x_3)	Pole diameter (x_4)
1	0.349	2		0.186	0.630	
2	0.340	2	-0.162		0.611	
3	0.337	1			0.600	
4	0.330	3	-0.194		0.630	0.120
5	0.327	3		0.182	0.638	0.056
6	0.324	3	0.067	0.248	0.636	
7	0.317	2			0.609	0.067
8	0.304	4	-0.352	-0.156	0.622	0.173
9	-0.021	1	-0.121			
10	-0.029	1		0.083		

The correlation of MC gradient (y) with heartwood percentage (x_2) was not significant (p>0.05). MC gradient (y) was, however, positively correlated with green MC (x_3) as shown in Figure 3.6.

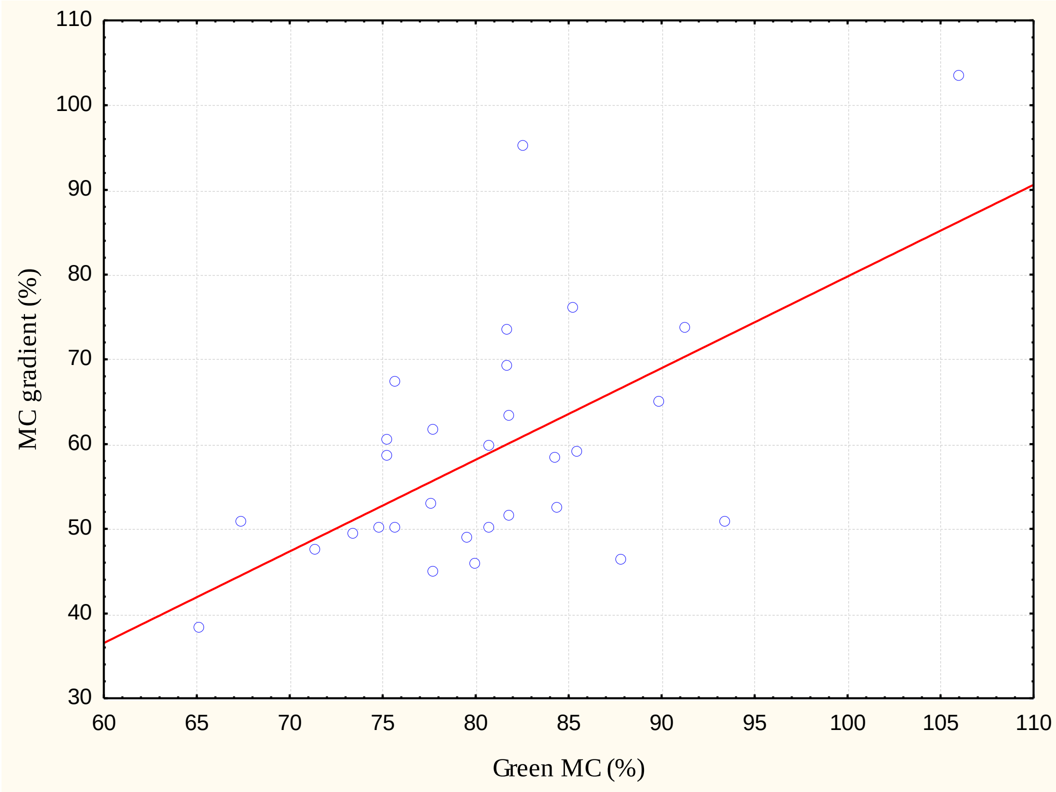

Figure 3.6: Plot of MC gradient and Green MC with correlation Spearman coefficient: r = 0.50 (p = 0.01)

3.4.3 Honeycomb percentage

When the transformed honeycomb percentage (HC*) i.e. $\arcsin\left(\sqrt{HC}\right)$ where HC = honeycomb percentage, was used as the dependent variable and sapwood depth (x_1), heartwood percentage (x_2), green MC (x_3) and pole diameter (x_4) as predictors in a regression model, the adjusted R^2 and Mallows' Cp were 0.450 and 5.000 respectively (Table 3.7). Using these criteria, the best model had three predictors; sapwood depth (x_1), heartwood percentage (x_2) and pole diameter (x_4), with the adjusted R^2 of 0.466 and confirmed by the smallest Mallows' Cp of 3.815 (Table 3.7).

Table 3.7: All-subsets, multiple regression analysis of HC* versus x_1, x_2, x_3 and x_4, Adjusted R^2, Mallows' Cp selection criteria and standardized regression coefficients for each model

Model no.	Adjusted R^2	Mallows' Cp	No. of effects	Sapwood depth (x_1)	Heartwood percentage (x_2)	Green MC (x_3)	Pole diameter (x_4)
1	0.466	3.815	3	1.348	1.907		-0.808
2	0.462	5.000	4	1.541	2.111	0.130	-0.857
3	0.431	4.522	2		0.620		-0.350
4	0.414	6.312	3		0.630	0.064	-0.341
5	0.373	6.624	1	-0.628			
6	0.370	7.585	2	-0.591			-0.144
7	0.353	8.482	2	-0.632		0.051	
8	0.350	8.590	2	-0.567	0.066		
9	0.347	9.541	3	-0.594		0.029	-0.139

x_3 was dropped from the regression equation (Equation 4) on the basis of a large adjusted R^2 and small Mallows' Cp.

$$y = 0.011x_1 + 0.009x_2 - 0.002x_4 - 0.305 \quad \ldots\ldots\ldots \quad (4)$$

Where: y = HC*

x_1 = sapwood depth (mm)

x_2 = heartwood percentage

x_4 = pole diameter (mm)

The associated ANOVA showed that the contribution of sapwood depth (x_1) to the variation in HC* was not significant (F (1, 26) = 2.726, p = 0.111), while both heart wood percentage (x_2) (F (1, 26) = 5.811, p = 0.023) and pole diameter (x_4) (F (1, 26) = 6.823, p = 0.015) contributed significantly.

The correlation of HC* with sapwood depth (x_1) was negative as shown in Figure 3.7. HC* and heartwood percentage (x_2) were positively correlated (Figure 3.8), as observed in the regression model (Equation 4). However, the correlation of HC* with pole diameter (x_4) was negative and not significant (p>0.05).

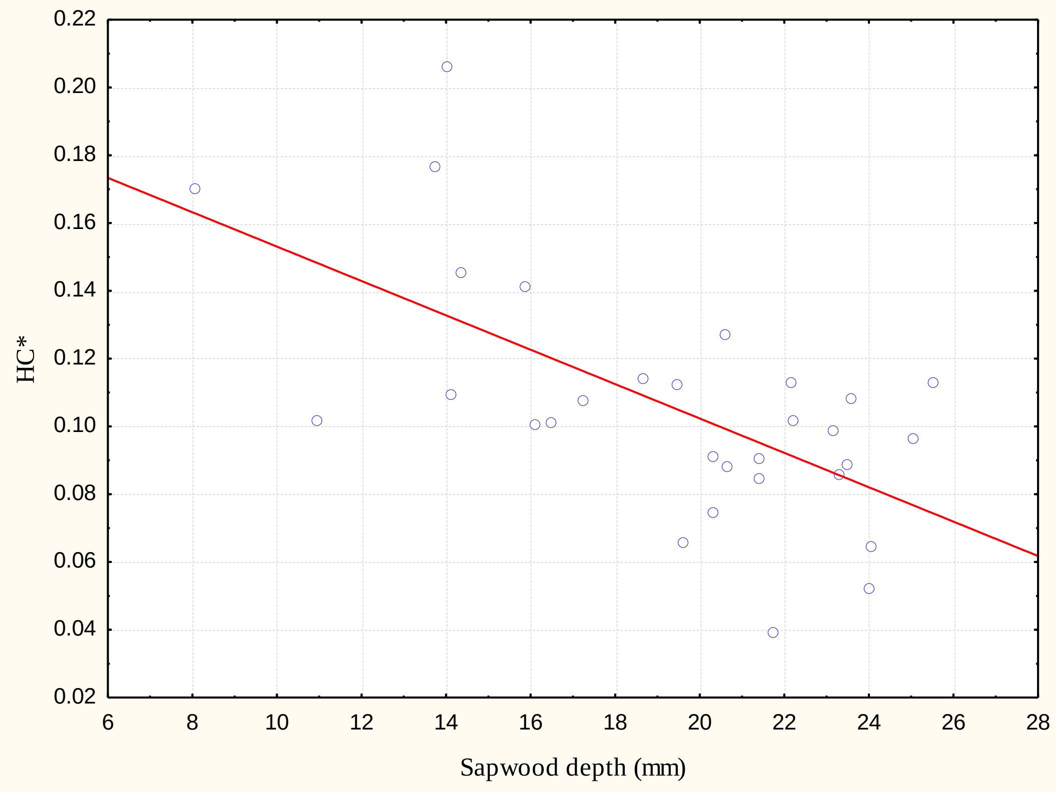

Figure 3.7: Plot of HC* and sapwood depth with Spearman correlation coefficient: r = - 0.55 (p = 0.00)

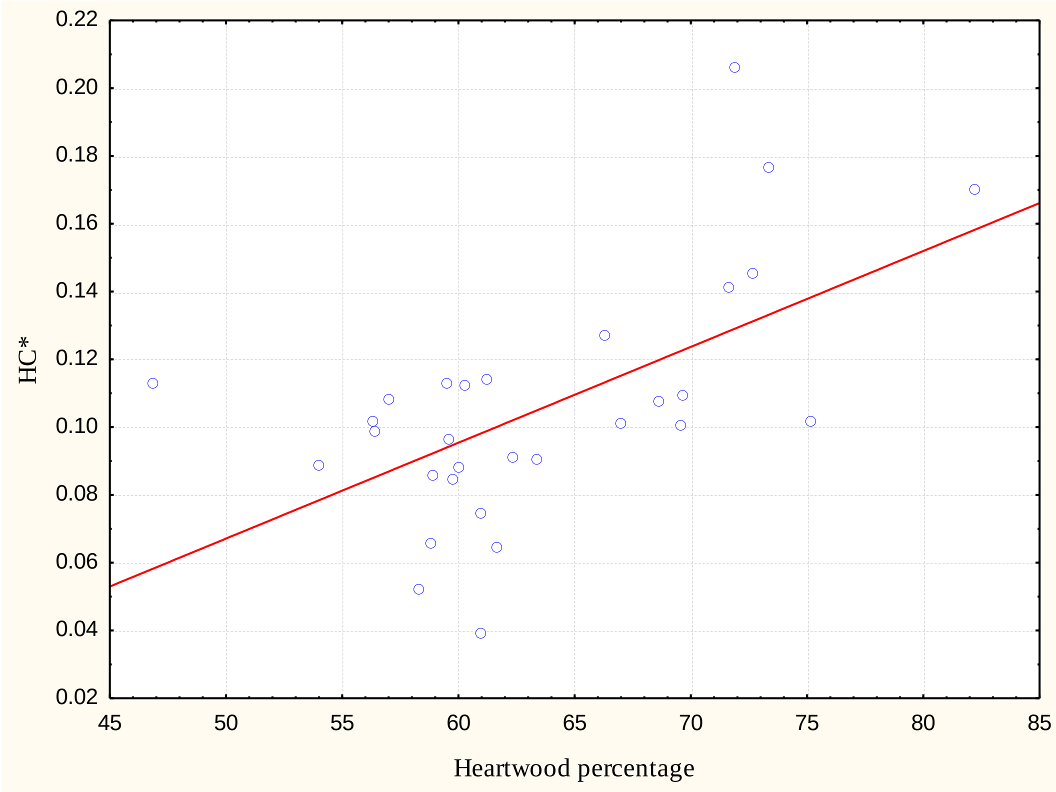

Figure 3.8: Plot of HC* and heartwood percentage with Spearman correlation coefficient: r = 0.49 (p = 0.01)

3.4.4 Collapse class

Collapse class (an ordinal variable) was positively correlated with heartwood percentage (Figure 3.9). The Spearman correlation of collapse with green MC was negative, contrary to what was expected (Figure 3.10).

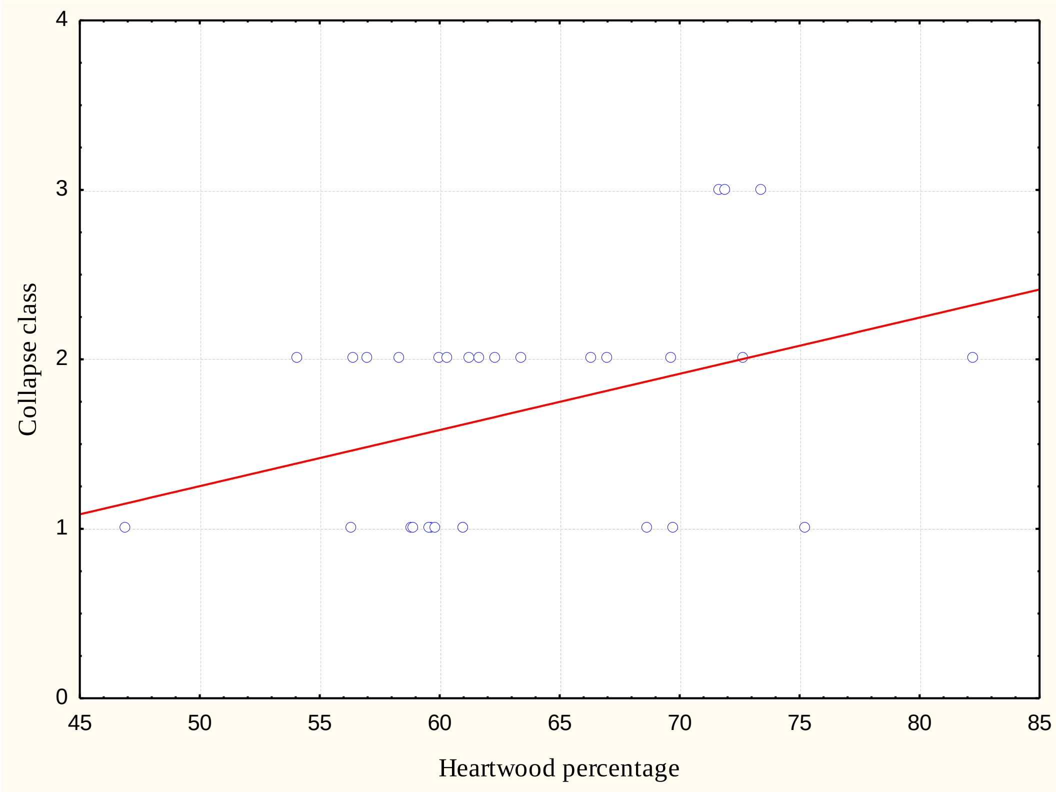

Figure 3.9: Plot of collapse class and heartwood percentage with Spearman correlation coefficient: r = 0.36 (p = 0.05)

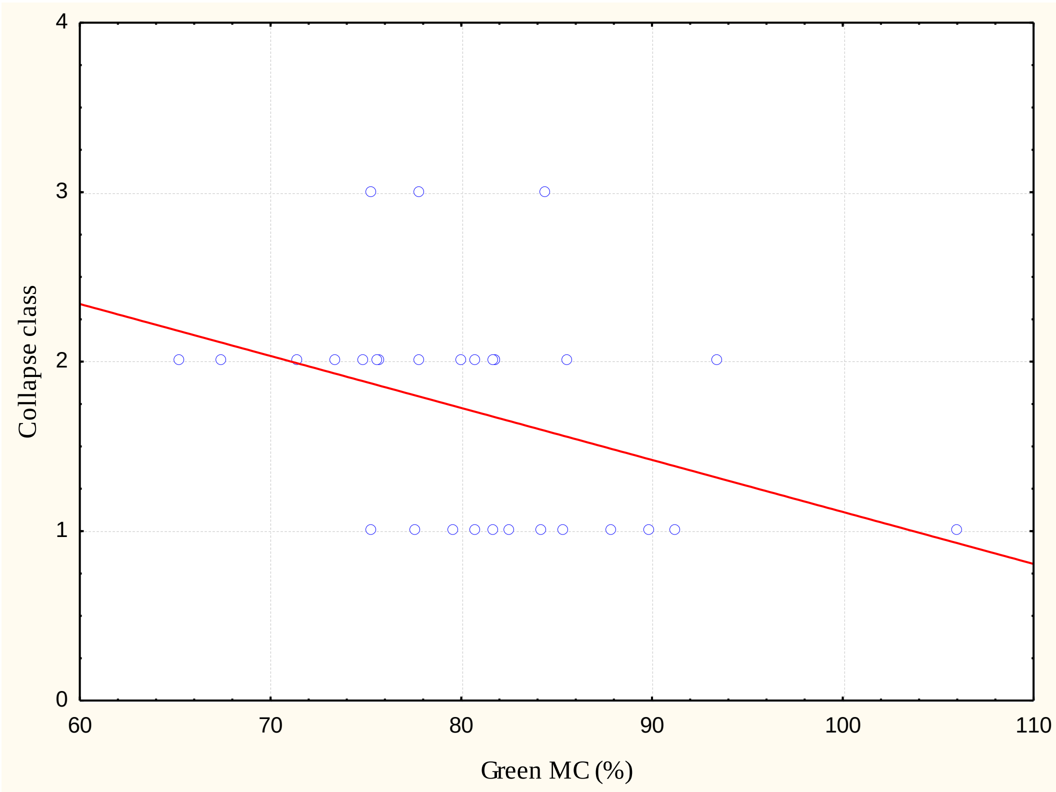

Figure 3.10: Plot of collapse class and green MC with Spearman correlation coefficient: r = -0.38 (p = 0.04)

3.5 Discussion

The average surface check depth (56 mm) was generally greater than the average sapwood depth (16.8 mm) at TGL, which means that surface checks extended beyond the treatable zone, thus exposing the impermeable heartwood. Wessels *et al*. (2004) indicated that even deep surface checks did not ensure creosote penetration into *Eucalyptus* heartwood (Figure 3.11). Such deep checks would offer avenues for water and wood degrading organisms to gain entry into the poles, thus reducing their service life.

Figure 3.11: Deep surface checks in a treated *Eucalyptus* pole with no creosote penetration in the heartwood (Wessels *et al*., 2004)

The positive correlation between surface check total length and sapwood depth was probably because the tensile strength of the surface layers decreased as the sapwood zone increased, thus weakening the capacity of wood to resist tensile stresses, leading to longer checks. According to Record (1914), sapwood may be inferior in strength to heartwood from the same log. Therefore, poles with a high growth rate or those that are relatively younger, may be more susceptible to surface checking than more mature ones due to a larger sapwood depth.

MC gradient was correlated with green MC. Poles with higher green MC's require longer drying times to reach the required MC and an acceptable MC gradient than poles with lower green MC, dried using the same kiln schedule. Therefore, in any particular drying schedule, poles with a high green MC would still have a very high MC in the core compared to the surface layers, hence the higher MC gradient.

The positive relationship between the transformed honeycomb percentage (HC*) and heartwood percentage was probably due to the higher density of the heartwood. Tsoumis (1991) noted that the magnitude of shrinkage is higher with higher density and this may explain the positive correlation of honeycomb with heartwood percentage. This corroborates observations by Harris and Araman (1995) and Harris *et al*. (1988) in a study on red oak lumber where a positive correlation was found between density and occurrence of honeycomb during kiln drying. The fact that HC* was negatively correlated with sapwood depth confirms the above explanation because the smaller the sapwood depth for a fixed diameter, the larger the heartwood percentage. Collapse was also positively correlated with heartwood percentage. Collapse occurs in parts of wood with poor air permeability (Koehler and Thelen, 1926). According to Wilkins and Wilkes (1987), deposition of extractives in the heartwood may reduce pore size and so increase the extent of collapse. This is because reduced pore size leads to reduced air permeability and increased capillary forces in the heartwood, thus causing collapse during drying (Yang, 1998). The correlation of collapse with green MC was negative, which was unexpected because collapse occurs above the fibre saturation point (during the early stages of drying) when free water leaves the cells (Chafe *et al*., 1992; Pratt, 1974; Tiemann, 1941). In addition, Chafe (1985) noted that if newly sawn *Eucalyptus regnans* timber had a high green MC, there was a high possibility that severe collapse will occur during drying. It is possible that collapse was negatively correlated with green MC because poles with higher green MC lost only a small percentage of the original moisture compared to poles with lower green MC, therefore, the heartwood MC hardly changed and collapse was less than that in poles with lower green MC.

3.6 Conclusions

- Surface check total length was positively correlated with sapwood depth i.e. the deeper the sapwood the greater the surface check length.

- The average depth of surface checks was greater than the average sapwood depth at TGL. Wood deteriorating organisms would, therefore, have entry points to the untreatable heartwood even if such poles were treated.

- MC gradient was positively correlated with green MC i.e. the higher the green MC the steeper the gradient at the end of drying.

- The transformed honeycomb percentage (HC*) and collapse were both positively correlated with heartwood percentage. However, correlation of collapse and green MC was unexpectedly negative.

- Sapwood depth, green MC and heartwood percentage are, therefore, important pole characteristics in drying. If sorting before drying of poles by these characteristics is done and appropriate kiln schedules used, drying defects can be minimised.

- For poles with large sapwood depths i.e. >15 mm, milder conditions at the beginning of a drying run should be used, since such poles may be more susceptible to surface checking. Also poles with a larger heartwood percentage should also be dried with suitable kiln schedules to minimize honeycomb and collapse.

- Poles with larger variations in size should be investigated in order to make reliable conclusions about the relationship of pole diameter with drying defects. A larger pole sample than was used in this study, should also be considered.

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Chapter 4: Suitability of auger drill sampling for the measurement of moisture content gradient in kiln-dried *Eucalyptus grandis* poles

4.1 Abstract

Moisture content (MC) gradient at the time of preservation plays a pivotal role in determining the success of the preservation process. The South African pole drying industry relies on auger drill sampling to determine whether the MC of dried poles is acceptable for preservative treatment. The objectives of this study were to determine: (i) the reliability and (ii) potential sources of errors of the auger drill MC sampling method on kiln dried *E. grandis* poles. Destructive oven-dry MC determination on sample blocks of 12.5 mm thickness and 25 mm width as the benchmark method and auger drill samples in increments of 25 mm were used to determine the MC gradient at the theoretical ground line (TGL) of poles. The MC of 25 mm increment auger drill samples did not differ from that measured using the block method. However, there were differences between MC values measured using the auger drill and block methods when single samples of 50 mm and 75 mm length were considered. Differences in MC values measured also occurred in parts of the poles where moisture was still high, i.e. above fibre saturation point after drying. It was concluded that SABS SM 983 (2000), which specifies taking single radial auger drill samples of depth 70±5 mm at mid length, is not a reliable method of measuring MC in a kiln dried *E. grandis* pole. It is recommended that MC be determined in auger increments of 25 mm at the most critical zone of a pole, such as the TGL rather than mid length.

4.2 Introduction

For effective preservative treatment, it is important that free water should be removed from the outer portion of poles to facilitate penetration and retention of preservatives. South African *Eucalyptus grandis* poles are usually kiln-dried in order to reach an acceptable moisture content (MC). According to SANS 754 (1994), poles should be dried until the average MC from the surface to 75 mm deep into the pole, measured at mid-length, is ≤25%. SANS 754 (1994) specifies two non-destructive MC measurement methods:

1. using an electric moisture meter (D.C. resistance) to take 2 readings at a depth of at least half the radius at the approximate pole mid-length (SABS SM 986, 1980) and

2. taking 75 mm deep drillings using a sharp auger at the pole mid-length (SABS SM 983, 2000) and oven-drying them (SABS SM 984, 1984).

Due to limitations of moisture meters such as inaccuracy at higher MC (>25%), and variation with temperature (Bowyer *et al.*, 2003), the auger drill method is regarded as more reliable and is recommended in industry (Hill *et al.*, 2006). In laboratory experiments, MC is often determined destructively by cutting block samples and oven-drying them.

Although the auger drill method is widely used in the South African pole drying industry, questions may arise as to whether it is actually suitable for kiln-dried *E. grandis*, especially with the reported increased number of premature utility pole failures (ESI Africa, 2000).

The goal of this study was to assess the suitability of the auger drill method for pole MC gradient measurement using the destructive method of MC measurement on blocks as control. The specific objectives of the study were: (i) to assess the reliability and (ii) to identify potential sources of errors in the auger drill sampling method.

4.3 Materials and methods

It was necessary to use more than one source of poles, and different drying schedules to simulate what normally happens in practice.

4.3.1 Timber

A total of 29 debarked *E. grandis* poles was investigated. Nineteen poles from Kwa-Zulu Natal (KZN) were stored at 3^{o}C for about one year and 5 months. The remaining 10 poles were collected from Coetzenburg, Stellenbosch. For all the poles, the diameter at the theoretical ground line (TGL), 1.5 m from the butt end, ranged between 175-210 mm. Due to the length limitation of the research kiln, only poles 2.1 m in length could be used. Full length utility poles were simulated by sealing and putting end plates at the top ends. End plates were also applied the butt ends of freshly cut poles, as is normally done in practice.

4.3.2 Drying

Pole drying was done in a Kiefer kiln using the following three schedules:

1. 80^{o}C dry bulb (T_{db}) and 59^{o}C wet bulb temperature (T_{wb}) for 8 days; used to dry 10 poles from KZN;

2. 80^{o}C T_{db} and 69^{o}C T_{wb} for 10 days; 9 poles from KZN and

3. 70^{o}C T_{db} and 59^{o}C T_{wb} for 12 days; 10 poles from Coetzenburg.

The air velocity of 4-5 ms^{-1} was maintained for all the schedules.

4.3.3 Sampling

Samples for MC measurement were taken at the theoretical ground line (TGL), 1.5 m from the butt end of the pole.

4.3.3.1 Non-destructive sampling

Three radial holes, approximately 120^{o} apart on the pole circumference, were drilled in the same disc plane using a 12 mm-diameter auger drill as shown in Figure 4.1. From each hole, three sample drillings in increments of 25 mm (Figure 4.1) were collected in airtight weighing bottles through an improvised funnel. Thus, samples 1, 2 and 3 corresponded to sample depths i.e. 0-25 mm, 25-50 mm and 50-75 mm into the pole. The samples were weighed, dried to constant mass in a laboratory oven at 102^{o}C, and reweighed.

4.3.3.2 Destructive sampling

A 25 mm disc was cut just adjacent to the auger drilled holes (Figure 4.1). Three 25 mm wide radial strips were cut from 3 positions approximately 120^{o} apart on this disc, corresponding to the 3 adjacent, previously drilled holes. From each strip, 12.5 mm thick sample blocks were cut as shown in Figure 4.1. The samples were weighed, dried to constant mass in a laboratory oven at 102^{o}C and reweighed. The MC of each auger and block sample was calculated according to the standard formula:

$$MC = \left[\frac{Wet\ mass\ of\ \ wood\ (g) - Ovendry\ mass\ of\ \ wood\ (g)}{Ovendry\ mass\ of\ \ wood\ (g)} \right] \times 100\ (\%)$$

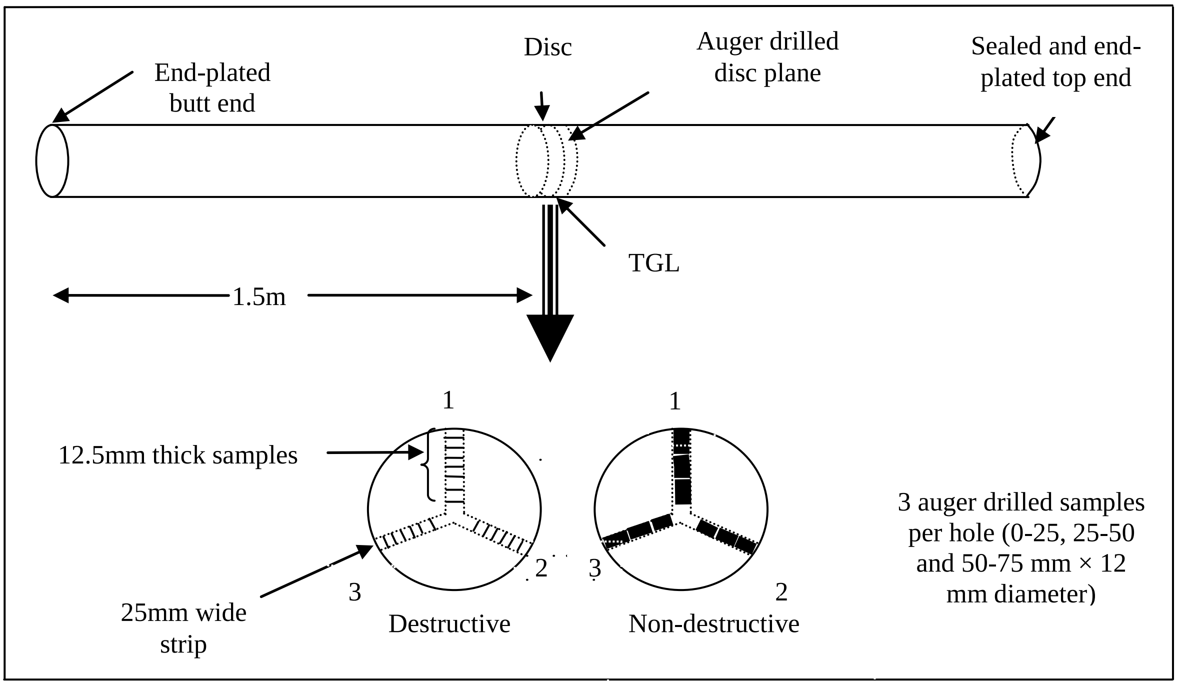


Figure 4.1: Pole sampling positions for MC gradient determination at TGL

4.3.4 Data analysis

The MC of each two successive 12.5 mm sample blocks was averaged to obtain values representing 25 mm, in order to be able to compare them with corresponding 25 mm auger drilled samples. The MC values for 0-50 and 0-75 mm, averaged as single samples, were also computed from the individual 25 mm samples, for both auger drillings and blocks. Repeated measures analysis of variance (RMANOVA) was performed to test for differences between corresponding MC measurements from blocks and auger drill samples. Where residuals proved to be not normally distributed, the results of the RMANOVA were confirmed by using a non-parametric equivalent i.e. the Friedman test. All tests were done at 5% level of significance.

4.4 Results

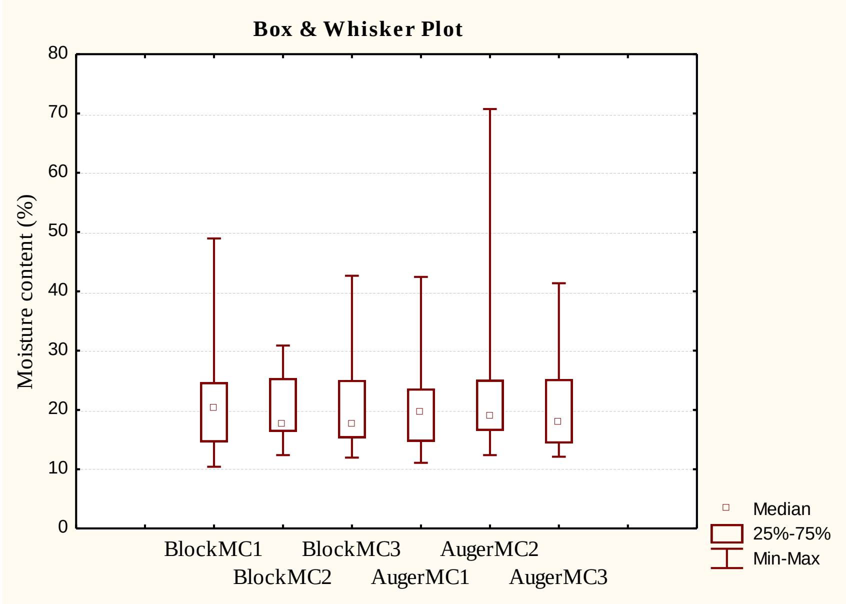
4.4.1 Samples in 25 mm increments

There were no significant ($p>0.05$) differences in MC between the two sampling methods at all three sample depths (Table 4.1).

Table 4.1: Non-significant differences in MC at TGL, measured using blocks and auger drill samples at 25 mm pole radial depth intervals, as determined with RMANOVA

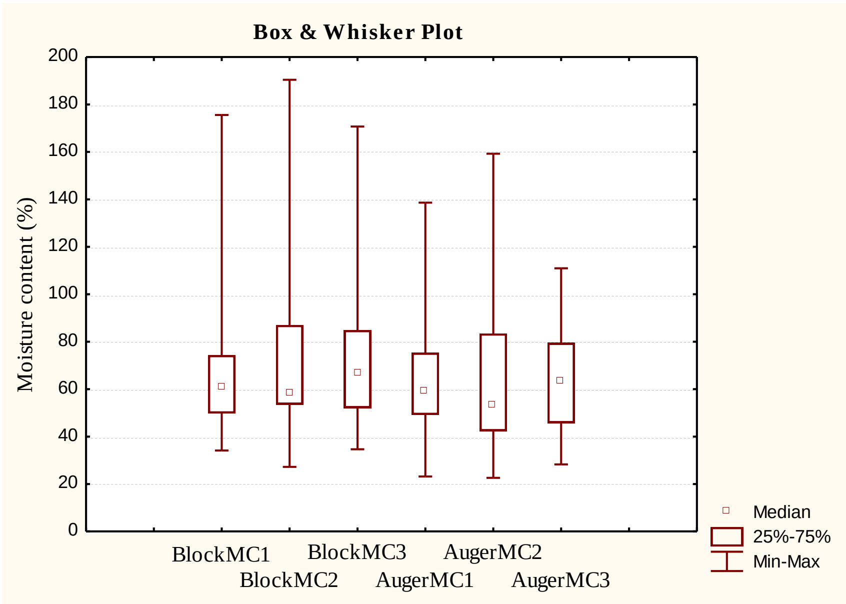
Sample depth (mm)	N	DF	F	p
0-25	29	5	0.878	0.497
25-50	29	5	1.945	0.091
50-75	29	5	0.677	0.642

Box and whisker plots depicted in Figures 2a, 2b and 2c show differences in MC values from blocks and auger drill samples. At 0-25 mm pole radial depth, results of block samples were generally closely matched with values obtained from auger drill samples (Figure 4.2a). At 25-50 mm and 50-75 mm radial depth, auger drill MC values generally had narrower ranges compared to measurements on blocks (Figure 4.2b and 4.2c).



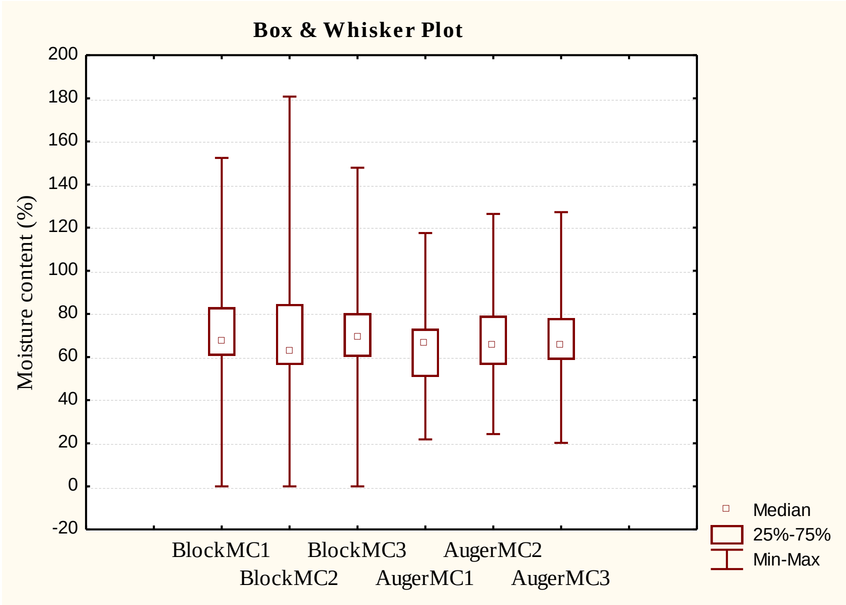
Key: MC1, MC2 and MC3 represent circumference positions 1, 2 and 3 respectively

Figure 4.2a: Variation in MC measurements of blocks and auger drill samples at 0-25 mm pole radial depth



Key: MC1, MC2 and MC3 represent circumference positions 1, 2 and 3 respectively

Figure 4.2b: Variation in MC measurements of blocks and auger drill at 25-50 mm pole radial depth



Key: MC1, MC2 and MC3 represent circumference positions 1, 2 and 3 respectively

Figure 4.2c: Variation of MC measurements of blocks and auger drill at 50-75 mm pole radial depth

The results indicated that the auger drill sampling method can be used to reliably determine the moisture content gradient of kiln-dried *E. grandis* poles (Table 4.1). However, as the depth of measurement increased from the pole surface to the pole centre, differences in MC values of blocks and auger drill samples increased as seen in Table 4.1 and Figure 4.2a, 4.2b and 4.2c.

4.4.2 Single samples of 50 mm

By considering 0-50 mm pole radial depth as individual 50 mm long samples, a significant ($p < 0.05$) difference in MC measured by the two test methods was noted at circumference position 2 (Table 4.2). The auger drill MC ($\overline{X}$ = 42.6%) was lower than MC by blocks ($\overline{X}$ = 45.8%). Taylor (1991) reported similar observations with the increment borer on kiln dried southern pine poles. The same author noted that on average, the MC of blocks was 10 percent higher than that of increment core samples.

Table 4.2: Differences in MC measured using blocks and auger drill samples of 50 mm at different positions around the pole, as determined with RMANOVA

Circumference position	N	DF	F	p
1	29	1	2.347	0.137
2	29	1	4.984	0.034*
3	29	1	2.541	0.122

Key: * = significant difference ($p < 0.05$)

4.4.3 Single samples of 75 mm

When 0-75 mm radial depth was considered as one sample, again MC measured using the auger drill test method was significantly ($p<0.05$) different from that measured using blocks in one of the three circumference positions sampled. It is important to note that the pole circumference position, in which there were differences when considering 50 mm samples (Table 4.2) i.e. position 2, was different from one that had differences when 75 mm samples were considered (Table 4.3) i.e. position 1. The auger drill MC ($\overline{X}$ = 49.4%) was significantly ($p = 0.034$) lower than MC by blocks ($\overline{X}$ = 54.2%).

Table 4.3: Differences in MC measured using blocks and auger drill samples of 75 mm at different positions around the pole, as determined with RMANOVA

Circumference position	N	DF	F	P
1	29	1	4.979	0.034*
2	29	1	1.264	0.270
3	29	1	3.169	0.086

Key: * = Significant difference ($p < 0.05$)

4.5 Discussion

Final MC after kiln-drying increased with increasing distance from the surface to the centre of a pole. This explains the observed lower reliability of the auger drill method with increasing radial depth. When using an increment borer, Purslow (1968) noted that reliable MC measurements were obtained once timber had dried to below 40 %. The same author explained that below 40% MC, there would be less water loss associated with compression of wood as the borer is forced in. Similarly, the leading part or tip of the auger drill goes into the wood ahead of the cutting edge, and in addition, some degree of pressure has to be exerted at the hind handle in order for the drill to penetrate the wood. This causes water losses since the pressure applied squeezes water out of the wood before the sample is actually taken. Therefore, higher water losses (too low MC values) would be expected when the MC in a pole is higher.

It should perhaps be noted that while it is possible with destructive pole sampling to detect possible causes of error in MC measurements such as the presence of pith, knots, honeycomb checks or closed surface checks, this is not picked up by the auger drill method. When one is using the auger drill, the centre of the pole is used as the reference point and in fact, the pith is rarely positioned exactly central. On the smaller radius side of a pole, it is, therefore, possible to drill through the pith when sampling is done. As such, the longer samples in terms of radial depth are likely to have larger deviations from the true value than smaller ones. This explains the differences in MC observed between the two test methods when samples of 50 mm and 75 mm were considered. In addition, it would take more time to drill a longer sample and the longer the drilling time, the higher the possibility of the drill heating up causing moisture losses and more errors.

4.6 Conclusions

- The auger drill can be used to reliably determine the MC of kiln dried *E. grandis* poles by taking 25 mm deep samples provided the poles are not still too wet (MC >60%).

- Auger drill MC measurements were lower than values determined using blocks when samples of 50 mm and 75 mm radial length were considered.

- It seems unreliable to consider a single measurement sample per pole radius, as there are various sources of errors that affect the measurement. For instance, the difference between the highest and lowest MC measurement along the radius is not noticed.

- Single auger drill MC measurements on 50 mm and 75 mm radial samples differed with the position on the pole circumference at TGL. It is, therefore, important to consider sampling more than one position on the pole circumference to cater for the MC variation around a pole. Thus, the minimum of 2 positions around the pole specified by SABS SM 983 (2000) should be adhered to.

- SABS SM 983 (2000), which specifies taking single radial auger drill samples of depth 70±5 mm at mid length, is not a reliable method of measuring MC in a kiln dried *E. grandis* pole as it is likely to underestimate the MC.

- The MC should be determined in increments of 25 mm at the most critical zones of a pole, such as the TGL and not higher up since there is normally considerable MC variation in the longitudinal direction, with the higher MC values found lower down in the pole.

4.7 References

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Chapter 5: Correlation between and within drying defect parameters in kiln-dried *Eucalyptus grandis* poles

5.1 Abstract

Non-destructive testing for drying defects in *Eucalyptus grandis* utility poles is essential since these defects can negatively affect creosote preservative treatment and in-service performance. The objective of this study was to assess correlations between and within defects such as surface checking, honeycombing, collapse and moisture content (MC) gradient in poles, to possibly find a simple and quick but reliable method to assess internal and external drying defects. Defects were measured on 39 kiln-dried *E. grandis* poles. After measuring surface check length, width and depth using a measuring tape, a ruler and a depth gauge, destructive sampling at the theoretical ground line (TGL) was done to measure the MC gradient between the shell and core of poles. Digital image analysis of cross sections of discs cut at TGL was used to measure honeycomb check width, length and area, as well as counting individual closed surface checks. Collapse was assessed using qualitative methods. Results showed that honeycombing and collapse were positively, and surface checking and MC gradient were negatively correlated. Surface check width, length and depth were also correlated. Honeycomb check width, length and area were strongly correlated. It was concluded that measuring any of these surface check and honeycomb parameters may give meaningful deductions on the extent of surface checking and honeycombing respectively. Since surface checking was not correlated with honeycombing or collapse, pole surface analyses such as its surface profile, and its relationship with internal defects need to be investigated in order to develop a practical non-destructive method of quantifying internal defects.

5.2 Introduction

Surface checking, honeycombing and collapse are common drying defects in Eucalypt poles. *Eucalyptus grandis* is prone to collapse (Brown, 1989), and kiln drying may increase chances of other defects to occur. Chudnoff (1955) noted that during the drying of heavy *Eucalyptus* poles, the stresses developed in the surface layers are far higher than in thinner members, and collapse is accompanied by severe surface checking and end splitting. Surface checking (Panshin *et al*., 1964), honeycombing (Wangaard, 1950; Garratt, 1931) and collapse (Bariska, 1992) all affect strength properties of wood.

After drying, it is, therefore, essential that utility poles are inspected for these defects before creosote preservative impregnation. Assessment of all types of drying defects is important, to be certain that acceptable limits are not exceeded. These three different defects or their parameters require different measurement methods. Some defect parameters are more difficult to assess than others. The South African National Standards specify maximum permissible number, width and length of end and surface checks but not the depth (SANS 754, 1994). Yet in fact, the depth of a surface check may be decisive as far as the success of preservation is concerned, especially if it goes deeper than the sapwood. Unfavourable moisture content (MC) gradient, closed surface checks and honeycombing are also not covered in the specification nor are they comprehensively assessed during pole inspection prior to treatment.

By determining meaningful correlations between easily quantifiable parameters within and between defects, reliable deductions may be made. The goal of this study was to assess correlations of defect parameters within and between different defects. The specific objectives of the study were:

(i) to assess correlations between MC gradient, collapse and surface and honeycomb check parameters;

(ii) to assess correlations between surface check length, width and depth and

(iii) to evaluate relationships between honeycomb check length, width and area.

5.3 Materials and methods

Given the large variation in pole material sources, processing such as drying using different schedules, kiln design and operational differences in practice, a large sample of poles is required to be able to generate reliable correlations between and within drying defects. The present work was, therefore, more of an exploratory nature.

5.3.1 Timber

A total of 39, debarked *E. grandis* poles was investigated. Nineteen poles from Kwa-Zulu Natal (KZN) were wrapped in waterproof plastic material and stored at 3^{o}C to minimise moisture loss and possible decay. The duration of storage was about one year and 5 months but the poles were still wet and did not show any signs of decay. It was, therefore, assumed that such storage would not affect correlations of drying defects. The remaining 20 poles were freshly collected from Coetzenburg, Stellenbosch. For all the poles, the diameter at the theoretical ground line (TGL), 1.5 m from the butt end ranged between 175-210 mm. Due to the length limitation of the research kiln, only poles 2.1 m in length could be used. Full length utility poles were simulated by sealing and applying end plates to the top-ends. To minimise end splitting, plates were also fixed to freshly cut butt-ends of poles.

5.3.2 Drying

Pole drying was done in a Kiefer kiln using the following three schedules:

1. 80^oC dry bulb (T_{db}) and 59^oC wet bulb temperature (T_{wb}) for 8 days. This schedule was used to dry 10 poles from KZN and was repeated on 10 poles from Coetzenburg, to investigate effect of the source of material;

2. 80^oC T_{db} and 69^oC T_{wb} for 10 days; 9 poles from KZN and

3. 70^oC T_{db} and 59^oC T_{wb} for 12 days; 10 poles from Coetzenburg.

The air velocity of 4-5 ms^{-1} was maintained for all the schedules.

5.3.3 Evaluation

5.3.3.1 Surface checking

Immediately after unloading the poles from the kiln, the lengths of all visible, individual surface checks ≥1 mm in width were measured using a measuring tape. Check depth and width were measured using a ruler and an improvised depth gauge. The depth gauge comprised of two 170 mm long and 1 mm thick wires fixed in a cork handle on one end, with a separation distance of 20 mm between them at the opposite end.

5.3.3.2 MC gradient

A 25 mm thick disc (disc1) was cut at the TGL and three, 25 mm wide, radial strips were then cut from 3 positions approximately 120^{o} apart on disc 1 (Figure 5.1). From each strip, 12.5 mm thick samples were cut as shown in Figure 5.1. The samples were weighed, dried to constant mass in a laboratory oven at 102^{o}C and re-weighed. The MC of each sample was calculated according to the standard formula:

$$MC = \left[\frac{Wet\ mass\ of\ \ wood\ (g) - Ovendry\ mass\ of\ \ wood\ (g)}{Ovendry\ mass\ of\ \ wood\ (g)} \right] \times 100\ (\%)$$

The MC gradient was then computed by subtracting the average MC of the 0-25 mm depth (shell) from the MC in the centre of the pole (core) at the same radius. The 0-25 mm depth represents more or less the sapwood depth where MC is critical in order to achieve complete preservative penetration during impregnation. Of the three radial strips (Figure 5.1), only the one with the steepest gradient rather than the average of all three strips was considered. This is because microbial degradation may begin from that side of the pole which happens to be insufficiently treated (a too high MC in a particular position leads to insufficient preservative penetration), thus creating a localised problem. If average radial MC gradients are considered, the one too steep gradient (out of 3) may go unnoticed especially if the remaining 2 are low enough to generate a permissible average.

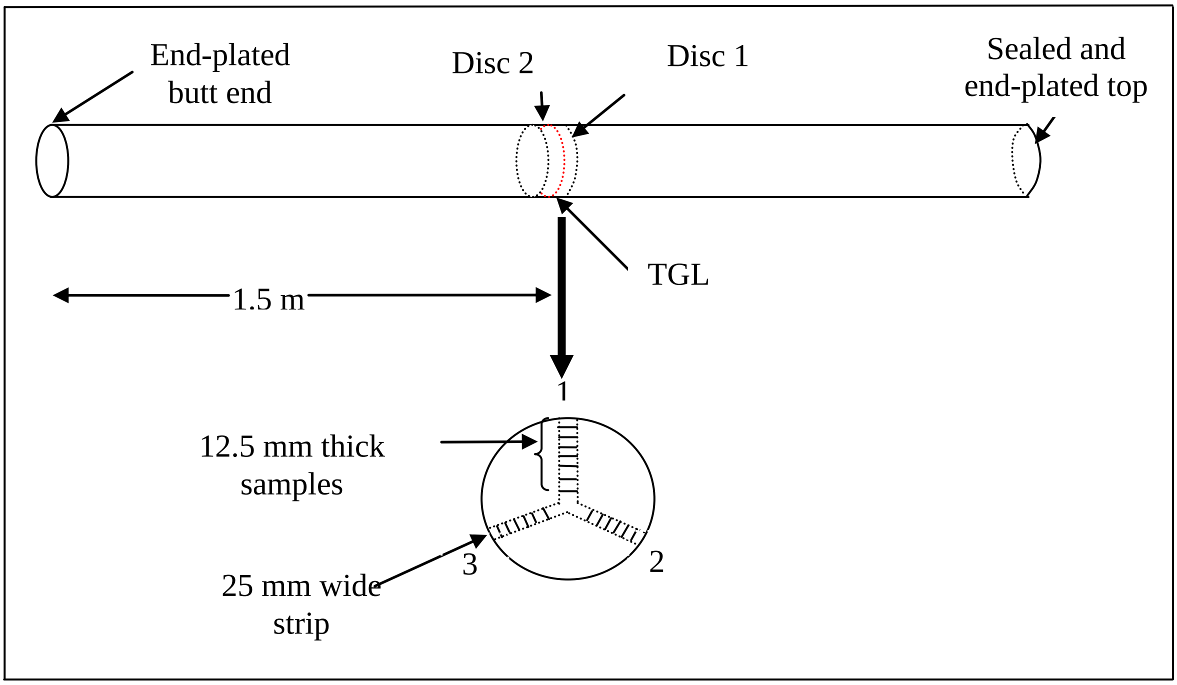
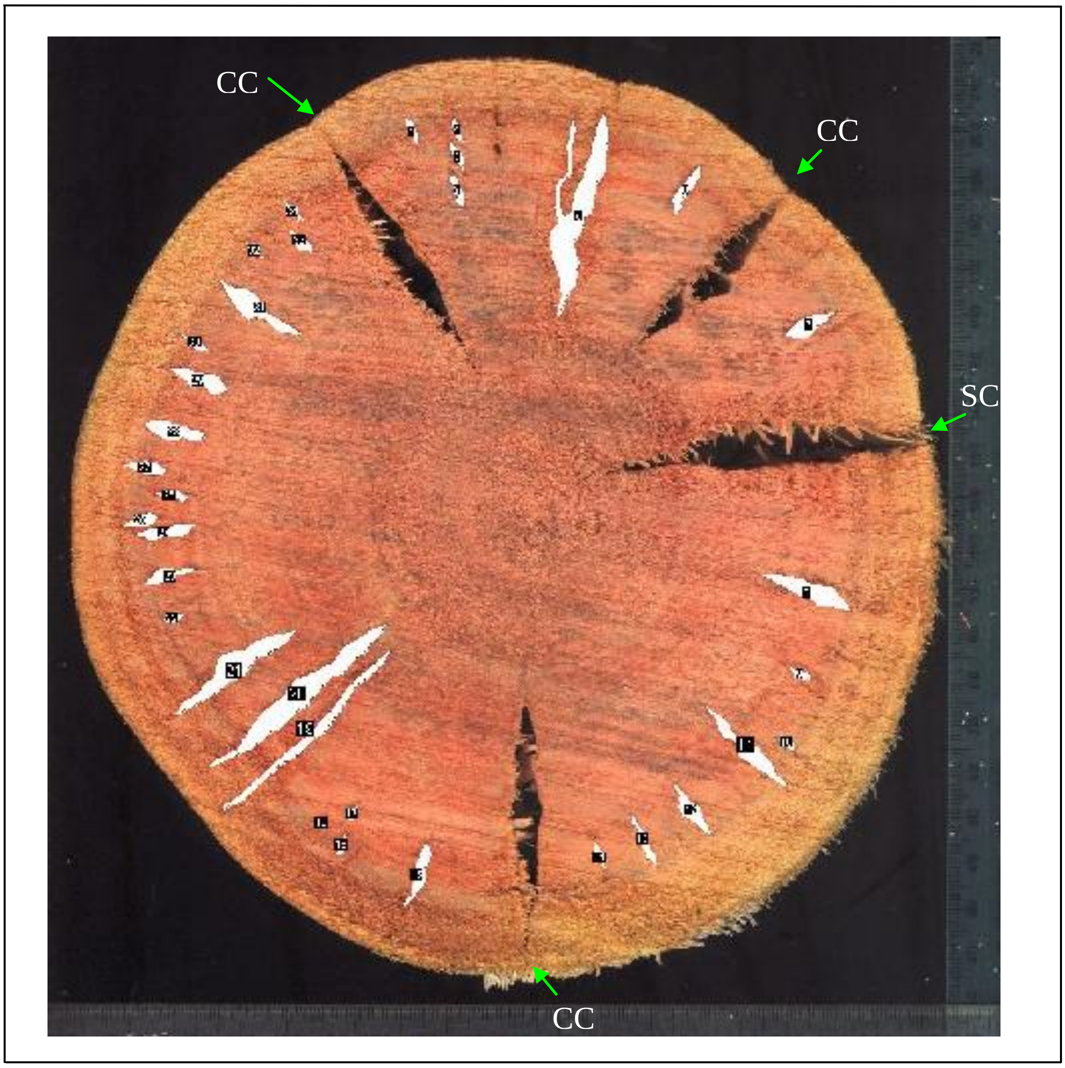


Figure 5.1: Pole sampling for moisture content gradient and honeycombing measurements

5.3.3.3 Honeycombing

A second disc (disc 2) was cut just adjacent to the first one (Figure 5.1). The exposed cross section on the TGL side was sprayed with a solution of 0.1 g dimethyl yellow dye in 100 ml of ethanol (95% v/v) to enhance the contrast of heartwood and sapwood, and scanned using a scanner (BRISA 620P VUEGO SCAN) to obtain digital images (Figure 5.2). Images were analysed using ImageJ software (http://rsb.info.nih.gov/ij) to measure the length, maximum width and area of honeycomb checks as well as the cross-sectional area of the disc. The number of individual closed surface checks, now visible on the image of the disc cross section, was also noted (Figure 5.2).



Key: Filled white = honeycomb
SC = surface checks
CC = closed surface checks

Figure 5.2: Cross section image of a pole disc at TGL

5.3.3.4 Collapse

Collapse was measured by assessing the outer surface of disc 2 (Figure 5.1) for corrugations or grooves developed during drying. The disc cross-sectional surfaces were also observed for presence of collapse. The pole was then classified as belonging to one of the categories 1, 2 or 3, category 3 being one with the worst and 1 the least affected by collapse.

5.3.4 Data analysis

A preliminary analysis of data was done to test for differences in correlations of drying defects caused by the source of material and kiln schedule. Data on all 39 poles were then grouped together and analysed. Since the data was not normally distributed, Spearman non-parametric correlations were used. Factor analyses were also performed to isolate component factors. All tests were carried out at 5% level of significance.

5.4 Results

Table 5.1 shows MC gradient and drying defect values in each pole.

Table 5.1: MC gradient and drying defects in poles

Pole	MC gradient	Surface check count	Surface check total length (mm)	Honeycomb count	Honeycomb percentage	Closed surface check count	Collapse class
1	98.58	9	1.60	34	1.81	6	3
2	67.08	9	2.14	7	0.57	3	1
3	62.34	16	4.62	10	0.65	0	1
4	56.11	2	0.45	11	0.62	1	1
5	84.55	9	1.93	21	0.99	4	2
6	109.35	2	0.65	5	0.10	1	1
7	81.20	0	0.00	38	2.34	4	2
8	68.82	2	0.72	33	1.39	3	2
9	173.32	2	0.61	20	1.35	1	2
10	60.84	12	2.81	5	0.14	4	1
11	73.97	0	0.00	41	5.85	2	3
12	75.64	0	0.00	18	1.82	3	2
13	120.08	1	0.70	31	3.21	1	3
14	77.66	1	0.34	10	0.48	0	1
15	120.20	5	0.67	34	3.13	4	3
16	128.17	6	0.98	31	2.64	1	2
17	161.11	0	0.00	49	3.68	0	3
18	45.99	12	3.12	4	0.13	4	1
19	82.98	3	0.60	25	2.35	0	2
20	58.98	15	2.72	25	0.97	1	2
21	63.25	18	3.05	4	0.78	4	2
22	46.33	14	3.93	12	1.26	1	1
23	69.19	1	0.23	11	1.18	0	1
24	59.69	10	1.46	15	1.27	0	1
25	48.83	17	4.20	10	0.71	2	1
26	76.09	7	1.31	12	0.73	0	1
27	95.08	0	0.00	22	1.03	0	1
28	58.51	29	2.78	3	0.15	1	1
29	73.41	5	1.08	7	1.01	1	2
30	50.76	3	1.11	4	0.27	2	2
31	52.89	2	0.29	5	0.43	0	1
32	50.10	14	1.83	12	1.16	0	2
33	64.92	0	0.00	27	1.14	0	1
34	50.76	12	1.96	14	1.29	0	2
35	38.29	19	3.72	9	0.77	3	2
36	52.35	24	2.65	20	1.98	4	3
37	47.56	3	0.52	6	1.00	1	2
38	50.01	15	2.21	23	1.61	1	2
39	45.75	9	0.52	19	2.08	0	2

In the preliminary analysis, different sources of poles and drying schedules showed different defect correlations. For KZN poles dried with schedule 1, factor analyses showed that honeycomb count, honeycomb checks as a percentage of pole cross section, closed surface checks and collapse class were strongly correlated and grouped together (factor 1) as shown in Table 5.2. Surface check count and surface check total length (factor 2) were also correlated, leaving MC gradient as a separate factor 3 (Figure 5.3).

Table 5.2: Varimax normalized factor loadings with principal components method for KZN poles

Variable	Component Factor 1	Component Factor 2	Component Factor 3
MC gradient	0.087063	0.209571	0.954322*
Surface check count	-0.081299	-0.981633*	-0.166935
Surface check total length	-0.213550	-0.948882*	-0.130191
Honeycomb count	0.905976*	0.311191	0.067153
Honeycomb percentage	0.862724*	0.295043	0.162719
Closed surface check count	0.805742*	-0.096176	-0.299079
Collapse class	0.921647*	0.072619	0.318547

Key: * = Loadings >0.70

Note that surface check width and depth as well as honeycomb check length and width were not included in determining correlations between defects (Table 5.2 and Section 5.4.1). Such parameters were excluded because in computing a single value per pole, averaging may be a potential source of errors. For instance a pole with just one, 4 mm wide surface check would seem to be in a worse condition than another pole with a 5 mm wide surface check and three other checks of 3 mm width (average = 3.5 mm). These parameters were, therefore, only used in determining the within defects correlations (section 5.4.2) where dimensions of individual checks were considered.

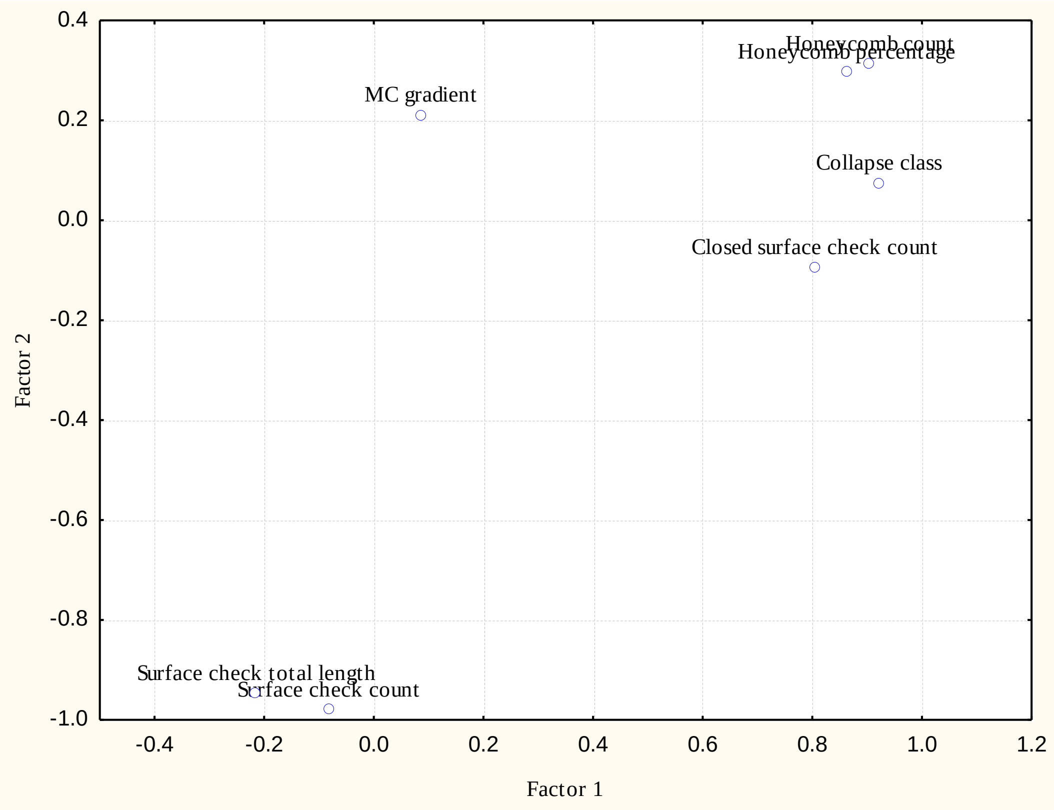


Figure 5.3: Principal component variables in KZN poles

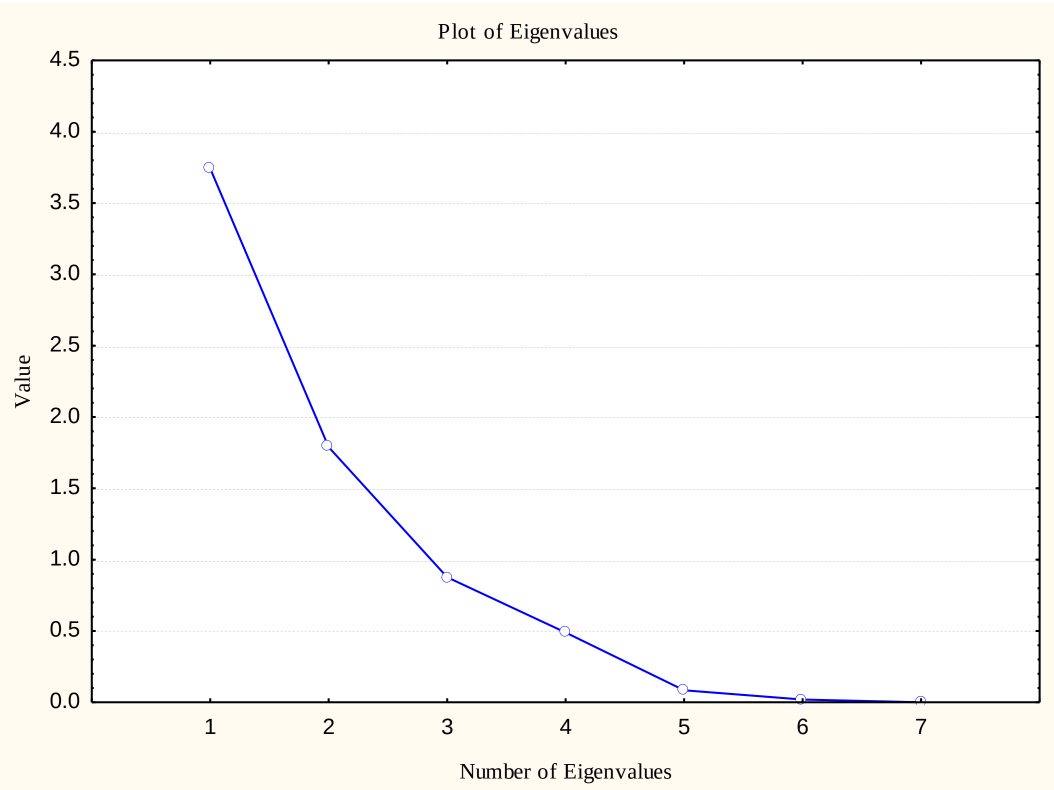


Figure 5.4: Scree plot of component variables in KZN poles

The three factors (Table 5.2) represented up to 90% of the variation in the data (Figure 5.4). Eigenvalues 1, 2 and 3 in Figure 5.4 represent component factors 1, 2 and 3.

Poles from Stellenbosch had defect correlations that differed from that observed in KZN poles although they were dried using the same kiln schedule (schedule 1). Surface check count, surface check total length, closed surface check count and collapse class (factor 1) were correlated (Table 5.3a). Honeycomb count and honeycomb checks expressed as a percentage of pole cross-sectional area were also correlated (factor 2) leaving MC gradient a separate factor (factor 3) as shown in a plot of factor 2 versus factor 1 (Table 5.3a).

Table 5.3a: Varimax normalized factor loadings with principal components method for schedule 1 Stellenbosch poles

Variable	Component Factor 1	Component Factor 2	Component Factor 3
MC gradient	-0.328338	0.150721	-0.904662*
Surface check count	0.795730*	0.423439	0.334190
Surface check total length	0.824069*	0.074457	0.374067
Honeycomb count	0.023242	0.850092*	-0.445013
Honeycomb percentage	0.151668	0.960066*	0.099838
Closed surface check count	0.945745*	-0.134921	-0.029593
Collapse class	0.761484*	0.322657	0.321118

Key: * = Loadings >0.7

Drying defect correlations of Stellenbosch poles dried using schedule 3 differed (Table 5.3b) from those observed in poles from the same source but dried using schedule 1 (Table 5.3a). Factor analysis showed that MC gradient and surface checking (factor 1) were correlated. Correlations also existed between closed surface check count and collapse class (factor 2), and honeycomb count and honeycomb percentage of pole cross sectional area (factor 3) as seen in Table 5.3b.

Table 5.3b: Varimax normalized factor loadings with principal components method for schedule 3, Stellenbosch poles

Variable	Component Factor 1	Component Factor 2	Component Factor 3
MC gradient	0.964177*	-0.001170	-0.042147
Surface check count	-0.697392	0.095908	0.618749
Surface check total length	-0.932515*	0.177267	0.207317
Honeycomb count	0.162382	-0.125271	-0.762255*
Honeycomb percentage	0.079837	0.019753	-0.919352*
Closed surface check count	-0.425203	0.739950*	0.369087
Collapse class	0.043396	0.950749*	-0.062101

Key: * = Loadings >0.70

Correlation results for all 39 poles grouped and analysed together, irrespective of source or drying schedule are shown in Table 5.4. Several relationships between the variables existed, for instance surface check total length was correlated to the rest of the variables except collapse class (Table 5.4), hence the use of factor analysis (section 5.4.1).

Table 5.4: Correlations of all variables

Variable	MC gradient	Surface check count	Surface check total length	Honeycomb check count	Honeycomb Percentage	Closed surface check count	Collapse class
MC gradient	-	-0.583*	-0.489*	0.514*	0.378*	0.013	0.263
Surface check count	-0.583*	-	0.928*	-0.402*	-0.310	0.225	-0.078
Surface check total length	-0.489*	0.928*	-	-0.425*	-0.396*	0.322*	-0.150
Honeycomb check count	0.514*	-0.402*	-0.425*	-	0.857*	-0.004	0.592*
Honeycomb percentage	0.378*	-0.310	-0.396*	0.857*	-	-0.016	0.733*
Closed surface check count	0.013	0.225	0.322*	-0.004	-0.016	-	0.343*
Collapse class	0.263	-0.078	-0.150	0.592*	0.733*	0.343*	-

Key: * = significant correlations ($p < 0.05$)

5.4.1 Correlations between defect types

A factor analysis of the data grouped together isolated three principal components. Collapse, honeycomb count and honeycomb checks expressed as a percentage of cross-sectional area were strongly correlated and were taken as component factor 1. MC gradient, surface check count and surface check total length were also strongly correlated (factor 2), leaving closed surface checks as a separate variable (factor 3) as seen in Table 5.5.

Table 5.5: Varimax normalized factor loadings with principal components method for all the data grouped together

Variable	Component factor 1	Component factor 2	Component factor 3
MC gradient	0.437	0.593*	0.085
Surface check count	-0.082	-0.945*	0.111
Surf check total length	-0.206	-0.890*	0.167
Honeycomb count	0.860*	0.334	0.039
Honeycomb percentage	0.920*	0.213	-0.080
Closed surface check count	0.116	-0.141	0.971*
Collapse class	0.864*	0.038	0.306

Key: * = Loadings >0.59

These three factors represented 84% of the variation in data as shown in the scree plot (Figure 5.5). Eigenvalues 1, 2 and 3 represent factors 1, 2 and 3 respectively (Figure 5.5). MC gradient was negatively correlated with surface checking (Table 5.4). The plot of MC gradient and surface check total length is shown in Figure 5.6.

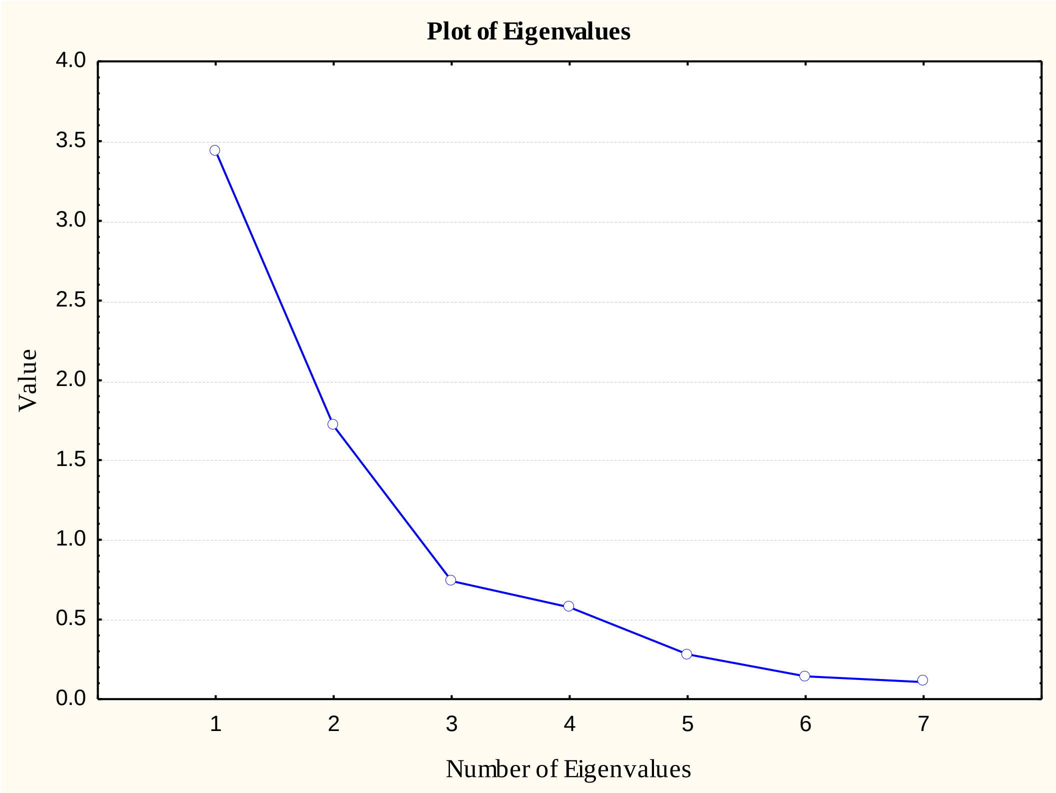


Figure 5.5: Scree plot of component variables

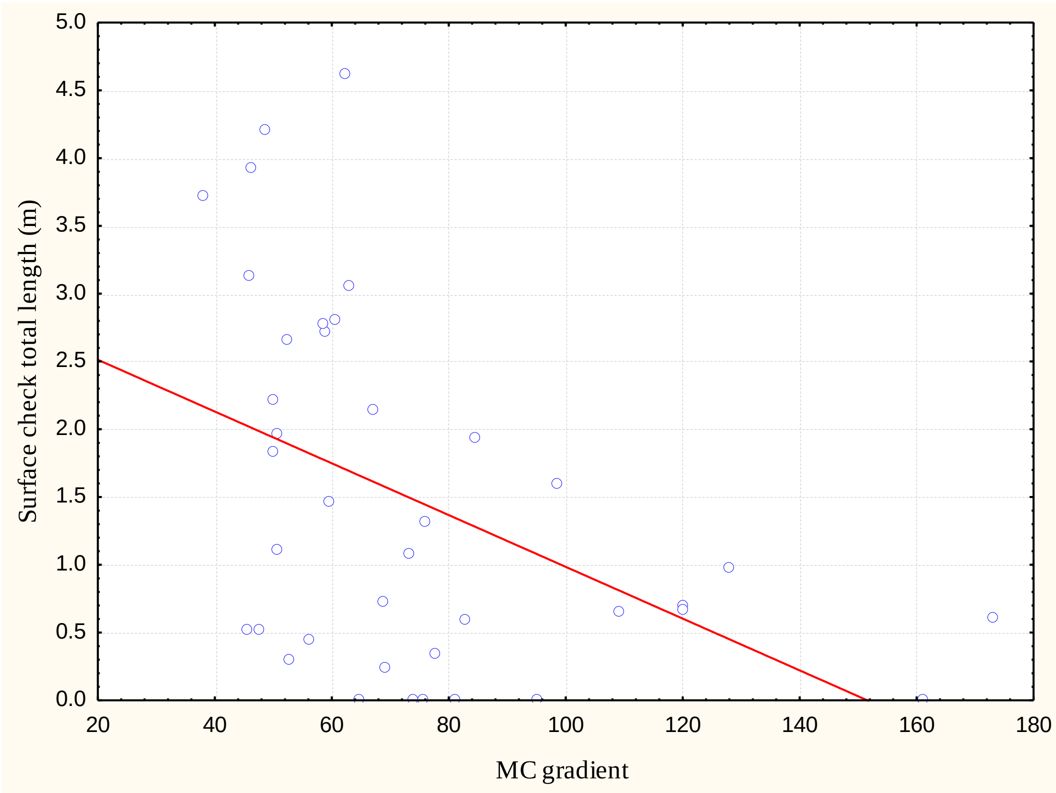


Figure 5.6: Plot of MC gradient and surface checking, with Spearman correlation coefficient: r = 0.49 (p = 0.00)

Where the MC gradient was very steep, MC was still high even in the outer portion, with values above fibre saturation point in the shell of some poles (Table 5.6).

Table 5.6: MC gradient between the centre and outer portion of the pole

Pole	MC at 25mm deep (%)	Highest (core) MC (%)	MC difference (%)
1	23.61	122.19	98.58
2	14.34	81.42	67.08
3	15.24	77.58	62.34
4	13.19	69.30	56.11
5	16.39	100.94	84.55
6	12.63	121.99	109.35
7	29.56	110.76	81.20
8	16.97	85.79	68.82
9	30.86	204.18	173.32
10	12.38	73.21	60.84
11	21.17	95.15	73.97
12	28.66	104.29	75.64
13	42.63	162.72	120.08
14	17.05	94.70	77.66
15	25.35	145.56	120.20
16	22.28	150.45	128.17
17	15.36	176.47	161.11
18	12.40	58.39	45.99
19	26.66	109.63	82.98
20	17.43	76.41	58.98
21	14.56	77.81	63.25
22	16.32	62.65	46.33
23	24.67	93.86	69.19
24	22.28	81.97	59.69
25	15.28	64.11	48.83
26	13.99	90.09	76.09
27	28.10	123.18	95.08
28	14.96	73.47	58.51
29	20.71	94.12	73.41
30	16.89	67.65	50.76
31	20.55	73.44	52.89
32	17.80	67.89	50.10
33	32.31	97.23	64.92
34	23.94	74.70	50.76
35	18.74	57.03	38.29
36	18.44	70.79	52.35
37	22.39	69.95	47.56
38	24.43	74.44	50.01
39	22.54	68.29	45.75

5.4.2 Correlations within defect types

Correlations between length, width and depth of surface checks were not strong but significant ($0.31 \leq r \leq 0.4$, $p<0.05$), while honeycomb check length, width and area were all strongly correlated ($r > 0.7$, $p<0.05$). The correlation of honeycomb width and length is as shown in Figure 5.7.

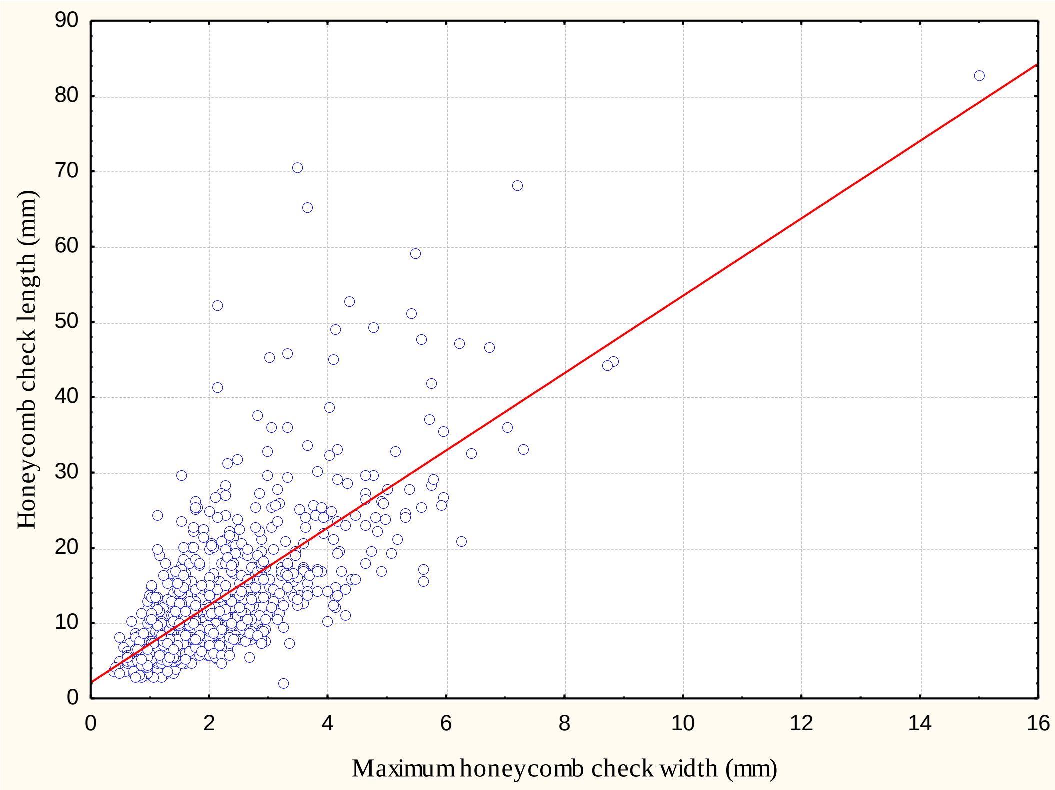


Figure 5.7: Plot of honeycomb check width and length, with Spearman correlation coefficient: r = 0.70 (p = 0.00)

5.5 Discussion

Variations in correlations of drying defects in poles from the two sources could have been caused by the different tree growth rates (and the associated growth stresses) in KZN and Stellenbosch. The combined effects of growth and drying stresses were possibly different in each case.

Varying levels of drying stresses that developed in poles dried with different kiln schedules may be responsible for the observed schedule to schedule differences in defect correlations. However, the limited sample used might have had an effect on the results.

Strong correlations between honeycombing and collapse corroborate observations by Brown (1989), that honeycombing may be associated with collapse where large aggregates of cells collapse and cause internal fractures. In fact, since the pole cores after kiln-drying were generally still wet with all MC's above the fibre saturation point, honeycombing most probably occurred as a result of collapse. Honeycombing associated with collapse occurs above fibre saturation point and may normally be distinguished from the internal checking occurring below fibre saturation point by the associated collapsed surfaces (Brown, 1989). Chudnoff (1955) also noted that the stresses that develop during the drying of heavy *Eucalyptus* poles are very high and collapse is normally accompanied by severe internal checking. Based on the association of honeycombing with collapse, it seems possible to measure one of them (honeycombing or collapse) and make reliably predictions about the other, during pole inspection.

The correlation between surface check total length and MC gradient (after drying) between the surface layers and the centre of poles was negative. Yet Rice (1994) and Pratt (1974) noted that if MC gradient (early in drying) becomes too steep, the outer parts of the wood tend to shrink excessively on to the inner, and severe stresses develop causing surface checking in case the tensile stresses on the surface exceed the maximum tensile strength of the wood perpendicular to the grain (Hildebrand, 1970). Perhaps MC gradient after drying did not relate to MC gradient early during drying and has no bearing on surface checks. It should also be noted however, that in poles where MC gradient (after drying) was too steep, the MC in the surface layers was still too high to cause appreciable shrinkage and stress development. In fact, in some poles, the MC in the outer 25 mm was still higher than the fibre saturation point and minimal shrinkage or none had occurred at all. Therefore, if treated at this moisture content, such poles would continue drying in service and new surface checks would develop and dimensions of already formed checks would also extend, exposing the inner untreated heartwood.

Although the length, width and depth of surface checks were correlated, it still is important to assess each one of them to get a comprehensive picture. For instance, surface checks may be of acceptable length and width but if the depth is not assessed and happens to be deeper than the sapwood, then the preservative impermeable heartwood is exposed. Such checks would present avenues for microbe entry into the poles in service. Although strong correlations between the length, maximum width and area of honeycomb checks were observed, measuring area as a parameter would be more reliable in cases where destructive methods are applicable.

5.6 Conclusions

- Defect correlations varied with the source of poles and drying schedule used. Since a small sample was used, it is recommended that further studies be done on sufficient samples to generate reliable conclusions.

- There were strong and positive correlations between honeycombing and collapse. It is possible, therefore, to make reliable deductions about one of them based on the results of the other.

- Surface checking was found to be negatively correlated with MC gradient (after drying) although the opposite is expected with MC gradient early during drying.

- Despite the positive correlations between width, length and depth of surface checks, it remains important to measure all three parameters to get the true picture of the defect condition.

- Honeycomb check width, length and area were positively and strongly correlated suggesting a possible prediction of one parameter from the other. Therefore, a method that effectively measures any of the dimensions would be appropriate in assessing the overall condition.

- Surface checking was not correlated with honeycombing and collapse, thus prediction of internal defects based on surface checking is not possible. Other pole surface analyses such as surface profile, and its relationship with internal defects need to be investigated in order to develop a practical non-destructive method of quantifying internal defects.

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Chapter 6: Surface profilometry and internal drying defects in kiln-dried *Eucalyptus grandis* poles

6.1 Abstract

After the kiln drying of poles, internal drying defects such as honeycombing and closed surface checks extending deep into the wood are likely to go undetected since successful compulsory proof loading does not guarantee that these internal defects are acceptable in relation to pole preservative treatment and suitability for use. It is, therefore, essential to non-destructively assess these internal defects before impregnation with preservative solutions. The possibility of making reliable conclusions about internal defects based on the visible exterior features of the pole was investigated. The relationship between surface profile, i.e. deviation from cylindrical shape, and honeycombing and closed surface checks was studied. The specific objectives were to assess the correlation of the number of valleys per unit length (VPUL) with: (i) honeycomb check total count; (ii) honeycomb check area as a percentage of the pole cross section; (iii) count of honeycomb checks with width ≥2.5 mm and (iv) closed surface check count. Discs were cut at the theoretical ground line (TGL) of 39 kiln dried *Eucalyptus grandis* poles and their exposed internal cross-sections scanned to produce digital images. Honeycombing and closed surface checks were then assessed using image analysis. Surface profiles were generated by plotting radial distances from the pith to the surface of the disc. VPUL was found to be positively correlated with honeycomb count and honeycomb expressed as a percentage of the pole cross-sectional area, as well as with closed surface check count. In a regression model where VPUL was a dependent variable, honeycomb total count and closed surface check count were the best two predictors. It was concluded that the use of VPUL as a parameter of the profile of pole circumference can be used to assess honeycomb and closed surface checks.

6.2 Introduction

Ward and Simpson (1997) reported that a corrugated appearance on the lumber surface after drying might indicate severe honeycomb. If this statement is true, it is theoretically possible to assess internal drying defects of a pole based on the condition of the surface. Honeycombing and closed surface checks are internal timber drying defects that can go undetected and result in losses during further processing such as machining of timber (Fuller *et al.*, 1995). In wooden utility poles where there is usually no further machining after drying, the possibility of not detecting these internal drying defects is even higher. Undetected honeycomb and closed surface checks may result in reduced strength (Wangaard, 1950; Garratt, 1931) and incorrect preservative penetration and distribution, despite sufficient overall retention after treatment. There is, therefore, a need to develop non-destructive methods of measurement of internal defects in wooden utility poles that can reliably be used in industry.

Surfaces of wood or other materials may be categorised by either topography or profile (Faust and Rice, 1986). Topography is a three-dimensional characteristic of surfaces, while surface profile is a two-dimensional measurement (Stumbo, 1963). Surface profiles are more commonly used in research and industry since there is less data acquisition and processing than with topography measurements (Faust and Rice, 1986). Many devices that can accurately measure and record profiles of sawn wood surfaces have been developed (Peters and Mergen, 1971; Peters and Cumming, 1970; Stumbo, 1963; Elmendorf and Vaughan, 1958; Hann, 1957). For example, Peters and Mergen (1971) developed a stylus tracing device specifically for measurement of sawn wood surface profiles. None of these devices was made for measurement of surface profiles of round wood, such as poles. The boundary of the cross section of a cylindrical object, such as a pole can also be presented as surface profile. A perfect cylindrical shape would generate a straight line surface profile. Generally in profilometry, the two most commonly measured properties of profiles are amplitude and frequency. Amplitude is defined as the deviation of the profile on the y-axis, and frequency is the measure of the number of deviations along the x-axis (Faust and Rice, 1986). The same authors noted that although roughness indices may measure any of these properties or a combination, the frequency parameter was the best.

The goal of this study was to assess the relationship between surface profile and internal drying defects in kiln-dried *Eucalyptus grandis* poles. The width of honeycomb checks might be an important determining factor in the formation of valleys on the pole surface. The specific objectives were to assess correlations of the number of valleys per unit length (VPUL) with:

(i) honeycomb check total count;

(ii) honeycomb percentage of cross-section;

(iii) count of honeycomb checks with width $\geq$2.5 mm and

(iv) closed surface check count.

6.3 Materials and methods

A large sample of poles is required to be able to generate statistically reliable correlations of VPUL with internal drying defects, since there is a large variation in pole material sources, drying using different schedules and kiln design and operational differences in practice. This study comprising a rather small sample, is, therefore, regarded as the first step.

6.3.1 Timber

A total of 39, debarked *E. grandis* poles was investigated. Nineteen poles from Kwa-Zulu Natal (KZN) were wrapped in waterproof plastic material and stored at 3^{o}C to minimise moisture loss and possible decay. The duration of storage was about one year and 5 months but the poles were still wet and did not show any signs of decay at the time of the experiment. It was, therefore, assumed that such storage would not affect the results of the study. The remaining 20 poles were collected from Coetzenburg, Stellenbosch. For all the poles, the diameter at the theoretical ground line (TGL), 1.5 m from the butt end ranged between 175-210 mm. Due to the length limitation of the research kiln, only 2.1 m long poles could be used. Full length utility poles were simulated by sealing and applying end plates to the top ends. To minimise end splitting, end plates were also fixed to freshly cut butt ends of poles.

6.3.2 Drying

Pole drying was done in a Kiefer kiln using the following three schedules:

1. 80^{o}C dry bulb (T_{db}) and 59^{o}C wet bulb temperature (T_{wb}) for 8 days; used to dry 10 poles from KZN and repeated on 10 poles from Coetzenburg.

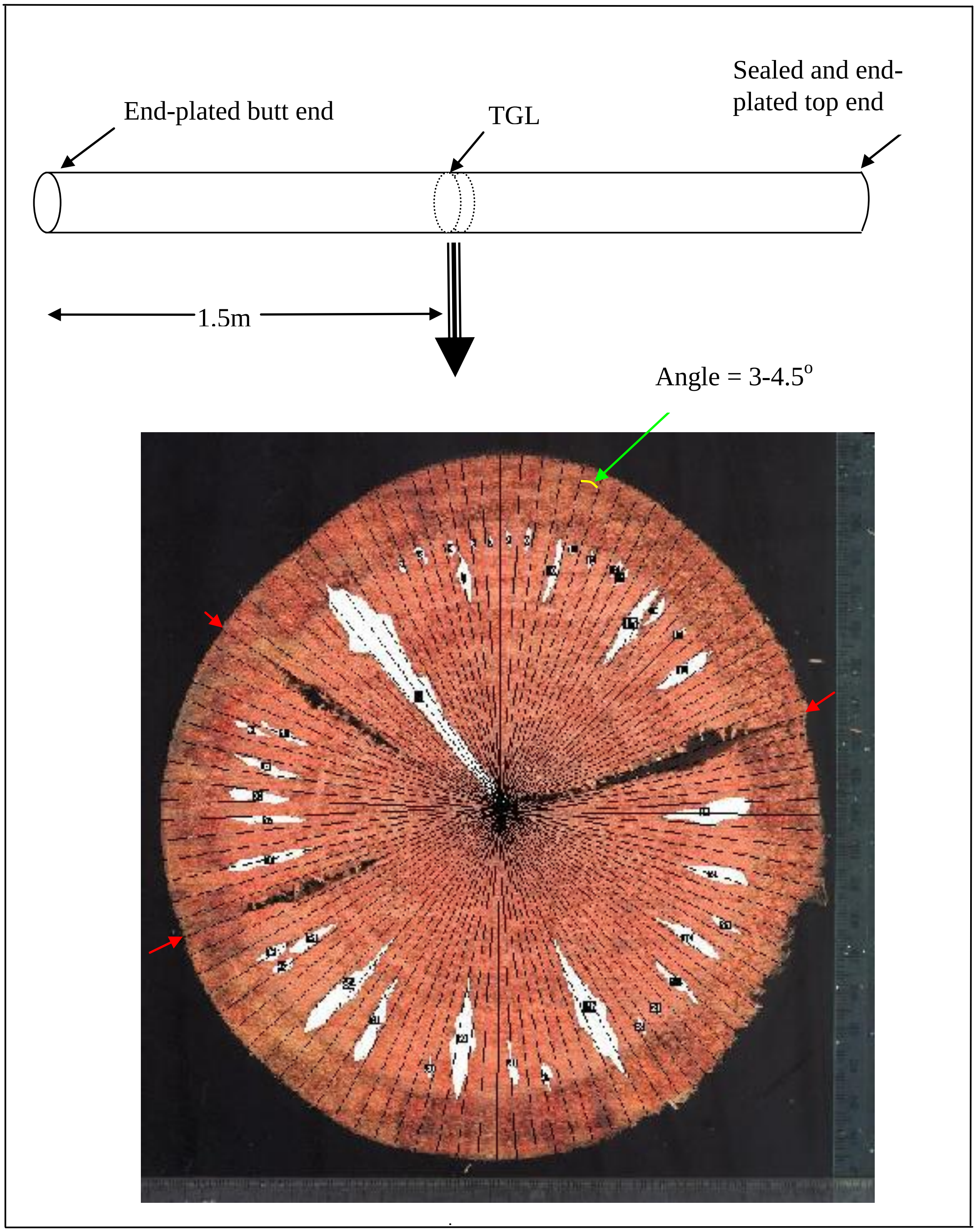
2. 80^{o}C T_{db} and 69^{o}C T_{wb} for 10 days; 9 poles from KZN.

3. 70^{o}C T_{db} and 59^{o}C T_{wb} for 12 days; 10 poles from Coetzenburg.

The air velocity of 4-5 ms^{-1} was maintained for all the schedules.

6.3.3 Evaluation

A disc was cut at the TGL (Figure 6.1) and the exposed cross-section was sprayed with a solution of 0.1 g dimethyl yellow dye in 100 ml of ethanol (95% v/v) to enhance the contrast of heartwood and sapwood, and scanned using a scanner (BRISA 620P VUEGO SCAN) to obtain digital images of internal drying defects. ImageJ software (http://rsb.info.nih.gov/ij) was used to measure the maximum width and area of honeycomb checks as well as the cross-sectional area and circumference of the disc. Individual closed surface checks were also counted. Only the total count of closed surface checks was considered because they were similar to honeycomb checks in shape and orientation (Figure 6.1). If correlations between VPUL and closed surface check count, and between VPUL and honeycomb check count were more or less similar, correlations between VPUL and width or area of internal checks were assumed to be also similar to that between VPUL and width or area of honeycomb checks. Radial distances from the pith to the surface of the disc were measured at intervals of 3-4.5^{o}, depending on the perimeter of a disc, position of the pith and width of honeycomb (Figure 6.2). The longer the radial distance from the pith to disc surface the larger the disc perimeter and for the same angle between 2 radial lines drawn from the pith to disc surface, the larger will be the distance between the two lines at the disc surface. Radial distances were then plotted to generate surface profiles such as shown in Figure 6.2. The total number of valleys was then counted (Figure 6.2). VPUL (m^{-1}) was obtained by dividing the number of valleys by the disc circumference.



Key: Filled white = honeycomb
Red arrows show closed surface checks
Black lines represent radial distances from pith to pole surface

Figure 6.1: Pole sampling for closed surface checks and honeycomb measurement at TGL

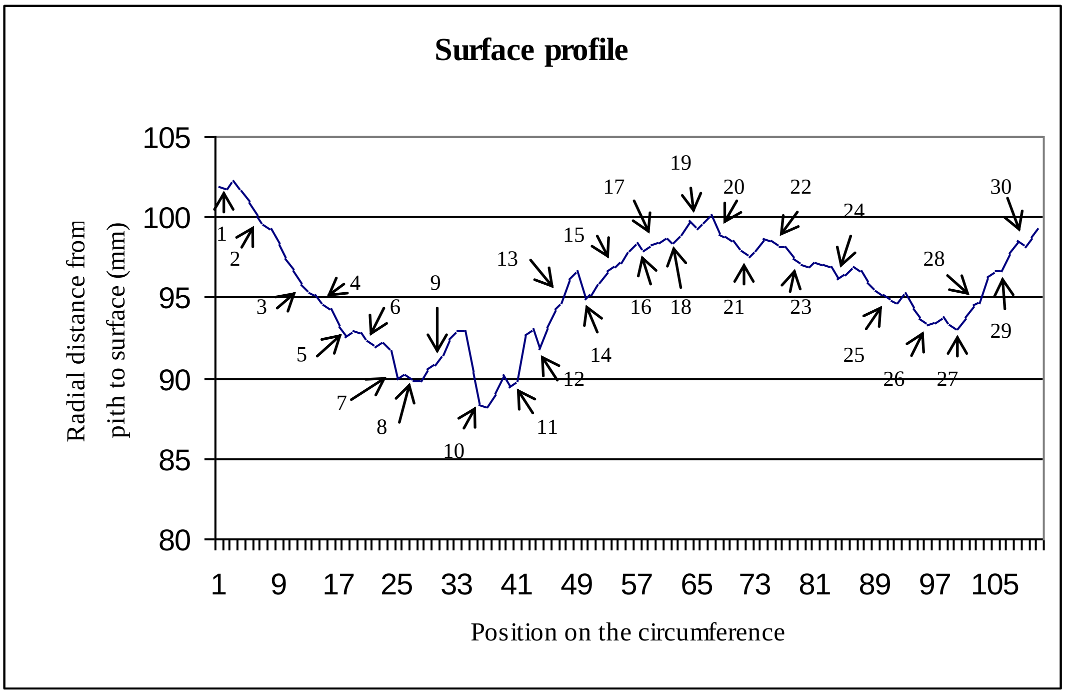


Figure 6.2: Pole circumference profile at TGL with valleys numbered 1 to 30

6.3.4 Data analysis

A preliminary analysis of schedule- and source of poles-specific data was done to test for differences regarding correlations of VPUL with internal defects. All data on the 39 poles were then grouped together and analysed. Correlations, general regression models and factor analyses were used. All tests were performed at 5% level of significance.

6.4 Results

Results from data on the separate samples of KZN and Stellenbosch poles, as well as schedule-specific data indicated that there were no significant ($p>0.05$) correlations of VPUL with any of the internal defect parameters tested. However, results from pooled data on all 39 poles regarded as a single sample, showed that there were positive and significant ($p<0.05$) correlations of VPUL with all the variables tested (Table 6.1).

Table 6.1: Correlations of valleys per unit length (VPUL) with honeycomb and closed surface checks

Variable	VPUL	
	r	p
Honeycomb total count (x_1)	0.542	0.000
Honeycomb width ≥2.5mm count (x_2)	0.467	0.003
Honeycomb percentage (x_4)	0.500	0.001
Closed surface check count (x_3)	0.395	0.013

Fitting the four input variables; honeycomb total count (x_1), honeycomb width ≥2.5 mm count (x_2), closed surface check count (x_3) and honeycomb percentage (x_4) as predictors in a regression model, with VPUL as the dependent variable, adjusted R^2 and Mallows' Cp were 0.361 and 5.000 respectively (Table 6.2). Using these criteria, the best model had two predictors: honeycomb total count (x_1) and closed surface check count (x_3), with the adjusted R^2 of 0.374 and confirmed by the smallest Mallows' Cp of 2.283 (Table 6.2).

Table 6.2: All-subsets, multiple regression analysis of VPUL versus x_1, x_2, x_3 and x_4, Adjusted R square, Mallows' Cp selection criteria and standardized regression coefficients for each model

Model no.	Adjusted R^2	Mallows' Cp	No. of effects	Honeycomb total count	Honeycomb width≥2.5mm count	Honeycomb percentage	Closed surface check count
1	0.374	2.283	2	0.504			0.339
2	0.373	3.354	3	0.317		0.225	0.351
3	0.361	5.000	4	0.383	-0.189	0.338	0.355
4	0.358	3.184	2			0.486	0.376
5	0.356	4.260	3	0.473	0.037		0.339
6	0.340	5.182	3		0.012	0.476	0.376
7	0.309	5.932	2		0.437		0.358
8	0.274	7.028	1	0.542			
9	0.263	8.531	2	0.406		0.164	
10	0.254	9.019	2	0.521	0.024		

On the basis of a large adjusted R^2 and small Mallow's Cp, x_2 and x_4 were dropped leaving the following regression equation:

$$y = 16.13 + 0.35x_1 + 1.69x_3$$

Where: y = VPUL

x_1 = honeycomb total count

x_3 = closed surface check count

The associated ANOVA showed that honeycomb total count (x_1) contributed significantly (F (1, 37) = 15.250, p = 0.0004) to the variation in VPUL. Similarly, the contribution of closed surface check count (x_2) to the variation in VPUL was significant (F (1, 37) = 6.883, p = 0.013).

A factor analysis on the four input variables x_1, x_2, x_3 and x_4 extracted 2 factors by grouping the 4 variables into two principal components. The three honeycomb parameters as one (factor 1) and closed surface check as the other factor (factor 2) as shown in the plot of factor 2 versus factor 1 (Figure 6.3).

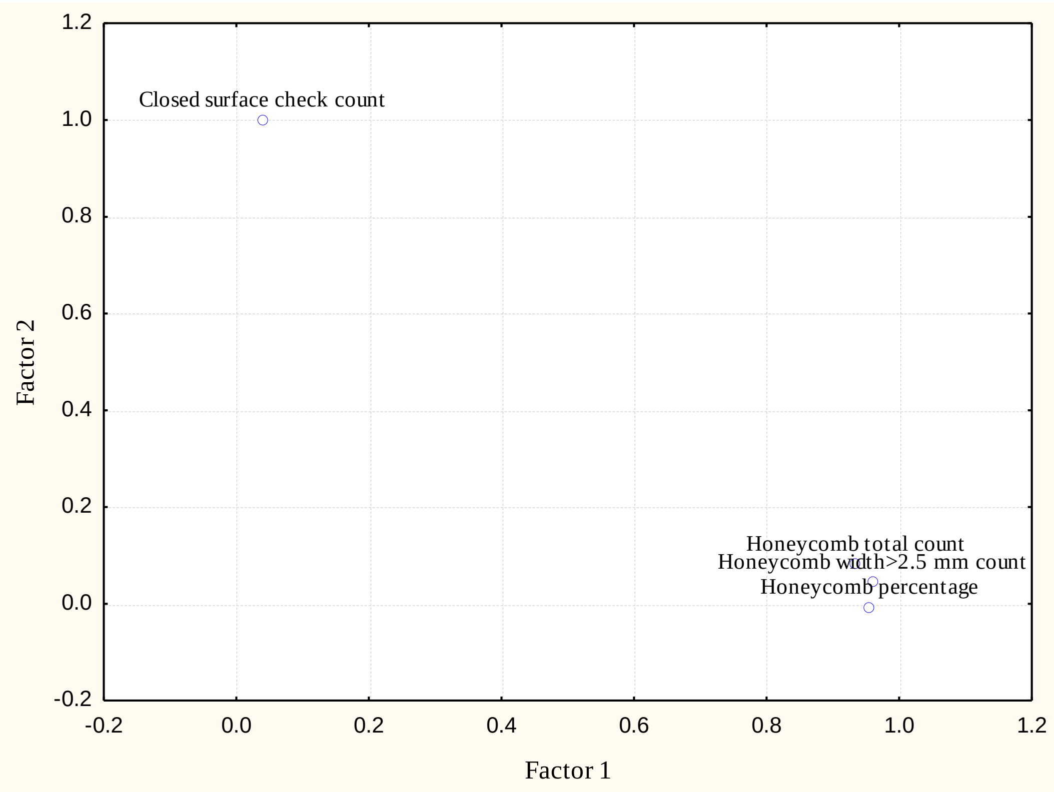


Figure 6.3: Principal component variables

The two principal component factors represented 92.9% of the variation in the data as shown in the scree plot (Figure 6.4). Eigenvalues 1 and 2 in Figure 6.4 represent factors 1 and 2 respectively.

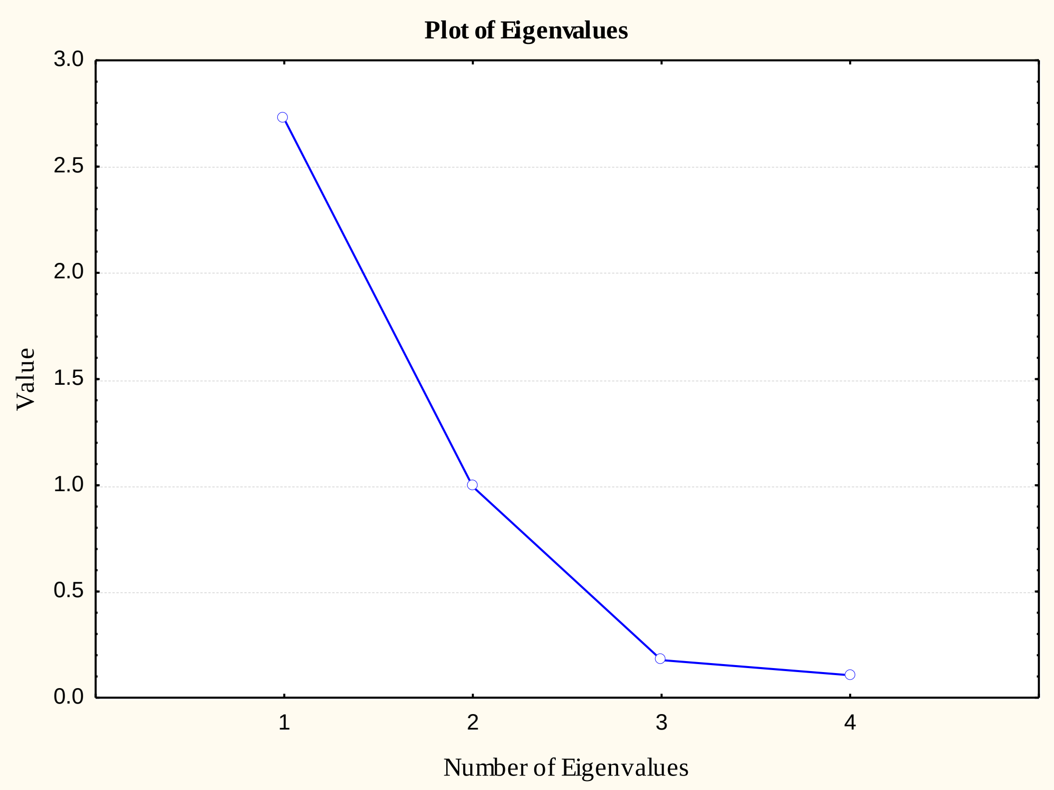


Figure 6.4: Scree plot of component variables

6.5 Discussion

The fact that no correlations of VPUL and internal defect parameters for the separate sets of data were observed in the preliminary analysis was probably because the sample used was too small; 10 poles per source (KZN or Stellenbosch), and 10 poles per schedule.

The positive correlation of VPUL with honeycomb count and closed surface check count is in agreement with what Ward and Simpson (1997) reported i.e. that a corrugated appearance on the lumber surface might indicate severe honeycombing. VPUL as a parameter of surface profile correlated strongest with honeycomb count. This suggests that in relating pole surface profile to honeycombing using the VPUL, the best results can be obtained when honeycomb count is used rather than honeycomb percentage of the cross-sectional area (see Figure 6.1). Whatever the case, factor analysis indicated that either honeycomb count or area expressed as a percentage of the pole cross-section, can properly represent the honeycombing situation. VPUL correlated stronger with honeycomb total count than the count of honeycomb with width ≥2.5 mm. This indicates that every single honeycomb check may contribute to the nature of the surface profile of a pole, even if its width is less than 2.5 mm.

Honeycomb count was generally greater than closed surface check count and tended to contribute more to the surface profile than closed surface check count as is evident in the regression equation.

The higher the VPUL, the greater the number of honeycomb and closed surface checks in *E. grandis* poles. On this basis, surface profiles can be used to assess with certainty the honeycomb and closed surface check phenomena in poles. Non-destructive evaluation of surface profiles of pole circumferences is essential for the industrial application. By modifying basic principles used in devices developed in earlier research (Peters and Mergen, 1971; Peters and Cumming, 1970; Stumbo, 1963; Elmendorf and Vaughan, 1958; Hann, 1957) for profiles of flat wood surfaces and tailoring them to fit the pole situation, pole circumference surface profile could be evaluated.

6.6 Conclusions

VPUL was positively correlated with honeycomb count and honeycomb expressed as a percentage of pole cross-sectional area, and closed surface check count. The single most correlated variable with VPUL was honeycomb total count. Honeycomb total count and closed surface checks were the best two predictors in a regression model, VPUL being the dependent variable. It can, therefore, be concluded that VPUL as a parameter of the profile of pole circumference, can be used to assess honeycomb and closed surface checks.

Further investigation on sufficient samples of poles from specific sources and drying schedules needs to be done to make reliable conclusions regarding possible variation in correlation of VPUL and internal defects.

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Chapter 7: Effect of kiln drying schedule on the quality of *Eucalyptus grandis* poles

7.1 Abstract

In specific cases, kiln drying is the prescribed method of pole seasoning in South Africa. The slow drying nature of *Eucalyptus grandis* poles makes rapid kiln drying potentially dangerous due to development of defects such as excessive surface checking, honeycomb and collapse. To be able to control these defects while maintaining the fastest drying rate possible, the effect of drying schedule on the drying quality of *E. grandis* poles was investigated. The specific objectives were to assess the effect of drying schedule on: (i) surface check total length; (ii) honeycomb checks expressed as a percentage of pole cross-sectional area; (iii) collapse as well as (iv) moisture content (MC) gradient. Pole drying was simulated in 30, 2.1 m long butt sections of poles of which the top ends were sealed. Three schedules differing in terms of dry bulb temperature (T_{db}), wet bulb depression and duration of drying were used to dry the poles. After measuring surface check length of each pole using a measuring tape, poles were cross-cut at the theoretical ground line (TGL), 1.5 m from the butt end, to measure the MC gradient between the shell and core of poles. Digital image analysis of cross-sections of discs cut at TGL was used to measure the area of honeycomb and disc cross-section. Collapse was assessed using qualitative methods. Schedule 3 (70^{o}C T_{db}/59^{o}C wet bulb temperature (T_{wb})/12 days) poles had the highest surface check total length yet the opposite was expected. In all three schedules, MC in the pole core was still very high with some poles having more than 25% even in the outer 25 mm zone. Reducing the wet bulb depression from 21^{o}C (schedule 1) to 11^{o}C (schedule 2) did not reduce honeycomb or collapse. A slight reduction in honeycomb was observed by reducing T_{db} from 80^{o}C (schedule 2) to 70^{o}C (schedule 3) while keeping the wet bulb depression at 11^{o}C. Poles should be dried longer than 8 days even at 80^{o}C T_{db}, and T_{db} lower than 80^{o}C should be considered in order to minimise potentially serious drying defects.

7.2 Introduction

Eucalyptus grandis is one of the major species grown for production of utility poles in South Africa. Its susceptibility to drying defects such as surface checking and honeycombing has, however, made its utilization difficult (Stöhr, 1982). Surface checking (Panshin *et al*., 1964), honeycombing (Wangaard, 1950; Garratt, 1931) and collapse (Bariska, 1992) all affect strength properties of wood. According to Stöhr (1982), a large percentage of defects are caused by the presence of growth stresses in standing trees which become unbalanced upon felling or cross-cutting. These defects usually enlarge during drying depending on the severity of drying conditions. Eucalypt wood generally dries slowly (Campbell and Hartley, 1978 quoted by Vermaas and Neville, 1988) yet collapse and honeycombing seriously limit use of rapid drying methods. According to Simpson and Boone (1997), the successful control of such drying defects as well as the maintenance of the fastest possible drying rate in hardwood lumber, depends on proper selection and control of temperature and relative humidity in the kiln. Therefore, the quality of drying may be influenced by the kiln schedule used. Once drying of a certain timber species has been done using a particular schedule without causing unacceptable defects, modification of the schedule can then be considered to reduce drying time (Simpson and Boone, 1997). However, the quest for shorter drying schedules should not compromise the quality of drying in terms of defect development.

In South Africa, there has been a general shift from air-drying to high-temperature kiln drying of utility poles (Wessels *et al*., 2004), with some companies such as ESKOM, already requiring that all poles longer than 7 m be kiln-dried (Hill *et al*., 2003). Yet a perception exists among wooden utility pole users (ESI Africa, 2000) that the percentage of in-service pole failures after a relatively short period has markedly increased over the past few years. Rypstra *et al*. (2004) suggested that the present wide-spread use of high temperature kiln drying could be one of the factors responsible for the recent reduced durability of poles.

The goal of this study was to assess the effect of drying schedule on some key utility pole drying quality indicators. The specific objectives were to assess the effect of schedule on:

(i) surface check total length;

(ii) moisture content (MC) gradient;

(iii) honeycomb checks expressed as a percentage of pole cross-sectional area and

(iv) collapse.

7.3 Materials and Methods

It was considered necessary that the poles be collected from the same source in order to ensure that the sample was as homogeneous as possible, that differences in drying defects would then be attributed to the particular kiln schedule used. There was, however, a limited number of poles in the required size class, and the kiln capacity was limited to 10 poles per load. The research was, therefore, conducted using the limited resources while conscious of the possible effects this could have on the statistical reliability the results.

7.3.1 Timber

A total of 30, debarked *E. grandis* poles from Coetzenburg, Stellenbosch was investigated. For all the poles, the diameter at the theoretical ground line (TGL), 1.5 m from the butt end ranged between 175-230 mm. Due to length the limitation of the research kiln, only 2.1 m long poles could be used. Full length utility poles were simulated by sealing and applying end plates to the top ends. To minimise end splitting, end plates were also fixed to freshly cut butt ends of poles.

7.3.2 Drying

Pole drying was done in a Kiefer kiln using the following three schedules:

1. 80^{o}C dry bulb (T_{db}) and 59^oC wet bulb temperature (T_{wb}) for 8 days; used to dry 10 poles;

2. 80^{o}C T_{db} and 69^{o}C T_{wb} for 10 days; 10 poles and

3. 70^{o}C T_{db} and 59^{o}C T_{wb} for 12 days; 10 poles.

The air velocity of 4-5 ms^{-1} was maintained for all the schedules.

7.3.3 Evaluation

7.3.3.1 Surface checking

Immediately after unloading the poles from the kiln, the lengths of all visible surface checks ≥1mm in width were measured using a measuring tape. The total surface check length was then computed for each pole.

7.3.3.2 MC gradient

A 25 mm disc (disc1) was cut at the TGL and three 25 mm wide radial strips were then cut from 3 positions approximately 120^{o} apart on disc 1 (Figure 7.1). From each strip, 12.5 mm thick samples were cut as shown in Figure 7.1. The samples were weighed, dried to constant mass in a laboratory oven at 102^{o}C and reweighed. The MC of each sample was calculated according to the standard formula:

$$MC = \left[\frac{Wet\ mass\ of\ wood\ (g) - Ovendry\ mass\ of\ wood\ (g)}{Ovendry\ mass\ of\ wood\ (g)} \right] \times 100\ (\%)$$

The MC gradient was then computed by subtracting the average MC of the 0-25 mm depth (shell) from the MC in the centre of the pole (core) at the same radius. The 0-25 mm depth represents more or less the sapwood depth where MC is critical in order to achieve complete preservative penetration during impregnation. Of the three radial strips (Figure 7.1), only the one with the steepest gradient rather than the average of all three strips was considered because microbial degradation may begin from that position in the pole which happens to be insufficiently treated (a too high MC in a particular position leads to insufficient preservative penetration), thus creating a localised problem. If average radial MC gradients are considered, the one too steep gradient (out of 3) may go unnoticed, especially if the remaining 2 are low enough to generate an acceptable average.

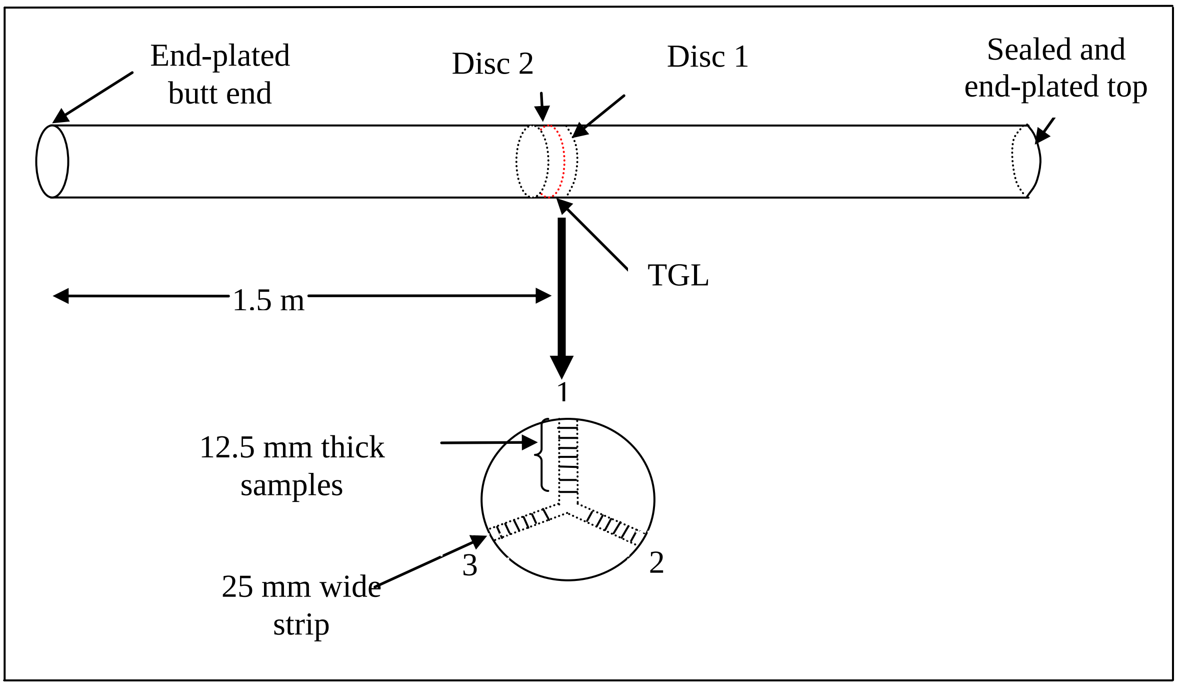

Figure 7.1: Pole sampling for moisture content gradient and honeycomb measurement.

7.3.3.3 Honeycombing

A second disc (disc 2) was cut just adjacent to the first one (Figure 7.1). The exposed cross-section on the TGL side was sprayed with a solution of 0.1 g dimethyl yellow dye in 100 ml of ethanol (95% v/v) to enhance the contrast of heartwood and sapwood, and scanned using a scanner (BRISA 620P VUEGO SCAN) to obtain digital images. Images were analysed using ImageJ software (http://rsb.info.nih.gov/ij) to measure the area of honeycomb checks as well as the cross-sectional area of the disc.

7.3.3.4 Collapse

Collapse was measured by assessing the outer surface of disc 2 (Figure 7.1) for corrugations developed during drying. The disc cross-sectional surfaces were also observed for presence of collapse. The pole was then classified as belonging to one of the categories 1, 2 or 3, category 3 being one with the worst and 1 the least affected by collapse.

7.3.4 Data analysis

One-way ANOVA was used to analyse the data, and where the residuals were not normally distributed, Kruskal-Wallis ANOVA was used. All tests were carried out at 5% level of significance.

7.4 Results

Table 7.1 shows values of drying defect variables measured in poles dried with all schedules.

Table 7.1: MC gradient and drying defects in poles dried with all schedules

Schedule	Surface check total length (m)	MC gradient (%)	Honeycomb percentage	Collapse class
1	1.11	50.76	0.27	2
	0.29	52.89	0.43	1
(80°C T_{db}/59°C T_{wb}/8 days)	1.83	50.10	1.16	2
	0.00	64.92	1.14	1
	1.96	50.76	1.29	2
	3.72	38.29	0.77	2
	2.65	52.35	1.98	3
	0.52	47.56	1.00	2
	2.21	50.01	1.61	2
	0.52	45.75	2.08	2
2	0.00	44.92	2.86	2
	0.09	58.21	0.92	1
(80°C T_{db}/69°C T_{wb}/10 days)	0.00	51.37	0.83	2
	0.62	73.69	1.02	1
	0.07	67.30	0.81	2
	0.44	103.29	0.55	1
	0.30	60.39	3.08	3
	0.14	49.38	1.25	2
	1.34	50.05	0.41	2
	0.12	61.66	4.18	3
3	2.72	58.98	0.97	2
	3.05	63.25	0.78	2
(70°C T_{db}/59°C T_{wb}/12 days)	3.93	46.33	1.26	1
	0.23	69.19	1.18	1
	1.46	59.69	1.27	1
	4.20	48.83	0.71	1
	1.31	76.09	0.73	1
	0.00	95.08	1.03	1
	2.78	58.51	0.15	1
	1.08	73.41	1.01	2

The ANOVA showed significant ($p<0.05$) differences between schedules with respect to surface check total length. Surface check total length was least in schedule 2 (80^{o}C T_{db}/69^{o}C T_{wb}/10 days) as shown in Figure 7.2. Although all schedules had some poles with no visible surface checks, schedule 3 (70^{o}C T_{db}/59^{o}C T_{wb}/12 days) poles had the longest surface checks contrary to what was expected (Figure 7.2) i.e. considering the relatively low T_{db} and small depression of 11^{o}C.

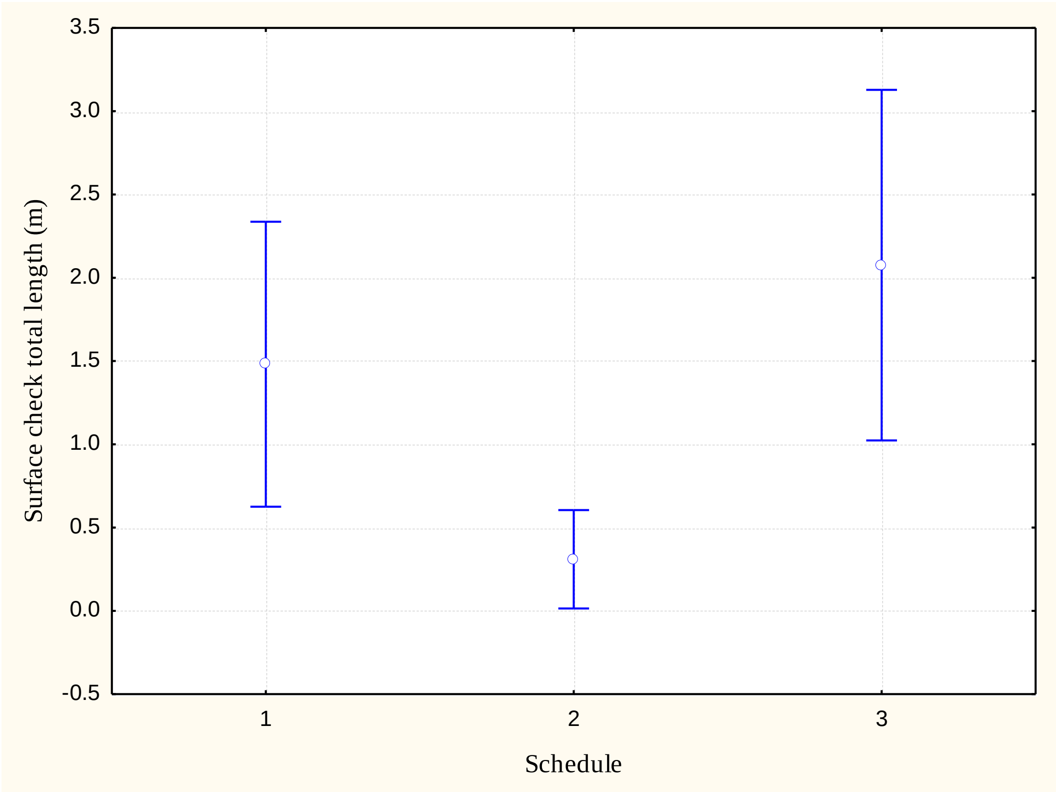

Figure 7.2: Plot of 95% confidence intervals of weighted means of surface check total length and kiln drying schedule ($F(2, 27) = 6.435$, $p<0.01$; Kruskal-Wallis $p = 0.01$)

Kruskal-Wallis tests showed no significant ($p>0.05$) differences between drying schedules with respect to MC gradient, honeycomb percentage and collapse class. Despite the non-significant variation between the medians, Figure 7.3 shows that MC gradient was generally highest in schedule 3 (70^{o}C T_{db}/59^{o}C T_{wb}/12 days) and lowest in schedule 1 (80^{o}C T_{db}/59^{o}C T_{wb}/8 days). Although MC at 25 mm deep into poles was mostly below the fibre saturation point, core MC's for all schedules were above 60%, in fact some poles had MC's even above 100% (Table 7.2).

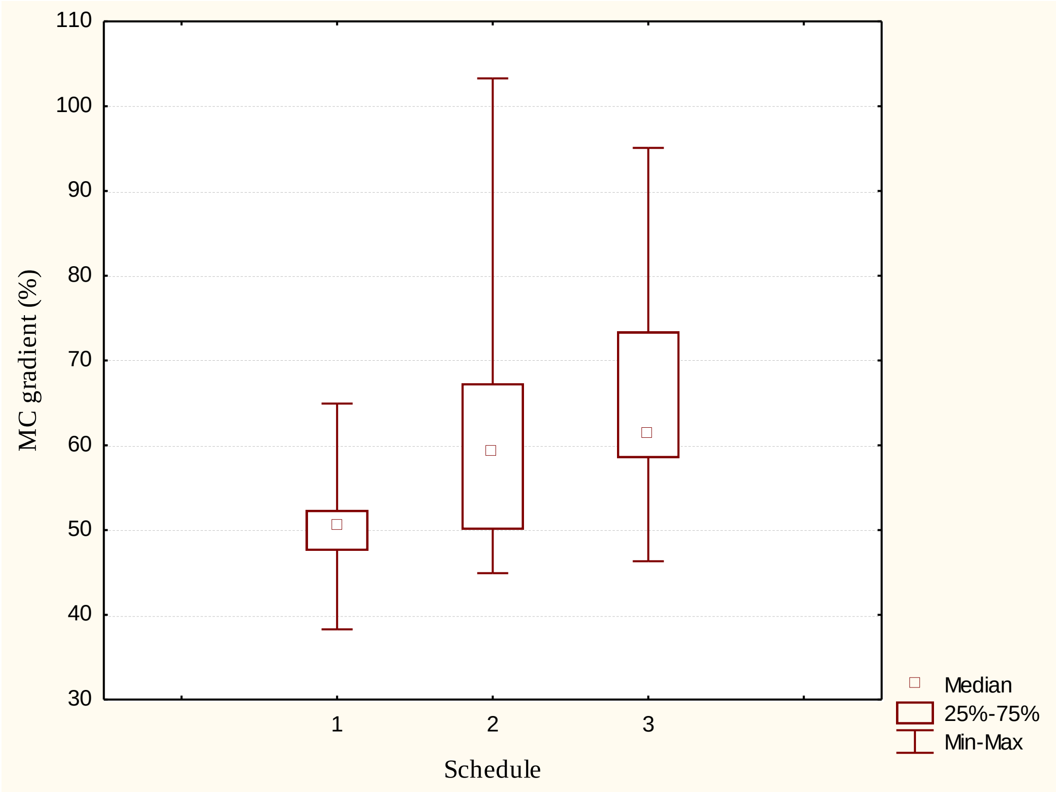

Figure 7.3: Variation of MC gradient at TGL in each kiln drying schedule, with no significant differences between medians

Table 7.2: MC gradient between the core and outer portion of poles at TGL

Schedule	Pole	MC at 25mm deep (%)	Highest (core) MC (%)	MC gradient (%)
1	1	16.89	67.65	50.76
	2	20.55	73.44	52.89
	3	17.80	67.89	50.10
	4	32.31	97.23	64.92
	5	23.94	74.70	50.76
	6	18.74	57.03	38.29
	7	18.44	70.79	52.35
	8	22.39	69.95	47.56
	9	24.43	74.44	50.01
	10	22.54	68.29	45.75
2	1	26.51	71.43	44.92
	2	18.49	76.7	58.21
	3	16.82	68.19	51.37
	4	18.58	92.27	73.69
	5	19.58	86.88	67.30
	6	20.17	123.46	103.29
	7	32.28	92.67	60.39
	8	17.44	66.82	49.38
	9	25.03	75.08	50.05
	10	26.35	88.01	61.66
3	1	17.43	76.41	58.98
	2	14.56	77.81	63.25
	3	16.32	62.65	46.33
	4	24.67	93.86	69.19
	5	22.28	81.97	59.69
	6	15.28	64.11	48.83
	7	13.99	90.09	76.09
	8	28.10	123.18	95.08
	9	14.96	73.47	58.51
	10	20.71	94.12	73.41

Honeycomb percentage (Figure 7.4) and collapse (Figure 7.6) were slightly higher in schedule 1 and 2 than schedule 3, albeit not significantly. Figure 7.5 *a*, *b* and *c* show images of worst cases of honeycomb and collapse for each schedule.

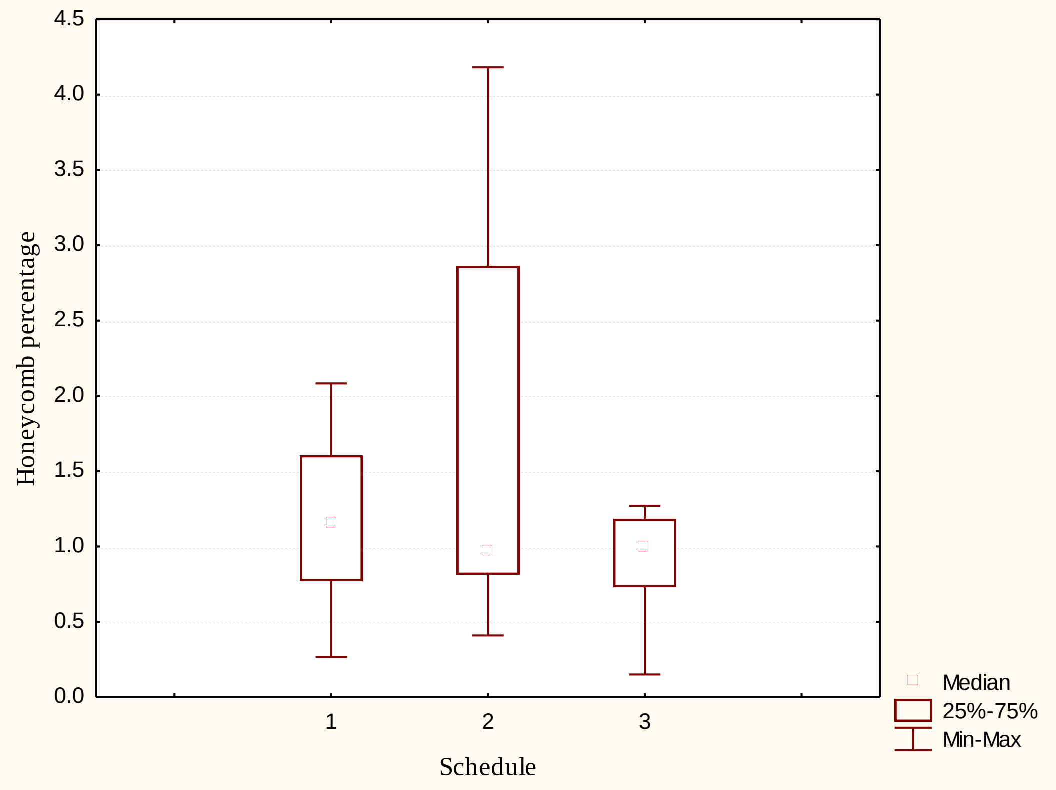

Figure 7.4: Variation of honeycomb percentage at TGL in each kiln drying schedule, with no significant difference between medians

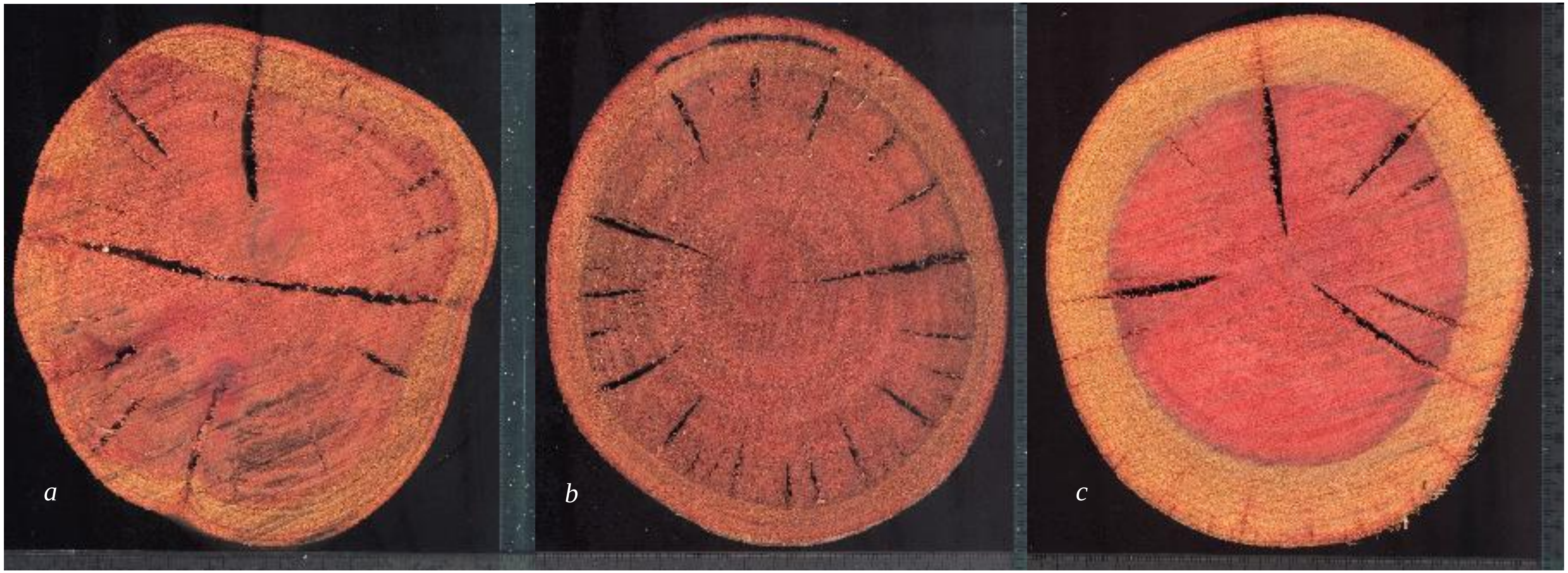

Figure 7.5: Representative images of honeycomb and collapse in poles at TGL. Pole images *a, b* and *c* represent kiln drying schedules 1, 2 and 3 respectively.

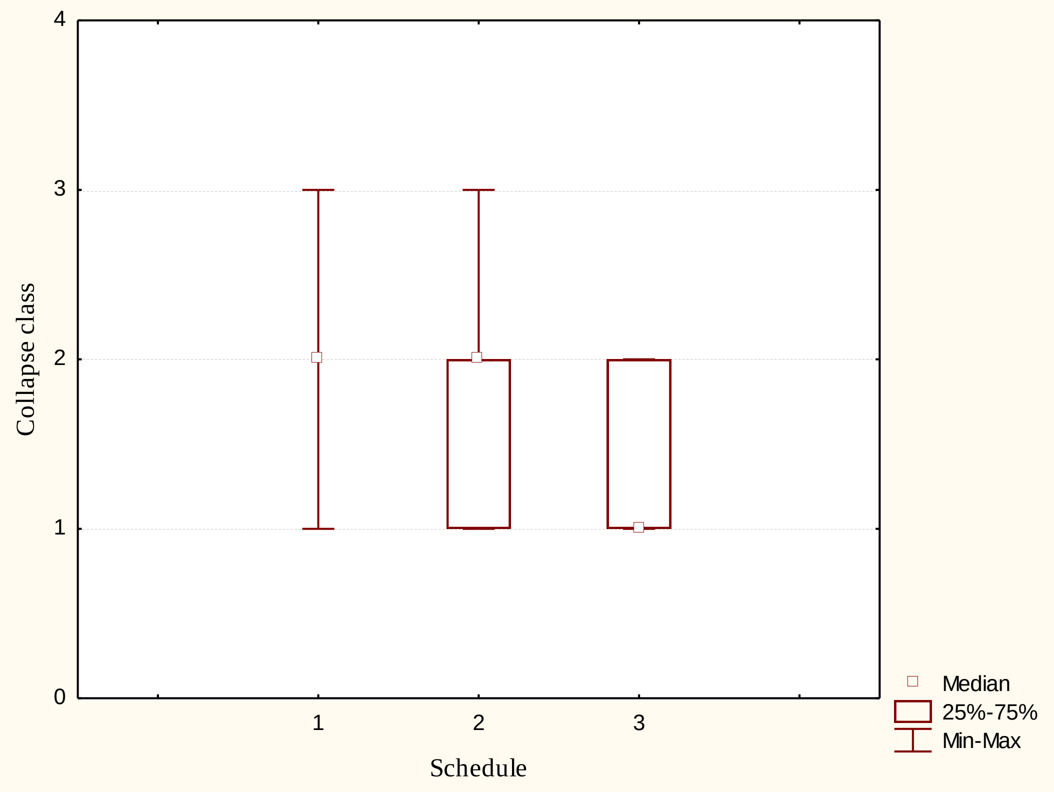

Figure 7.6: Variation in collapse class at TGL in each kiln drying schedule, with no significant differences between medians

7.5 Discussion

Surface check total length was highest in poles dried with schedule 3 (70^{o}C T_{db}/59^{o}C T_{wb}/12 days), possibly because some surface checks in poles dried with schedules 1 (80^{o}C T_{db}/59^{o}C T_{wb}/8 days) and 2 (80^{o}C T_{db}/69^{o}C T_{wb}/10 days) started closing when MC in the core dropped and the tension in the surface layers of poles reduced. In the final stages of drying, surface checks tend to close as the surface layers fall under compression (Pratt, 1974; Wangaard, 1950). Schedule 3 poles still had relatively higher core MC and closure of surface checks had not yet occurred. Poles dried using schedule 1 had longer surface checks than poles dried using schedule 2 due to lower humidity used in schedule 1. Use of low humidity during drying leads to faster moisture loss from the wood surface (Stöhr, 1977; Pratt, 1974), setting up stresses that cause surface checking.

Schedule 3 poles had slightly steeper MC gradient than poles dried with schedule 1 and 2 partly because of the lower T_{db} (70^{o}C) used. The higher the temperature used during drying, the higher the rate of moisture loss from the surface of wood (Stöhr, 1977). Although Schedule 3 had the longest drying duration, 12 days was still not long enough to cater for the comparably slower drying rate due to high humidity (11^{o}C wet bulb depression) and lower T_{db} of 70^{o}C, in order for drying to occur in the pole cores. In comparison, schedule 1 which had the shortest duration of 8 days, but had higher T_{db} (80^{o}C) and lower humidity (21^{o}C wet bulb depression), produced the lowest MC gradient, although core MCs were still a lot higher than the fibre saturation point. As Graham and Womack (1972) noted, irrespective of the drying temperature, there are small reductions in the MC of the inner heartwood of large pole section. The authors indicated that even at elevated temperature, long drying times would still be necessary to achieve an appreciable reduction in MC of the inner portion of poles. In such a case where only the surface layers have sufficiently dried and the core is still wet, the preservative will only penetrate and be retained in this drier zone after treatment. This means that the wood may continue to dry in service thus causing enlargement and deepening of initially acceptable checks to occur, exposing the untreated core.

The high drying rate associated with use of high T_{db} is responsible for the slightly higher honeycomb percentage of pole cross-section in schedules 1 (80^{o}C T_{db}) and 2 (80^{o}C T_{db}) compared to schedule 3 (70^{o}C T_{db}). The high rate of drying causes wood surface layers to dry and shrink too quickly while the core is still wet. The tendency to shrink in the shell, opposed and prevented by the very wet core, causes a large amount of set strain in the shell. The amount of set strain in the surface determines to a large extent, how much tension occurs inside the pole. If large amounts of set occurred as the surface dried, the ultimate tension inside the pole will be high because the surface is much larger than it would be if no strain occurred early in drying (Rice, 1994), thus causing severe honeycombing. High T_{db} also caused slightly more collapse in poles of schedules 1 and 2 compared to schedule 3. According to Yang (1998) and Ward and Simpson (1997), collapse occurs due to use of excessively high temperatures early in kiln drying. Heating wet wood at high kiln drying temperatures makes cell walls soft and plastic and more liable to collapse (Mackay and Oliveira, 1989; Tiemann, 1941).

7.6 Conclusions

- Surface check total length was higher in schedule 3 (70^{o}C T_{db}/59^{o}C T_{wb}/12 days) than schedules 1 (80^{o}C T_{db}/59^{o}C T_{wb}/8 days) and 2 (80^{o}C T_{db}/69^{o}C T_{wb}/10 days), contrary to what was expected.

- Even at T_{db} of 80^{o}C and 21^{o}C wet bulb depression, 8 days was still too short a time for all poles to attain MC less than 25%, 25 mm deep into the pole at TGL. In addition, MC was still very high in the pole cores after 12 days of drying, when T_{db} of 70^{o}C and 11^{o}C wet bulb depression was used.

- There was no reduction in honeycombing and collapse by changing the wet bulb depression from 21^{o}C (schedule 1) to 11^{o}C (schedule 2), though surface checking was reduced. However, there was a slight reduction in honeycombing and collapse by changing from 80^{o}C T_{db} (schedule 2) to 70^{o}C T_{db} (schedule 3) while keeping the wet bulb depression at 11^{o}C.

- Further research on more drying schedules should be done since only 3 schedules were tested in this study. Also more poles per schedule should be considered in order to obtain statistically reliable results.

- Poles should be dried for longer than 8 days even at T_{db} as high as 80^{o}C. T_{db} lower than 80^{o}C should be considered in order to reduce potentially serious defects with regard to preservation, to acceptable levels.

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Chapter 8: General conclusions and recommendations

8.1 Conclusions

Surface check total length was found to be positively correlated with sapwood depth, and moisture content (MC) gradient was positively correlated with green MC. The transformed honeycomb percentage (HC*) and collapse were both positively correlated with heartwood percentage. Therefore, sapwood depth, green MC and heartwood percentage are important pole growth characteristics that need to be considered in possible sorting before drying. Poles can then be dried using appropriate kiln schedules to minimise drying defects.

The auger drill can be used to reliably determine the MC gradients of kiln dried *E. grandis* poles by taking samples in increments of 25 mm i.e. 0-25, 25-50 and 50-75 mm provided the poles are not still too wet (MC ≥60%). In single samples of 0-50 mm and 0-75 mm depth, the auger drill MC measurements were lower than MC values determined with the destructive wood block method. Therefore, SABS SM 983 (2000), which specifies taking single radial auger drill samples of depth 70±5 mm at mid length, is not a reliable method of measuring MC in a kiln dried *E. grandis* pole.

There were strong and positive correlations between honeycomb and collapse. It is possible, therefore, to make reliable deductions about one of them based on the results of the other. Honeycomb check width, length and area were also positively and strongly correlated suggesting a possible prediction of one parameter from the other. Therefore, a method that effectively measures any of the honeycomb dimensions would be appropriate in assessing the overall condition.

Although the width, length and depth of surface checks were positively correlated, it remains important to measure all three parameters to get the true picture of the defect condition. Surface checking was not correlated with honeycombing and collapse, thus prediction of internal defects based on surface checking is not possible.

The number of valleys per unit length (VPUL) of the pole circumference at the theoretical ground line (TGL) was positively correlated with honeycomb check count, honeycomb check percentage of disc cross-sectional area, and closed surface check count. It can, therefore, be concluded that VPUL as a parameter of the profile of pole circumference could be used to assess internal defects i.e. honeycomb and closed surface checks.

At dry bulb temperature (T_{db}) of 80^{o}C and 21^{o}C wet bulb depression, 8 days was still too short a time for all poles to attain MC less than 25%, 25 mm deep into the pole at TGL. In addition, MC was still very high in the pole cores after 12 days of drying at 70^{o}C T_{db} and 11^{o}C wet bulb depression.

There was no reduction in honeycomb and collapse by changing the wet bulb depression from 21^{o}C to 11^{o}C at 80^{o}C T_{db}, though surface checking reduced. However, there was a slight reduction in honeycomb and collapse when T_{db} was reduced from 80^{o}C to 70^{o}C, while keeping the wet bulb depression at 11^{o}C.

8.2 Recommendations

- For poles with large sapwood depths, mild drying conditions at the beginning of a drying run should be used, since such poles may be susceptible to surface checking. Poles with large heartwood percentages should also be dried with suitable kiln schedules i.e. with low T_{db} to minimise honeycomb and collapse. In general, T_{db} lower than 80^{o}C should be considered in order to reduce these defects to acceptable levels when considering possible performance of treated poles in service.

- Poles should be dried for longer than 8 days even at T_{db} as high as 80^{o}C to reduce the MC to acceptable values and gradient.

- In order to use the auger drill method to reliably determine the moisture content of a pole, samples in increments of 25 mm should be taken.

- MC measurements should be made at the most critical zones of a pole such as the TGL and not higher up, since there is normally considerable MC variation in the longitudinal direction. It is also important to consider sampling more than one position around the pole circumference to cater for the MC variation in a pole.

- More drying schedules should be investigated to make reliable conclusions about the effect of schedule on drying defects since only 3 schedules were tested. In addition, more poles per schedule should be considered in order to obtain statistically reliable results. The relationship of pole diameter with drying defects also requires further investigation.

- Since a limited sample was used to test for the effect of source of poles and drying schedules on defect correlations, it is recommended that further studies be done on sufficient samples to come up with reliable conclusions. It is also necessary to further investigate the possible variation in correlation of VPUL and internal defects on sufficient samples of poles from specific sources and drying schedules.