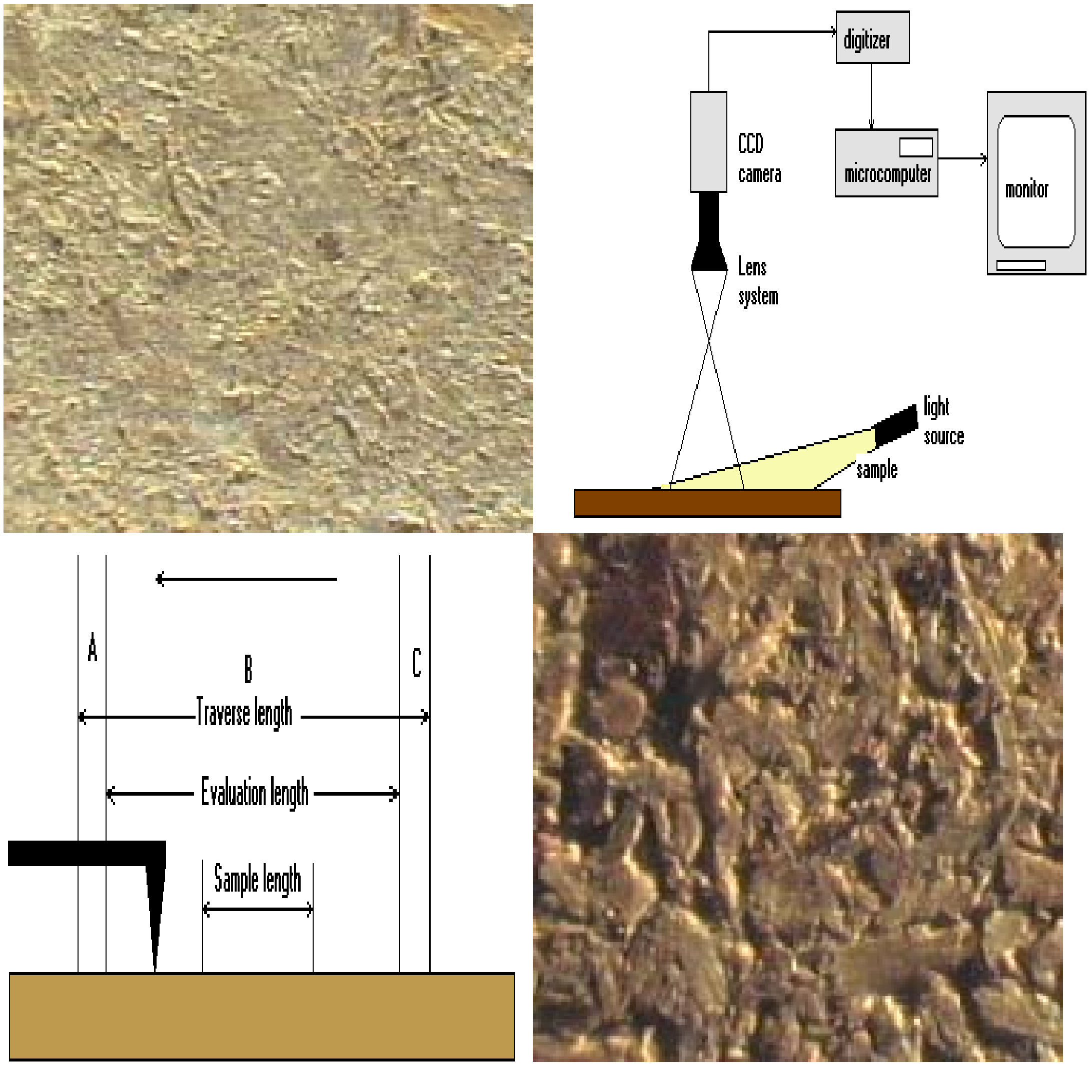
Aldo Rolleri

# Characterization of wood-based panels surfaces by contact and non-contact methods



# Characterization of wood-based panels surfaces by contact and non-contact methods

## Dissertation

Submitted in partial fulfilment of the requirements of the
degree of Doctor of Forestry
at
The Faculty of Forest Sciences and Forest Ecology
of Georg-August-University Göttingen

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To my appreciated father, sweetheart mother and sister,
beloved wife, darling son
and children

**May God bless them**

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# 1 Introduction and objectives of the work

## 1.1 Introduction

In Germany, nearly seventy percent of the particleboards and more than ninety percent of all medium density fiberboards (MDF) are used in the furniture industry, where the surface properties of particleboards and fiberboards are of a primary importance. In particular, adhesion issues of paints and overlays depend to a large extent on the surface properties of the boards. Under different climatic conditions the physical and chemical characteristics of board surfaces many change noticeably depending e.g., on the wood species used in the boards as well as on the binders applied. The sorption behaviour of wood-based panels depends largely on the binders used (Roffael, 1993). In many publications the hygroscopic behaviour of wood is covered, however, so far only sporadic data are available on the influence of climatic conditions on the physical properties of the surface in different wood-based panels bonded with different adhesives.

One of the most important surface properties of wood-based panels is their roughness. It can be defined as the measure of the fine irregularities of a surface. Their size and frequency establish the surface quality. In case of painted or overlaid composite boards irregularities may have a negative impact on the adhesion of paints and overlays and so far on the quality of the final product. The degree of surface roughness is primarily a function of the wood furnish properties including wood species, particle size and geometry. Other factors like type and amount of resin, press cycle, sanding and moisture content of the boards may also affect the surface properties (Hiziroglu, 1998).

The common technique used to characterize roughness of surfaces of e.g., metals, woods and wood-based panels is the so called contact method according to DIN 4768 (Sander, 1989). One of the main disadvantages of this method is the relatively long time necessary to perform several measurements. Moreover, it is very restricted because one measurement traces only a short and small single-line. Therefore, in the last decades a lot of research work has been carried out to develop alternative and more efficient non-contact methods. One main principle of non-contact methods is measuring the intensity of light reflected from the surface of a tested sample and to evaluate the reflected light by means of optical sensors. Optical sensors measuring surface roughness have the advantage of high speed and the possibility to collect many data from a relatively large sample area (DeVoe et al., 1992).

Roughness is a pure physical property of the surface. However, adhesion between paints and the wood surface is a physical-chemical process which depends on many other factors rather than roughness of the surface.

One of the main factors affecting adhesion is the wettability of wood surface. The wettability of a solid surface by a liquid is usually measured by the contact angle between the solid surface and the liquid. A smaller contact angle signifies higher wettability, a greater contact angle is signifying low wettability (Adamson, 1982; Kalnis and Feist, 1993).

Wetting plays an important role in many applications that involve spreading of liquids on solid surfaces (Chow, 1998). Independent of the kind of coating system applied, good wetting characteristics of the surface are necessary to obtain a high quality surface finishing (Wulf et al., 1997).

The performance of any wood surface towards coating is determined by the natural characteristics of the wood species and the manufacturing processes used (Cassens, 1991; Richter et al., 1995). One basic requirement for durable paint performance on the surface of wood-based panels is a good adhesion between the wood surface and the coating material. Manufacturing parameters for producing medium density fiberboards (MDF) such as the mixture of round timber types, the amount of adhesives, sanding, storage and conditioning of the boards appeared to be closely linked with the surface properties and their performance towards coating (Barbu et al., 2000).

## 1.2 Objectives of the work

The main objective of this study was, therefore, to evaluate the influence of the surface roughness of particleboards and medium density fiberboards on their performance towards coating. Within the framework of the study, different aspects pertaining to surface properties of particleboards (PB) and medium density fiberboards (MDF) were studied. These include:

- effect of fresh particles and recycling particles from UF-bonded boards, fresh fibers and recycling fibers from UF-bonded boards and recycling cork particles on the surface properties of wood-based panels bonded with a urea-formaldehyde resin (UF-resin), a melamine-urea-formaldehyde resin (MUF-resin) and a tannin-formaldehyde resin (TF-resin),

- effect of storage under three climatic conditions (20ºC / 30 % relative humidity, 20ºC / 65 % relative humidity and 20ºC / 85 % relative humidity) on the surface roughness of wood-based panels,
- influence of surface roughness of different particleboards on their performance towards coating using different methods of testing and appearance,
- effect of surface roughness on the wettability of fiberboards stored under different climatic conditions,
- comparison of contact and non-contact methods to measure surface roughness of wood-based panels.

## 2 Wood-based panels

The growth of wood composites has been immense over the past 50 years. At the dawn of the 20th century plywood and fiberboards were developed, in the forties the invention of particleboards (PB) was a major breakthrough. In the past three decades other wood-based composites were developed such as oriented strand boards (OSB), laminated veneer lumber (LVL), and laminated strand lumber (LSL). In Europe, particleboards and medium density fiberboards (MDF) are, nowadays, the most important wood-based panels, there was a steady increase in the production of particleboards as well as in the production capacity. Wood composites are more uniform in both physical and mechanical properties compared with solid wood and the history of wood-based panels has largely been one of composite panels replacing lumber. In general, the global consumption of panel products has been growing at a faster rate than that of lumber (Roffael and Schäfer, 1997).

In the early days of the industry in Europe, mainly round timber from thinning operations in the forest was used as a raw material for wood-based panels, in the last decades, however, the raw material in the most developed countries within Europe, especially in Germany, has changed due to many reasons dramatically: Environmental regulations forced the use of waste wood in the last few years. In 1995 about 3.5 % of the raw material used in the particleboard industry in Germany was waste wood. At the turn of the century nearly 20 % of the lignocellulosic raw material in the particleboard industry was from recovered wood. Recently, a number of methods have also been developed to recycle wood-based panels, some of them have reached industrial application as they are economically feasible. In the Wilhelm-

Klauditz-Institute (WKI) in Braunschweig (Germany), particleboards were mechanically disintegrated and thereafter impregnated with urea and other additives and steam treated at temperatures between 100ºC and 120ºC. The treated material can be mixed with virgin chips, dried and glued in the conventional manner (Kharazipour and Roffael, 1997).

The use of recycled woods and used particleboards as a raw material is increasing due to many reasons. The challenge for the future will be to produce increasingly better performing, more consistent, environmentally friendly products at lower cost and using increasing amounts of recycled material in the process (Roffael and Schäfer, 1997).

## 2.1 Particleboards

Particleboard is a product made by gluing wood particles together. The particleboard industry grew rapidly due to the possibility of utilizing wood of small dimensions including residues from other wood industries as saw dust and plywood trimmings.

### 2.1.1 Production of particles

Particle geometry (shape and size) is a prime factor affecting both board properties and manufacturing process. Indeed, the performance of particleboard is, in large part, the reflection of particle characteristics. Particle geometry indirectly influences the finishing, gluing, and overlaying characteristics of particleboards (Moslemi, 1974). Also the presence of bark can be harmful for veneering and overlaying at least in the surface layers. In the presence of bark the application of overlays with a glossy surface can lead to problems when using dispersion adhesives, as the absorption of the aqueous adhesive will not be uniform and thus leads to telegraphing or orange peel effects (Bandel, 1995).

Particles are produced by cutting, breaking or friction, and by use of machines which include: chippers, cutter mills, flakers, impact mills, hammer mills, and attrition mills (Deppe and Ernst, 1977; Kollmann, 1966; Tsoumis, 1991).

### 2.1.2 Drying particles

The moisture content of particles is one the most important factors to be controlled in the wood-based panels industry. The drying process brings the moisture content of the produced particles to 3-4 %. During the next phase of blending the moisture content of the particles increases, as water is again introduced with the resins. The final moisture content of the resinated particles should, in general, not exceed 7-9 % to avoid problems during hot pressing (Moslemi, 1974).

Excessive moisture in the glued particles increases the pressing time as well as formation of blisters and holes within the particleboard and along the panel surface (Bandel, 1995).

### 2.1.3 Adhesives and blending process

The development of the particleboard industry has been linked to that of the synthetic resins. In the early days of the particleboard manufacture only acid-curing urea-formaldehyde resins (UF-resins) were used. Today, particleboards are manufactured using urea-formaldehyde resins (UF-resins), melamine–urea-formaldehyde resins (MUF-resins), phenol-formaldehyde resins (PF-resins) and diphenylmethane diisocyanate resins (MDI-resins). Tannin-formaldehyde resins (TF-resins) can also be used as binders for chipboards. Nowadays, in Germany tannin-formaldehyde resins are used as a binder for particleboards and medium density fiberboards (Roffael and Schäfer, 1997; Anonymous, 2003).

MUF-resins differ from UF-resins in having higher moisture resistance. The addition of small amounts of melamine to urea-formaldehyde resins (UF-resins) leads to a marked improvement to the moisture resistance of the cured resins. The choice of a suitable adhesive for a specific purpose depends on the required moisture resistance of particle-to-particle-bonding, dimensional stability, durability etc (Roffael and Schäfer, 1997).

#### 2.1.3.1 Thermosetting adhesives

Thermosetting adhesives are those glues which set under heat with or without the addition of special hardeners to form cross-linked polymers. Therefore, the process entails the formation of a three-dimensional structure (Bandel, 1995).Thermosetting adhesives are produced by a controlled reaction of their constituents. For the production of e.g., urea-formaldehyde resins the condensation between urea and formaldehyde is interrupted before completion. The intermediate product is a viscous liquid. The completion of the reaction takes place during pressing by application of heat or catalysts (Tsoumis, 1991).

According to Bandel (1995) the thermosetting adhesives include:

- Adhesives derived from the polymerisation of formaldehyde with urea, melamine, phenol or resorcinol in various combinations as urea-formaldehyde resins (UF-resins), melamine-urea-formaldehyde resins (MUF- resins), phenol-formaldehyde resins (PF-resins) and phenol-resorcinol resins (PR-resins),
- Adhesives derived from the combination of formaldehyde with tannin as tannin-formaldehyde resins (TF-resins),
- Isocyanate resins as diphenylmethane diisocyanate resins (MDI-resins),
- Epoxy resins.

#### 2.1.3.1.1 Urea-formaldehyde adhesives (UF-resins)

UF-resins are condensation products of formaldehyde with urea, whereas the molar ratio of formaldehyde to urea can cover the range from 1.0 : 1 up to 2.0 : 1. Urea and formaldehyde are mixed in appropriate proportions and heated in an alkaline medium reacts to mono- and dimethylol urea. The adhesive properties are induced during a second phase in a slightly acidic environment (pH 4-6), when the methylol urea reacts in a condensation process to form polymers with methylene and methylenether bridges. Subsequently, the final hardening process continues with the formation of a three dimensional network (Bandel, 1995).

#### 2.1.3.1.2 Tannin-formaldehyde adhesives (TF-resins)

Extractable polyphenolics from certain woods and barks belong either to the so called hydrolysable tannins or to the so called condensed tannins. Reaction between formaldehyde and condensed tannins leads to cross-linked polymers, which can serve as a binder in the particle- and fiberboards. Acacia bark and quebracho wood are the two main raw materials used commercially for extraction of condensed tannins.

Different wood species have a significant influence on bonding wood chips with tannin-formaldehyde resins and on the physical-technological properties of the boards. According to results of recent investigation it is possible to use tannin as a binder even without adding any cross-linking agent (cited from Roffael et al., 2001).

#### 2.1.3.2 Adhesion and hardening mechanisms

Cohesive strength is concerned with the force of attraction which is developed between the atoms and molecules. However adhesion is concerned with the force of attraction between the layer of adhesive and the adherent (Bandel, 1995).

In case of thermosetting adhesives such as urea-formaldehyde resins the hardening process occurs with the condensation of the precondensated polymers under addition of hardeners and the application of heat (Bandel, 1995).

### 2.1.4 Blending

In the wood-based panels industry the adhesives are usually applied in an aqueous solution, containing 35-60 % water (Marian, 1967; Tsoumis, 1991). The adhesive is applied to the particles by spray jets and mixed into a drum system. The particles are stirred by rotating the drum. The mixed particles are removed mechanically or by air; this process is known in the particleboard industry as a discontinuous process (Tsoumis, 1991).

### 2.1.5 Forming and pressing

#### 2.1.5.1 Forming

In this phase the resinated particles are conveyed to special machines which form the mats. Nowadays, many types of mat forming machines exist depending on the system. The one layer or multilayer mats are subsequently loaded into a hot press to complete the hardening process of the added glue (Bandel, 1995).

#### 2.1.5.2 Pressing

Pressing is the most important phase of board manufacture during which pressure and heat are applied to the mats (Bandel, 1995). The press closing time can be defined as the period of time between the initial pressure application and the moment at which the board is compressed to the final thickness (Suchsland, 1967; Hiziroglu and Graham, 1998). The press cycle depends on many factors like moisture content of the resinated mat, press temperature and thermosetting behaviour of the used resin. During the pressing process heat is transmitted from the press platens over the surface layers into the inner layer of the formed mat. The inner layers of the panel are heated by steam convection. High moisture plasticizes the wood (Maloney, 1977; Hiziroglu and Graham, 1998).

## 2.2 Fiberboards

Fiberboards are wood-based panels containing fibers generated by thermo-mechanical pulping from wood or other lignocellulosic materials. Adhesives are not always needed for bonding the fibers (Tsoumis, 1991).

According to ISO definitions, fiberboards can be divided into three categories:

- Low density fiberboards (density less than 350 kg/m³)
- Medium density fiberboards (density between 350 kg/m³ and 850 kg/m³)
- High density fiberboards (density above 850 kg/m³)

### 2.2.1 Production of fibers by thermo-mechanical pulping (TMP)

Fiberboards can be made from different lignocellulosic materials including soft- or hardwoods. For the production of fiberboards wood is usually debarked. Efficient drum debarking maximizes fiber yield. After debarking logs are reduced to chips by disk- or drum-chippers (F.A.O. / U.N., 1966; Tsoumis, 1991). The application of efficient debarking, combined with chip screening, enables the grit content of the chips to be reduced. Thereafter, a washing step of the chips is necessary to remove impurities. The chips are then presteamed at a temperature of 70-80ºC. This equalizes the moisture of the incoming raw material and softens the chips. Thereafter, the chips are subjected to a thermo-mechanical pulping process under pressurized steam (about 170 ºC) for a few minutes. Finally, the chips are defibrated in a refiner by friction. In dense hardwoods chemical treatment with sodium hydroxide or sodium sulfite or a combination thereof, facilitates the pulping process.

### 2.2.2 Fiber drying and gluing

The equipment used for drying fibers is very similar to that used for particleboard industry. Dryers can be classified into two types, drum dryers and tube dryers. In the wet process for making fiberboards the self-bonding capacity of the fibers can be used to make binderless boards. In the dry process synthetic adhesives like urea–formaldehyde resins (UF-resins), melamine-urea–formaldehyde resins (MUF-resins), phenol–formaldehyde resins (PF-resins), and tannin-formaldehyde resins (TF-resins) are generally applied (F.A.O. / U.N., 1966; Tsoumis, 1991; Roffael et al., 2001).

### 2.2.3 Forming and pressing

Wet forming is a process where the fibers are transported in a water suspension. The mat is formed on an oscillating endless wire screen, and the water in excess is removed by vacuum and rolls pressure (Suchsland, 1986; Tsoumis, 1991). Dry Forming is an advantageous process, which uses air to transport the fibers. This system permits the orientation of fibers. The fibers are aligned in the machine direction. Both, in the wet and dry fiberboard process pressing under temperature and pressure is used to consolidate the mat. Pressing can be done in a multi opening or single opening press.

# 3 Fundamental principles

## 3.1 Surfaces of wood-based panels

The surfaces of wood-based panels are very difficult to characterize. Endogenous factors such as raw material, binders and exogenous factors like climatic conditions may also induce some changes in the surface characteristics of wood-based panels. Moreover, during the pressing process the closing time influences directly the density of surface layers. The sanding process determines the final surface characteristics of the panels.

Sanding is a widely used operation in wood-based panels industry. The purpose is to generate a smooth panel surface and to produce a uniform thickness all over the board. Surface smoothness is one of the most important properties of particleboards, especially for applications, where the surface of the product will be overlaid. The use of fibers, fine granular particles and saw dust for surface layers has become very common. Other techniques such as the use of higher resin level for particles and a high moisture content in the surface prior to pressing also help to create a smooth panel surface (Moslemi, 1974).

## 3.2 Surface roughness measurement by contact method

To understand what surface roughness means it is necessary to understand what a surface is. A surface is a border separating an object from another. This original so called nominal surface does not include the surface roughness. When the nominal surface deviates as a result of any physical or chemical processes, the new surface is called real surface.

The deviations in the surface topography from a nominal surface to a real surface induce form, waviness and roughness (Figure 1). Form is the predominant direction of surface texture. Waviness includes wavelength deviations of surfaces from its nominal shape. Finally roughness embraces the finest irregularities of a surface (PDI, 1998). All together are called surface texture.

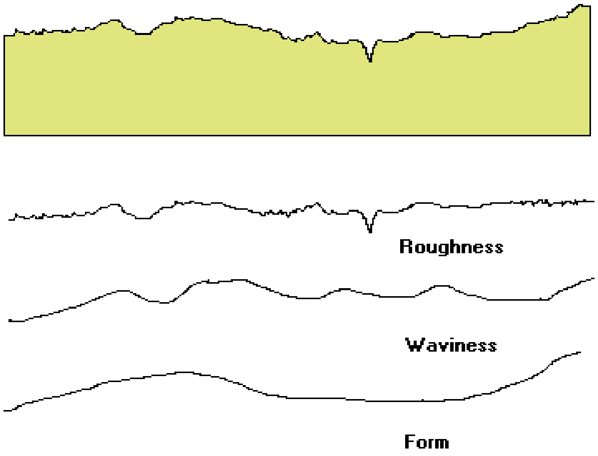


**Figure 1:** Profiles from real surfaces (roughness, waviness and form)

### 3.2.1 Roughness profiles

Roughness profiles contain many elements which help to make an interpretation of the surface characteristics. The surface roughness defines how a surface feels, looks and how it works in contact with another surface as well as how it behaves by overlaying or painting. According to Precision Devices Inc. (PDI, 1998),

- Roughness profile is the modified profile obtained by filtering a measured profile to attenuate the longer wavelengths associated with waviness.
- Mean line is a reference line from which profile deviations are measured. It is the zero level for a total or modified profile.

- Least square mean line is a line from which profile such that the sum of the squares of the deviations of the profile from the mean line is minimized.

- Profile height is the height of a profile at a particular point. It is the distance from the profile to its mean line. Profile height is considered positive above the mean line and negative below the mean line.

- Profile peak is a region in the profile that lies above the mean line and intersects the mean line at each end. The peak is defined to be the point of maximum height within the region.

- Profile valley is analogous to a profile peak. It is a region in a profile that lies below the mean line and intersects it at each end. The depth of the valley is the lowest point within the valley.

- Local peak is a region in a profile between two successive "high points" (local maxima) in the profile.

- Local valley is a region in a profile between successive "low points" (local minima) in the profile.

### 3.2.2 System of coordinates to determine roughness

#### 3.2.2.1 Profiling the system of coordinates

The system of coordinates for a surface profile is three-dimensional (Figure 2). The X-axis defines the trace direction, the Y-axis is normal to the trace in the plane of the surface and Z-axis is perpendicular to the surface. However, when referring to surface features, it is much easier to speak of vertical and horizontal, peak and valley, height and depth, and up and down, rather than trying to express everything as X-, Y-, and Z-displacements or distances. The surface height is generally measured in micrometer (μm).

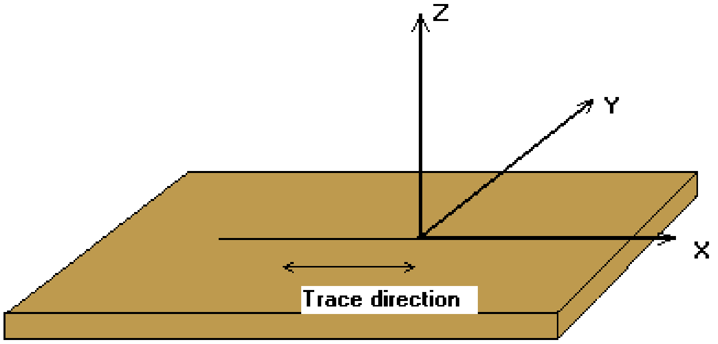


**Figure 2:** The system of coordinates for profiling a surface has an X-axis in the trace direction, a Y-axis normal to the trace in the plane of the surface and a Z-axis perpendicular to the surface.

Surface traces are magnified moderately in the horizontal direction and significantly in the vertical direction in order to be presented on a computer screen or a piece of paper (PDI, 1998).

### 3.2.2.2 Profile measurement lengths

Traverse length is the total distance travelled by the profiling instrument pick up during data collection. Evaluation length is the entire length of a profile over which data has been collected (Figure 3).

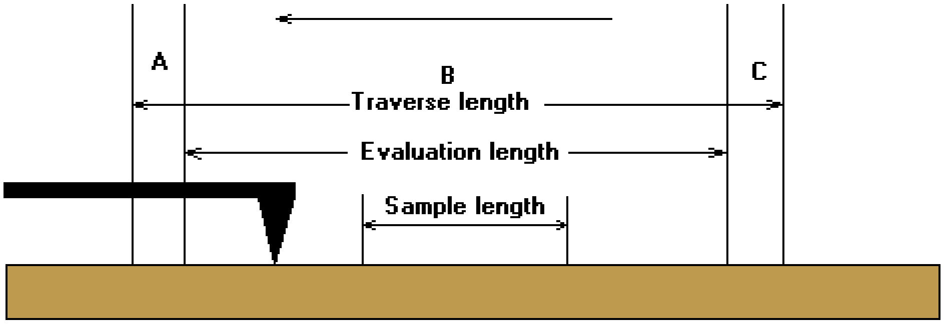


**Figure 3:** In a profile measurement the evaluation length, the length over which data may be collected, is shorter than the physical traverse length because of the end effects in the motor control and settling times for optional electronic filters. An evaluation length consists of one or more sample length (PDI, 1998).

In a profile measurement the evaluation length is usually shorter than the physical traverse length because of end effects in the motor control, A (motors accelerating) and C (motors deaccelerating) and settling time for optional electronic filters. For roughness measurements one evaluation length consists of several (ordinarily five) sample length. Many roughness parameters are statistical averages of values for the individual sample lengths (PDI, 1998).

### 3.2.3 General description of a surface profiling instrument

The main objective of a surface profiling instrument is to convert the real surface profile into an electrical analogous or digital representation of the profile.

To separate certain frequency components of a surface profile special electrical filters are used. A surface profile embraces a range of frequency components. The high frequency (or short wave) components correspond to those that are perceived to be rough and hence called roughness. The low frequency (or long wave) components correspond to more gradual changes in the profile and are often associated with the terms waviness or even form. The Gaussian filter is designed to separate roughness from waviness precisely (PDI, 1998).

### 3.2.4 Roughness parameters

The characterization of a surface through contact method employs mathematical and statistical parameters for its interpretation. The most important parameter is the so called average roughness ($R_a$). It is the average distance from the profile to the mean line (Hiziroglu, 1996). $R_a$ is also called arithmetic mean deviation and is defined as the mean depth of all depths between the surface profile and the main line. As figure 4 shows, $R_a$ is determined as the height of a rectangle with length lm and the same area as between the surface profile and the mean line (Östman, 1983).

$$R_a = \frac{1}{L_m}\int_0^{L_m} lyl \; dx$$

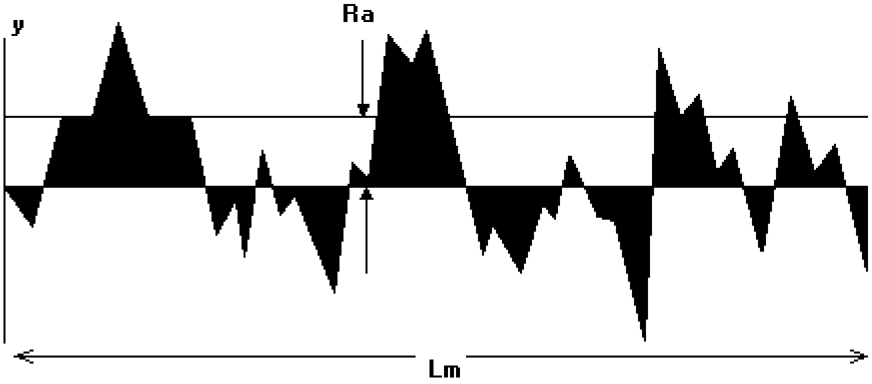
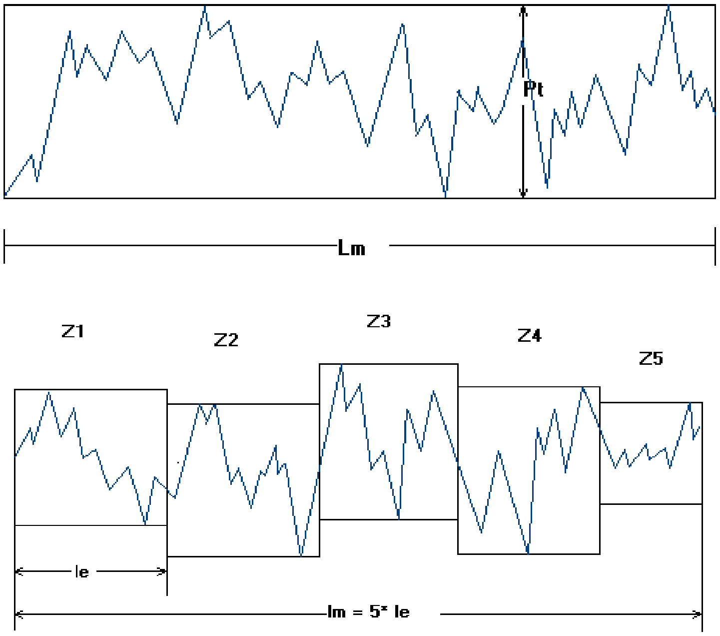


**Figure 4:** Average roughness ($R_a$) is determined as the height of a rectangle with length lm and the same area as between the surface profile and the mean line (Östman, 1983).

As can be seen from Figure 5 $P_t$ is defined as the peak-to-valley distance between two parallel limiting lines containing the profile within the measuring length Lm.



$$R_z = \frac{1}{5}(Z_1 + Z_2 + Z_3 + Z_4 + Z_5)$$

**Figure 5:** $P_t$ is defined as the peak-to-valley distance between two parallel limiting lines containing the profile within the measuring length ($L_m$). $R_z$ is defined as the mean peak-to-valley height of five consecutive lengths ($l_e$).

The mean peak-to-valley height ($R_z$) is defined as an average of five consecutive peak-to-valley heights within the profile (Hiziroglu, 1996). $R_{max}$ is the maximum peak-to-valley height within a tracing length.

The parameters $R_k$, $R_{pk}$ and $R_{vk}$ are part of the material ratio curve which is the graphical representation of the relationship between the air and the surface of the material (Figure 6). They are derived from the graphical curve by dividing it into three parts describing the peaks, the valleys, and the core roughness of the surface (Hiziroglu, 1996).

The $R_k$ value is calculated from the ratio curve (Figure 6). It consists in to slide a window, with 40 % of wide, across the curve looking for the minimum secant slope. Then a line is drawn through, where the windows intersect the bearing ratio curve A-B to find the intercepts at 0 % (C) and 100 % (D). In Figure 7 the parameters $R_k$, $R_{pk}$ and $R_{vk}$ are shown. $R_{pk}$ is the height of the triangle CEG which has the same area as the shaded area. $R_{vk}$ is the height of triangle FDH that has the same area as the shaded area (PDI, 1998).

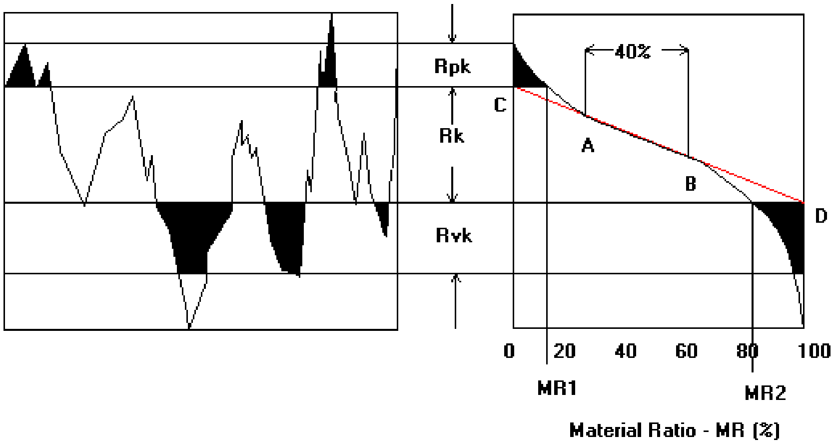


**Figure 6:** Bearing ratio analysis

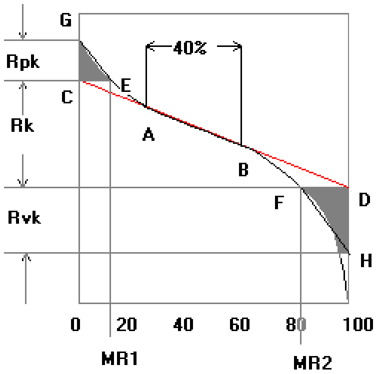


**Figure 7:** $R_{pk}$ is the height of the triangle CEG which has the same area as the shaded area. $R_{vk}$ is the height of triangle FDH that has the same area as the shaded area (PDI, 1998).

## 3.3 Surface roughness measured by non-contact method

The characterization of wood surfaces by non-contact methods, such as optical methods, has been developed with the purpose to find a high speed tool for quality control which is also compatible with the manufacturing process (Lefevre, 1996). Non-contact methods for measuring surface roughness have been developed in the metal industry. The technique is as follows: A light source sends high culminated light under a special angle to the surface. A light detector receives the reflected light and measures the degree of dispersion of the culminated light. The degree of dispersion is a function of the roughness of the surface (Faust, 1987).

A preliminary technique used by Lutz (1952) utilizes collimated light directed to the wood surface at a sharp angle of incidence. A photograph of the sample is taken directly above the point where the plane of light strikes the surface. The plane of light, from the cameras perspective, appears as a wavy line corresponding to the profile of the sample surface (Faust, 1987).

Image analysis is a preliminary sensing and control technique in the emerging field of robotics. The first function of this technique is to capture an image from a video camera and store the image in a standard computer memory where it can be processed into usable information (Faust, 1987).

### 3.3.1 Fundamental principles of image analysis

Image analysis takes two-dimensional data from a variety of sources. The data could be described as a digital photograph obtained from a scanner. Each picture element (pixel) in the image has an X- and a Y-coordinate, therefore the pixels are often specified by X and Y. The number of pixels in an image determines the resolution of the picture, typically it has 512 x 512 pixels. Normally 257 proportional levels of digital light intensity are used, therefore each pixel can take a value between 0 and 256. Each possible value is associated with the a shade of gray (gray level) between black (0) as a minimum value and white (256) as maximum value. This determines the limits of contrast and brightness.

In the following steps analogue information is converted by an analogue-digital-convert (ADC) into digital information (binary language).

### 3.3.2 Measuring surface roughness using image analysis

Non-contact methods used to measure surface roughness with e.g., optical sensors have on the one hand advantages of being fast in assessing surface roughness on the other hand there are no clear standards according to which measurements can take place (Ettl, et al., 1997).

In this thesis the light scattering theory developed by Beckman and Spizzichino (1963) and proposed by DeVoe, et al. (1992) was applied. According to both of them the intensity of light scattered from a rough surface can be described as a function of the surface topography.

The principle is as follows (Figure 8): An analogous-charge-coupled-device camera (CCD camera) is used. The CCD camera collects the scattering light from a sample and sends a video signal to a frame grabber which converts the video signal into a digital image in real time. This digital image is processed by a computer that examines the light scattering pattern of the image and calculates the roughness parameters of the surface with an image gray level histogram. Optical roughness is calculated as the standard deviation of the gray level histogram. Standard deviation is calculated as follows:

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=0}^{255} F_i\left(x_i - \bar{x}\right)^2}$$

n= pixels in the image, $x_i$= gray level ($0 \leq i \leq 256$), $F_i$ = frequency count of pixels at gray level $x_i$.

Most applications employ a CCD camera and digital conversion hardware to produce digital images of surfaces. The optics associated with the camera may incorporate filters and magnifying lens to enhance contrast and improve resolution. The CCD camera has a chip which consists of a grid of tiny CCD elements, converting the light into electric charges. Each signal is converted to a digital value, representing the light intensity. 256 proportional levels of digital light intensity are used. The digital image appears as a two-dimensional array of picture elements (pixels) (Kamke, et al., 2000).

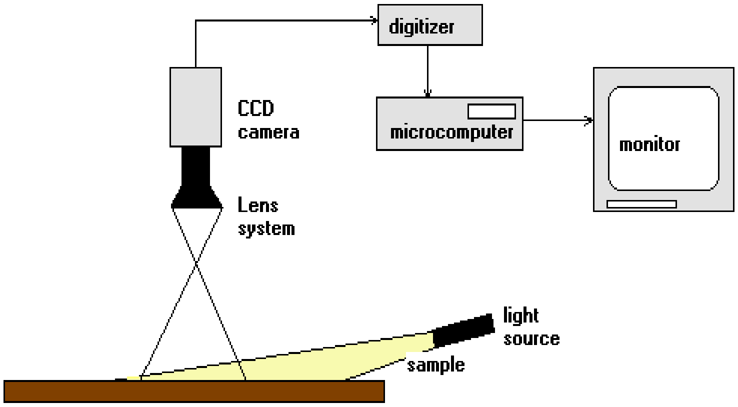


**Figure 8:** Hardware for measuring surface roughness by the non-contact method

## 3.4 Wettability

Wettability on wood by a liquid element is measured by the angle of contact to the surface of the wood (Figure 9). Various factors have influence on the wettability of wood, e.g., porosity, density and chemical composition of the wood surface, as well as temperature, viscosity, and surface tension of the liquid (Wellons, 1977; Tsoumis, 1991).

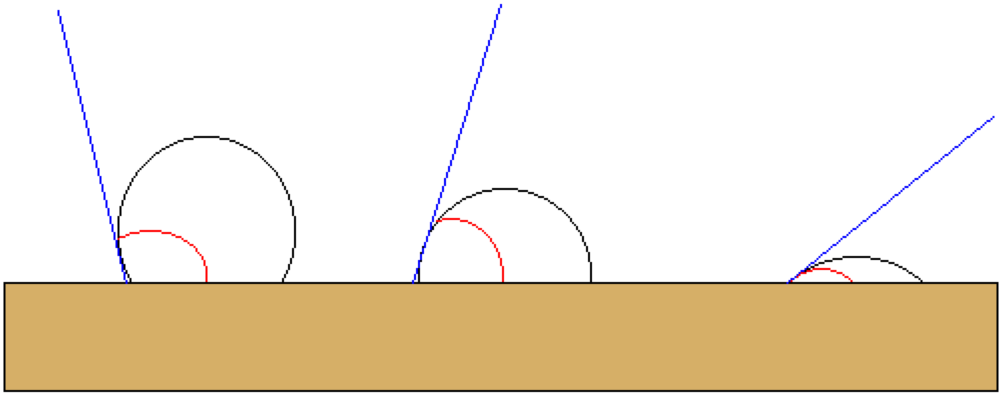


**Figure 9:** Measurement of the contact angle between fluids and surfaces. Wettability is higher at smaller angles (right part of the picture) and lower at bigger angles (left part of the picture)

Surface tension can be defined as the tangential force which tends to reduce the surface of a liquid. The higher the surface tension of the fluid the lower will be its capacity to wet the surface (Bandel, 1995).

### 3.4.1 Fundamental principles of wetting

The wettability of a solid by a liquid is characterized by the angle of contact between the solid and the liquid. The contact angle θ is obtained from a balance of interfacial tensions and defined from Young's equation. Surface free energy σ is defined as the energy needed to create a new surface of unit size. It can be expressed as energy/area (J/m²) (Wulf, et al., 1997).

$$\sigma_s = \sigma_{sl} + \sigma_l \cos\theta \qquad (1)$$

At $\theta < 90°$ the solid is well wetted by the liquid, and $\theta > 90°$ indicates less wetting, with the limits $\theta = 0$ (complete wetting) and $\theta = 180°$ (complete non-wetting) (Asthana and Sobezak, 2000).

In Young's equation only the surface tension of the liquid and the contact angle can be measured directly. To calculate the surface free energy of a solid, a second equation is needed to eliminate the interfacial tension from Young's equation (Li and Neumann, 1992; Wulf, et al., 1997; Netuschil, 2000).

$$\sigma_{sl} = \sigma_s + \sigma_l - 2\sqrt{\sigma_s \sigma_l} * e^{-\beta(\sigma_l - \sigma_s)^2} \qquad (2)$$

The result of the combination of both equations is:

$$(1 + \cos\theta) * \sigma_l = 2\sqrt{\sigma_s \sigma_l} * e^{-\beta(\sigma_l - \sigma_s)^2} \qquad (3)$$

with the empirical constant $\beta = 0{,}0001247\ (\mathrm{m}^2/\mathrm{J})^2$.

Wetting is important to many industrial processes. In many cases wetting is an essential prerequisite for application, e.g., in gluing and coating (Tadros, 2001).

## 3.5 Finishing on wood-based panels

Paint, varnish and stain protect the wood surface and help to maintain a certain appearance (Williams, et al., 1996). Paint can be defined as an oil- or alkyd-based solvent borne opaque system comprising primer, undercoat and a glossy topcoat. Varnish is, on the contrary, a solvent borne transparent, clear glossy coat. Stain is a low solid penetrating semi-transparent composition, containing a fungicide (Lambourne and Strivens, 1999). Many factors including wood, properties of finishing materials, and application methods as well as severity of exposure determine the performance of wood finishing (Williams, et al., 1996).

Different methods can be used to overlay wood-based panels. Wood-based panels can be coated with decorative paper. Moreover, particleboards and fiberboards can also be painted. Surfaces of fiberboards accept and hold paint very well. The surfaces of fiberboard can be improved with the addition of resin treated paper overlay (Williams, et al., 1996).

### 3.5.1 Durability of paints and coatings

#### 3.5.1.1 Mechanical properties of paints and coatings

The mechanical properties of paints and coatings have a great importance in maintaining the protective and decorative functions of the paints. Paint films are exposed to a variety of mechanical forces and deformations. One of the tests for measuring mechanical properties of paints is the so called impact test. In the impact test a force is applied to a small surface area for a very short time (Lambourne and Strivens, 1999).

In the adhesion test a die with a number of close-set parallel blades is pressed into the test surface successively in two directions at right angles to each other. A strip of self-adhesive tape is stucked over the pattern. Then the tape is removed sharply and the adhesion of the film is assessed from the amount of the coating removed (Lambourne and Strivens, 1999).

### 3.5.2 Appearance qualities of paints

Paint has an almost infinite capacity to modify the appearance of the substrate. Appearance qualities are: gloss, opacity and colour.

#### 3.5.2.1 Physics of reflection by paint-air interfaces

When light reaches an interface between two materials of different optical density a proportion of the light is reflected. The remainder light travels on with a change of direction (refraction), into a second material. The proportion of reflected light depends on the refractive indices of the two media and on the angle of incidence. Gloss of paint films is classified according to the degree to which they exhibit specular reflection (Lambourne and Strivens, 1999).

# 4 Materials and Methods

## 4.1 Materials and methods to manufacture particleboards

During the research work three layer particleboards were produced with different raw materials in the surface and by using different binders. The raw materials used for the surfaces of the chipboards were industrially produced fresh particles, recycled particles from industrially produced UF-bonded particleboards and recycled cork particles. For the core layers of the chipboards industrial produced fresh particles were used in all cases.

The fresh particles for the surface and core layers of the particleboards were supplied by a German particleboard company. The particles were a mixture of Picea abies (Spruce) and Pseudotsuga menziesii (Douglas fir). The size of the fresh surface particles was between 0.2 mm and 1.0 mm.

The same company offered 19 mm uncoated urea-formaldehyde bonded particleboards for the production of recycled surface particles. The recycled particles were produced by a dry process in the laboratories of the Institute of Wood Biology and Wood Technology. Therefore, the UF-bonded particleboards were cut into pieces of 5.0 cm x 5.0 cm and thereafter grinded with a special aggregate (electra industrie). After the grinding process the recycled particles were screened and classified according to their sizes. Only recycled particles between a size of 0.2 mm and 1.0 mm were used for the surface layers of the recycling particleboards.

The cork particles were supplied by a German company. The surface cork particles were also meshed and classified between a range of 0.2 mm and 1.0 mm.

For preparation of particleboards a commercial urea-formaldehyde resin (UF-resin, BASF K 350) and a tannin-formaldehyde resin (TF-resin) were used. The fresh and recycled particles were dried to 4 % moisture content (M.C.), the cork particles were dried to 2 % moisture content (M.C). Six different series of particleboards were made; from each type three boards were produced. Tables 1 – 6 show the conditions for preparation of the different boards.

**Table 1:** Conditions for preparation of three layer UF-bonded particleboards with fresh particles in the surface layer (variant 1)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | UF-resin, BASF K 350 (65 % solids content) |
| Binder level: | Surface layer 10 % (solids based on o.d. particles) |
| | Core layer 8 % (solids based on o.d. particles) |
| Hardener: | Ammoniumsulfate |
| Hardener level: | Surface layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| | Core layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 10 s/mm (exl. closing time of the press) |

**Table 2:** Conditions for preparation of three layer TF-bonded particleboards with fresh particles in the surface layer (variant 2)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | TF-resin (45 % solids content) |
| Type of tannin: | Colatan GT 5 Industria Argentina |
| Binder level: | Surface layer 14 % (solids based on o.d. particles) |
| | Core layer 12 % (solids based on o.d. particles) |
| Added formaldehyde: | 10.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 20 s/mm (exl. closing time of the press) |

**Table 3:** Conditions for preparation of three layer UF-bonded particleboards with recycled particles in the surface layer (variant 3)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | UF-resin, BASF K 350 (65 % solids content) |
| Binder level: | Surface layer 10 % (solids based on o.d. particles) |
| | Core layer 8 % (solids based on o.d. particles) |
| Hardener: | Ammoniumsulfate |
| Hardener level: | Surface layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| | Core layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 10 s/mm (exl. closing time of the press) |

**Table 4:** Conditions for preparation of three layer TF-bonded particleboards with recycled particles in the surface layer (variant 4)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | TF-resin (45 % solids content) |
| Type of tannin: | Colatan GT 5 Industria Argentina |
| Binder level: | Surface layer 14 % (solids based on o.d. particles) |
| | Core layer 12 % (solids based on o.d. particles) |
| Added formaldehyde: | 10.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 20 s/mm (exl. closing time of the press) |

**Table 5:** Conditions for preparation of three layer UF-bonded particleboards with cork particles in the surface layer (variant 5)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | UF-resin, BASF K 350 (65 % solid content) |
| Binder level: | Surface layer 10 % (solids based on o.d. particles) |
| | Core layer 8 % (solids based on o.d. particles) |
| Hardener: | Ammoniumsulfate |
| Hardener level: | Surface layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| | Core layer 3.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 36 s/mm (exl. closing time of the press) |

**Table 6:** Conditions for preparation of three layer TF-bonded particleboards with cork particles in the surface layer (variant 6)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 3 |
| Target density: | 700 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 19 mm (sanded) |
| Binder type: | TF-resin (45 % solids content) |
| Type of tannin: | Colatan GT 5 Industria Argentina |
| Binder level: | Surface layer 8 % (solids based on o.d. particles) |
| | Core layer 10 % (solids based on o.d. particles) |
| Added formaldehyde: | Surface layer 6.5 % (active formaldehyde based on o.d. tannin) |
| | Core layer 8.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190 °C |
| Pressing time: | 45 s/mm (exl. closing time of the press) |

After production the particleboards were trimmed to the target dimensions (410 mm x 410 mm) and sanded (grain 120) to the target thickness (19 mm). Thereafter, the particleboards were conditioned about four weeks prior to evaluating their surfaces at three different climatic conditions. These were 20ºC / 30 % relative humidity, 20ºC / 65 % relative humidity and 20ºC / 85 % relative humidity. Table 7 shows the particleboard variants of the experiment.

**Table 7:** Particleboard variants 1 - 6 of the experiments

| Material of the particleboard surface layers | Binder type | Climatic conditions °C / rel. humidity % | Variants |
|---|---|---|---|
| Fresh particles | UF-resin | 20 / 30 | V 11 |
| | | 20 / 65 | V 12 |
| | | 20 / 85 | V 13 |
| | TF-resin | 20 / 30 | V 21 |
| | | 20 / 65 | V 22 |
| | | 20 / 85 | V 23 |
| Recycled particles | UF-resin | 20 / 30 | V 31 |
| | | 20 / 65 | V 32 |
| | | 20 / 85 | V 33 |
| | TF-resin | 20 / 30 | V 41 |
| | | 20 / 65 | V 42 |
| | | 20 / 85 | V 43 |
| Recycled cork | UF-resin | 20 / 30 | V 51 |
| | | 20 / 65 | V 52 |
| | | 20 / 85 | V 53 |
| | TF-resin | 20 / 30 | V 61 |
| | | 20 / 65 | V 62 |
| | | 20 / 85 | V 63 |

## 4.2 Measuring surface roughness of uncoated particleboards

### 4.2.1 Measuring roughness by contact method

For measuring surface roughness by contact method a perthometer S4P of the FEINPRÜF PERTHEN Company (Göttingen, Germany) was used. The measuring begins with the calibration of the instrument. In this experiment the length of the traverse (LT, Figure 3) was 5.6 mm and the vertical limit (VB) was 250 µm. The number of sample lengths ($l_e$) within the evaluation length ($l_m$) was 5 (Figure 5).

For each variant of Table 7 ten measurements were taken systematically all over the surface. During each measurement the parameters $R_a$, $R_z$ and $R_{max}$ (Chapter 3.2.4) were calculated by perthometer software.

### 4.2.2 Measuring roughness by non-contact method

A non-contact method (image analysis) was used for measuring roughness of the uncoated particleboards. According to the procedure already described under Chapter 3.3, the first step was to find out the optimal angle of the light source. Preliminary investigations showed that the minimal standard deviation (SD) of the gray level histograms was obtained when the light was sent at an angle of 15º to the surfaces of the samples. A CCD camera was installed at a distance of 1 meter above the surface. A light detector inside the CCD camera received the reflected light and converted it into a video signal which was set as a photograph. Subsequently, the photograph was transformed by the software Leica Q500MC to binary language to process the images. From the light scattering pattern processed by the software the optical roughness parameter (SD) of the surface of the image was calculated.

## 4.3 Preparing and measuring the surface performance of painted particleboards

### 4.3.1 Choosing the particleboards and application of paint

After measuring the surface roughness parameters, the uncoated particleboards of Table 7 which were stored at 20°C / 65 % relative humidity (6 particleboards) were transported to the Institute of Forest Technical Products at the University Austral de Chile, Valdivia, Chile. Here the surface performance of the particleboards was evaluated. In Valdivia, the particleboards were painted with nitrocellulose paint in an air-conditioned paint application chamber under a high volume, low pressure finishing process. After painting, the particleboards were conditioned at 20°C and 65 % relative humidity for about three weeks. The following tests (Aidima, 1999) were made on the conditioned painted particleboards samples:

- Adherence strength (according to UNE-standard 48032),
- Speculate brightness (according to UNE-standard 48026),
- Impact strength (according to UNE-standard 11019/6),
- Abrasion strength (according to EN-standard 438-2, article 6).

Before testing the particleboards according to the above mentioned standards it was necessary to make a characterization of its surfaces. First the roughness parameters of the coated particleboards were measured by a contact method with a Mitutoyo apparatus SJ201p (Figure 10). Also the thickness of the paint layer was controlled by DIN method (50986) (Figure 11).

**Figure 10:** Roughness measurement of a particleboard coated with nitrocellulosic paint.

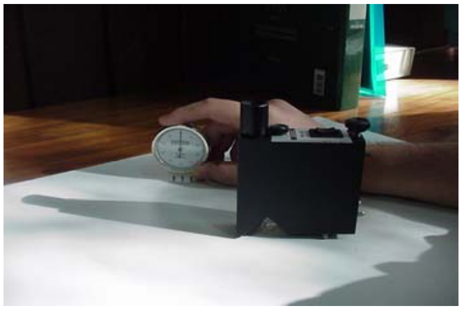


**Figure 11:** Thickness measurement of a particleboard coated with nitrocellulosic paint.

### 4.3.2 Adherence strength (according to UNE-standard 48032)

Objective of the test: Determination of the adherence strength between a substrate (e.g., surface) and a coating layer or among multiple dry layers of paint or varnishes by a grating method.

**Figure 12:** Determination of adherence strength according to UNE-standard 48032

General procedure of the test: Over the tested surface a grating composed of two perpendicular groups of 6 parallel slits is made with a roll cutter (Figure 12). The distance between the slits ranges between 1.0 mm – 2.0 millimetre (generally 2.0 mm). Afterwards the slitted surface is covered with an adhesive tape. The adhesive tape is fitfully remoted. The damaged area of the slitted surface is analysed visually.

### 4.3.3 Speculate brightness (according to UNE-standard 48026)

Objective of the test: Evaluate the reflect capacity of a finished surface by speculate brightness.

**Figure 13:** Determination of speculate brightness according to UNE-standard 48026

General procedure of the test: The determination of surface brightness was made by using a brightness meter (Figure 13). Collimated light is sent from the top of the instrument at different angles (20°, 60° and 85°) to the surface of the tested sample. The instrument measures the amount of reflected light (reflection capacity %), sent from the sample surface. Preliminary calibration of the device is necessary prior to measuring of the brightness.

### 4.3.4 Impact strength (according to UNE-standard 11019/6)

Objective of the test: Determination of finish strength of the product against mechanical damage. The test simulates the damages on the surface of furniture which can be generated by impact or crash.

General procedure of the test: A standard steel ball falls down on the surface of a sample from a distance of two meters height and causes damage (Figure 14). The degree of damage is evaluated optically by using a scale level from 1 to 5.

**Figure 14:** Determination of impact strength according to UNE-standard 11019/6

### 4.3.5 Abrasion strength (according to EN-standard 438-2 article 6)

Objective of the test: Determination of the abrasion strength of finished surfaces.

General procedure of the test: The sample is set on a rotating desk under the action of an abrasive wheel. The basic principle is to find out the number of cycles necessary to reach a definite level of abrasion.

**Figure 15:** Determination of abrasion strength with a Taber abrasion instrument according to EN-standard 438-2, article 6

## 4.4 Materials and methods to manufacture fiberboards

During the research work one and also three layer medium density fiberboards (MDF) were produced using different raw materials in the surface layers and also different binders. The raw materials for the surfaces were industrially produced fresh fibers (thermo-mechanical pulp, TMP), recycling fibers generated from industrially produced UF-bonded fiberboards. In another set of experiments recycled cork was used in the surface layers. Nowadays, fiberboards coated with a surface layer of cork are commercially available.

The fresh fibers (TMP) were supplied by a German MDF company. The pulp was obtained from a mixture of Picea abies (spruce) and Pinus silvestris (pine). The pulping temperature was approximately 180ºC. The defibrated fibers were transported to the Institute of Wood Biology and Wood Technology and dried in an oven at 70ºC to moisture content of about 5%.

The same company offered 7 mm uncoated urea-formaldehyde bonded fiberboards (MDF) for the production of recycled surface fibers. The recycled fibers were produced by a thermo-hydrolytic process in the laboratories of the Institute of Wood Biology and Wood Technology. The process was as follows:

The 7 mm uncoated UF-bonded MDF were cut into pieces of 5.0 cm x 5.0 cm and thereafter crushed with the special aggregate (electra industrie). After crushing the fine material (<0.5 mm) was rejected. The crushed MDF material (6.0 kg atro material) was pulped in a 50-Litreautoclave using 1 % sodium hydroxide (NaOH) (based on oven dry material) at a liquor ratio of 1:6. The autoclave was heated to a maximum temperature of 130ºC, after reaching 130ºC the cooking was continued for 1 hour. During pulping the autoclave rotated over 360º.

After cooking the fibers were left to cool down in the autoclave to room temperature for about 18 hours. Thereafter, the fibers obtained were collected and dried at 70ºC to moisture content of about 5%. After drying the fibers were processed in a Pallmann-mill PXL 18 at about 12.400 rpm to a fluff. The fibers were sifted, screened and fine and coarse fibers were separated. For producing recycled MDF, only recycled fibers between 0.2 mm and 2.0 mm were used for the surface layers.

The cork particles were also supplied by a German company. The surface cork particles were also screened and classified between a range of 0.2 mm and 1.0 mm. The cork particles were dried to approximately 2.0% moisture content (M.C).

For preparation of medium density fiberboards (MDF) a commercial melamine-urea-formaldehyde resin (MUF-resin, BASF K 407 with a melamine content of about 1%) and a tannin-formaldehyde resin (TF-resin) were used as binders.

Figure 16 shows the dried UF-recycling fibers after the thermo-hydrolytic process, after gluing with melamine-urea-formaldehyde resin (MUF-resin), and after refining in the Pallmann-mill PXL 18.

**Figure 16:** Dried UF-recycling fibers after the thermo-hydrolytic process (left part of the picture), after gluing with MUF-resin (middle of the picture), and after refining in the Pallmann-mill PXL 18.

Six different series (types) of medium density fiberboards (MDF) were made. From each type three boards were produced (totalling 18 boards). One layer MDF were made with the fresh and the recycled fibers as well as three layers MDF with recycled cork particles in the surface layer and fresh fibers in the core layer. Tables 8 – 13 show the conditions for preparation of the different MDF.

**Table 8:** Conditions for preparation of one layer MUF-bonded medium density fiberboards (MDF) with fresh fibers (TMP) (variant 1)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 1 |
| Target density: | 800 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 13 mm (sanded) |
| Binder type: | MUF-resin BASF K 407 (69 % solids content) |
| Binder level: | 12 % (solids based on o.d. fibers) |
| Hardener: | Ammoniumsulfate |
| Hardener level: | 4.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190°C |
| Pressing time: | 30 s/mm (exl. closing time of the press) |

**Table 9:** Conditions for preparation of one layer TF-bonded medium density fiberboards (MDF) with fresh fibers (TMP) (variant 2)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 1 |
| Target density: | 800 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 13 mm (sanded) |
| Binder type: | TF-resin (45 % solids content) |
| Type of tannin: | Colatan GT 5 Industria Argentina |
| Binder level: | 14 % (solids based on o.d. fibers) |
| Added formaldehyde: | 10.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190°C |
| Pressing time: | 40 s/mm (exl. closing time of the press) |

**Table 10:** Conditions for preparation of one layer MUF-bonded medium density fiberboards (MDF) with recycled fibers from UF-bonded MDF (variant 3)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 1 |
| Target density: | 800 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 13 mm (sanded) |
| Binder type: | MUF-resin BASF K 407 (69 % solids content) |
| Binder level: | 12 % (solids based on o.d. fibers) |
| Hardener: | Ammoniumsulfate |
| Hardener level: | 4.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190°C |
| Pressing time: | 30 s/mm (exl. closing time of the press) |

**Table 11:** Conditions for preparation of one layer TF-bonded medium density fiberboards (MDF) with recycled fibers from UF-bonded MDF (variant 4)

| | |
|---|---|
| Number of boards: | 3 |
| Layers: | 1 |
| Target density: | 800 kg/m³ |
| Size of the boards: | 410 mm x 410 mm |
| Thickness of the boards: | 13 mm (sanded) |
| Binder type: | TF-resin (45 % solids content) |
| Type of tannin: | Colatan GT 5 Industria Argentina |
| Binder level: | 14 % (solids based on o.d. fibers) |
| Added formaldehyde: | 10.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190°C |
| Pressing time: | 40 s/mm (exl. closing time of the press) |

**Table 12:** Conditions for preparation of three layer MUF-bonded medium density fiberboards (MDF) with cork particles in the surface layer (variant 5)

| | | |
|---|---|---|
| Number of boards: | 3 | |
| Layers: | 3 | |
| Target density: | 500 kg/m³ | |
| Size of the boards: | 410 mm x 410 mm | |
| Thickness of the boards: | 13 mm (sanded) | |
| Binder type: | MUF-resin BASF K 407 (69 % solids content) | |
| Binder level: | Surface layer | 12 % (solids based on o.d. fibers) |
| | Core layer | 10 % (solids based on o.d. fibers) |
| Hardener: | Ammoniumsulfate | |
| Hardener level: | Surface layer | 4.0 % Ammoniumsulfate (solids based on o.d. resin) |
| | Core layer | 4.0 % Ammoniumsulfate (solids based on o.d. resin) |
| Pressing temperature: | 190°C | |
| Pressing time: | 60 s/mm (exl. closing time of the press) | |

**Table 13:** Conditions for preparation of three layer TF-bonded medium density fiberboards (MDF) with cork particles in the surface layer (variant 6)

| | | |
|---|---|---|
| Number of boards: | 3 | |
| Layers: | 3 | |
| Target density: | 500 kg/m³ | |
| Size of the boards: | 410 mm x 410 mm | |
| Thickness of the boards: | 13 mm (sanded) | |
| Binder type: | TF-resin (45 % solids content) | |
| Type of tannin: | Colatan GT 5 Industria Argentina | |
| Binder level: | Surface layer | 10 % (solids based on o.d. fibers) |
| | Core layer | 14 % (solids based on o.d. fibers) |
| Added formaldehyde: | Surface layer | 6.5 % (active formaldehyde based on o.d. tannin) |
| | Core layer | 8.5 % (active formaldehyde based on o.d. tannin) |
| Pressing temperature: | 190°C | |
| Pressing time: | 60 s/mm (exl. closing time of the press) | |

After pressing and cooling the medium density fiberboards were trimmed to the target dimensions (10 mm x 410 mm) and sanded (grain 120) to the target thickness (13 mm).

The main objective of this experiment was to investigate the influence of moisture content of the boards on their surface roughness. To do that MDF (18 boards) were conditioned in a first step at a climate of 20°C / 30% relative humidity until the boards reached equilibrium moisture content. The surface roughness of the MDF was then measured by using the contact method (Perthometer (S4P)) and the non-contact method (image analysis, Leica Q500MC and JVC-CCD camera). Thereafter, boards were conditioned at 20ºC and 65% rel. humidity to a higher M.C. until the boards reached equilibrium moisture content. Thereafter, the same surface parameters were measured. In the last step of the experiment the MDF were stored at 20°C and 85% rel. humidity and their surface roughness was again evaluated. The whole experiment lasted nine weeks; in each climate the MDF needed about three weeks to reach equilibrium moisture content.

**Table 14:** MDF variants (V1-V6) of the experiments

| MDF surface material | Binder type | Climatic conditions °C / rel. humidity % | Variants |
|---|---|---|---|
| Fresh fibers (TMP) | MUF-resin | 20/30, 20/65, 20/85 | V 11, V 12, V 13 |
| | TF-resin | 20/30, 20/65, 20/85 | V 21, V 22, V 23 |
| Recycled fibers | MUF-resin | 20/30, 20/65, 20/85 | V 31, V 32, V 33 |
| | TF-resin | 20/30, 20/65, 20/85 | V 41, V 42, V 43 |
| Recycled cork | MUF-resin | 20/30, 20/65, 20/85 | V 51, V 52, V 53 |
| | TF-resin | 20/30, 20/65, 20/85 | V 61, V 62, V 63 |

## 4.5 Measuring the surface roughness of uncoated MDF

To measure the surface roughness of uncoated medium density fiberboards (MDF) the same procedure was used as in case of uncoated particleboards. Both methods the contact method (by perthometer) and the non-contact method (by image analysis) were used.

## 4.6 Measuring surface wettability

The wettability of the MDF surfaces was measured by using different mixtures of distilled water and isopropanol. The following mixtures were used in the experiment: 100% distilled water; 5% isopropanol and 95% distilled water; 10% isopropanol and 90% distilled water; 15% isopropanol and 85% distilled water; 20% isopropanol and 80% distilled water, and 30% isopropanol and 70% distilled water.

The samples used for measuring surface roughness were also used for measuring surface wettability. In the experiment the opposite surface of the samples were used. The surfaces were divided in 8 equal sections (Figure 17). In section 1 surface wettability against 100% distilled water was measured. In section 2 surface wettability against a mixture of 5% isopropanol and 95% distilled water was measured and so on.

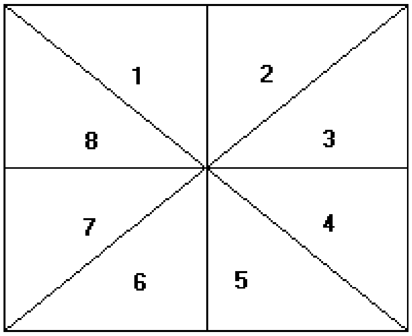


**Figure 17:** Preparation of MDF-sample surface for measuring wettability. The surface area is divided in 8 proportional sections.

The contact angle between the liquid drops and the sample surface was measured with a static technique using the Leica software Q500 MC. The principle of the method is shown in Figure 18. Drops of 50 µl volume were placed over the surface at constant velocity using a micro-pipette. At intervals of two seconds the drop was photographed with a JVC-TK 1280E video camera (Figure 18). The contact angle was measured automatically.

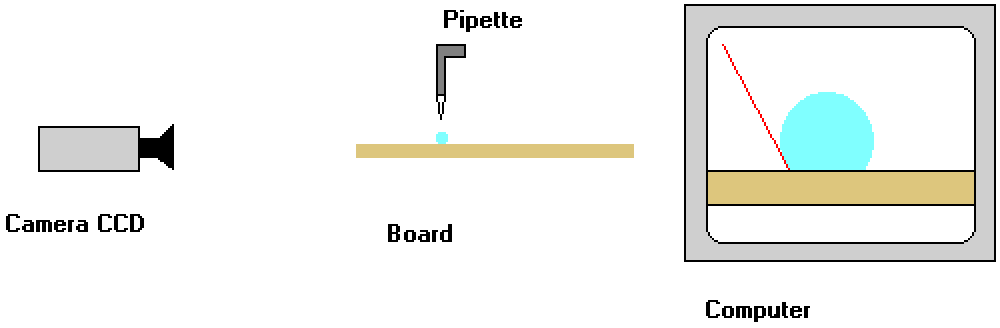


**Figure 18:** Device to measure surface wettability on medium density fiberboards (MDF)

# 5 Results and Discussion

## 5.1 Particleboards

### 5.1.1 Influence of raw material, type of adhesive and climatic conditions on the surface roughness of uncoated particleboards as assessed by the contact method

#### 5.1.1.1 Influence of raw material and climatic conditions on the surface roughness of uncoated UF-bonded particleboards as assessed by the contact method

For all uncoated UF-bonded particleboards (PB) the equilibrium moisture content (E.M.C.) was measured after storage under different climatic conditions (20°C / 30 % relative humidity (r.h.), 20°C / 65 % relative humidity and 20°C / 85 % relative humidity). The results are shown in Figure 19.

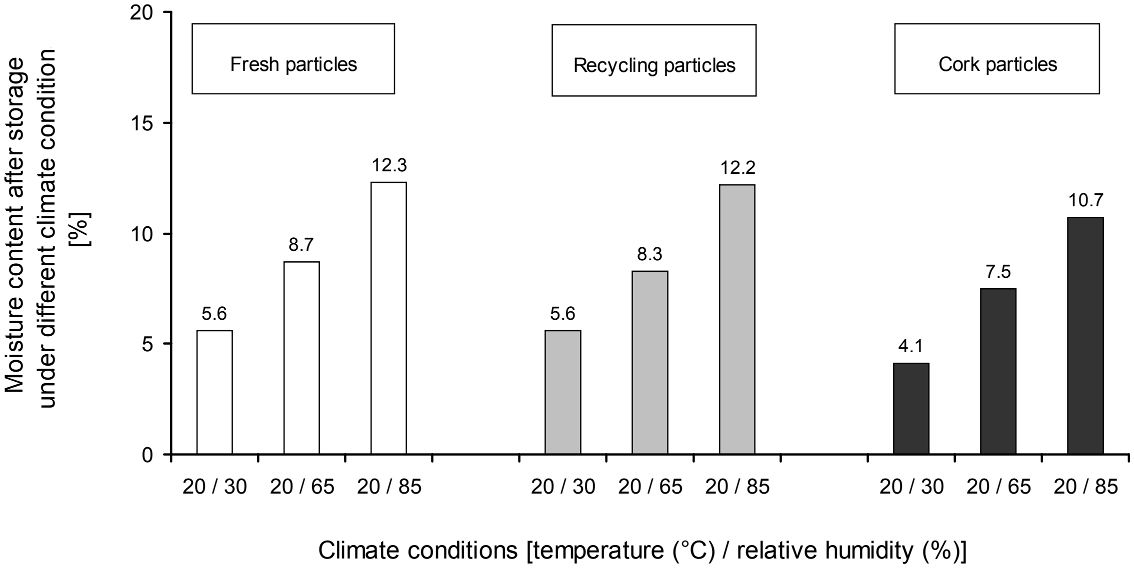


**Figure 19:** Equilibrium moisture content (E.M.C.) (%) of uncoated UF-bonded particleboards, made using with different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

As can be seen from Figure 19 the moisture content of all UF-bonded particleboards increased with increasing relative humidity irrespective of the lignocellulosic raw material used in the manufacture of the boards. UF-bonded particleboards made with fresh and recycled particles in the surface layers showed more or less the same rise in moisture content with increasing relative humidity during storage.

For UF-bonded particleboards made with fresh and recycled particles the equilibrium moisture content after storage at 20°C / 30 % r.h. was 5.6 %. After storage at 20°C / 65 % r.h. the moisture content of both types of boards increased to 8.7 % (UF-bonded PB with fresh particles) and 8.3 % (UF-bonded PB with recycled particles) respectively. The highest moisture contents (12.3 % and 12.2 %) were reached, when the particleboards were stored under a climate of 85 % relative humidity. Boards with recycled chips in the surface showed slightly lower equilibrium moisture content.

The equilibrium moisture content of the uncoated UF-bonded particleboards with cork particles in the surface layer was lower than that of UF-particleboards made with fresh and recycled particles. The equilibrium moisture content of uncoated UF-bonded PB with cork particles in the surface layer increased with increasing relative humidity from 4.1 % E.M.C. (20°C / 30% r.h.) over 7.5 % E.M.C. (20°C / 65% r.h.) to 10.7 % E.M.C. (20°C / 85% r.h.).

Figure 20 shows an individual measurement of a roughness profile of an uncoated UF-bonded particleboard, made using fresh particles in the surface layer after reaching equilibrium moisture content (8.7 %) at climate 20°C / 65% relative humidity (variant 1). The profile gives information which describes the surface characteristics, e.g., average roughness ($R_a$), the mean peak-to-valley height ($R_z$), maximum-peak-to-valley height ($R_{max}$). The measured profile parameters help in the interpretation of the surfaces. In case of this work $R_a$ was chosen as the main parameter to describe the surfaces.

PB-Measurement-no.: 124

| | | |
|---|---|---|
| $R_a$ | 5.5 | µm |
| $R_z$ | 33.2 | µm |
| $R_{max}$ | 50.7 | µm |

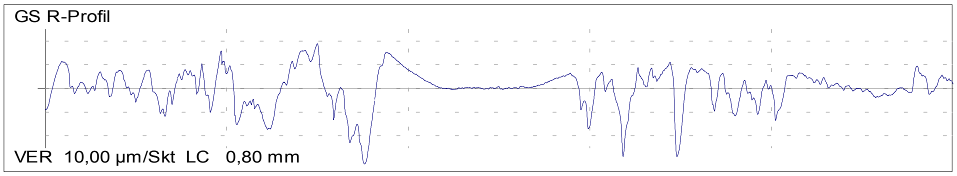


**Figure 20:** Individual measurement of a roughness profile of a uncoated UF-bonded particleboard, made using fresh particles in the surface layer after reaching equilibrium moisture content (8.7 %) at climate 20°C / 65% relative humidity (variant 1)

In Figure 21 the influence of the raw material and the moisture content on the roughness of UF-bonded particleboards is presented. Figure 21 shows on the one hand that UF-bonded particleboards with recycled particles are of higher roughness irrespective of the moisture content ($R_a$ = 10.5 µm at 20ºC / 65% r.h.) in comparison to fresh particles ($R_a$ = 5.5 µm at 20ºC / 65% r.h). On the other hand UF-bonded PB with cork particles on surface layers do have the smoothest surfaces ($R_a$ = 2.7 µm at 20ºC / 65% r.h.).

Moreover, Figure 21 shows the general influence of different climatic conditions on the roughness of UF-bonded particleboards. Independent of the raw material used the roughness of UF-bonded particleboards increased with increasing moisture content. The $R_a$-value increased with raising relative humidity in the region of 30% r.h. over 65% r.h. to 85% r.h. from 4.3 µm over 5.5 µm to 5.7 µm. In case of recycled particles $R_a$ increased in the same region from 10.5 µm up to 12 µm.

As the results indicate cork particles showed a quite different behaviour; there was no detectable increase in the roughness of the boards due to increase in the moisture content of the boards.

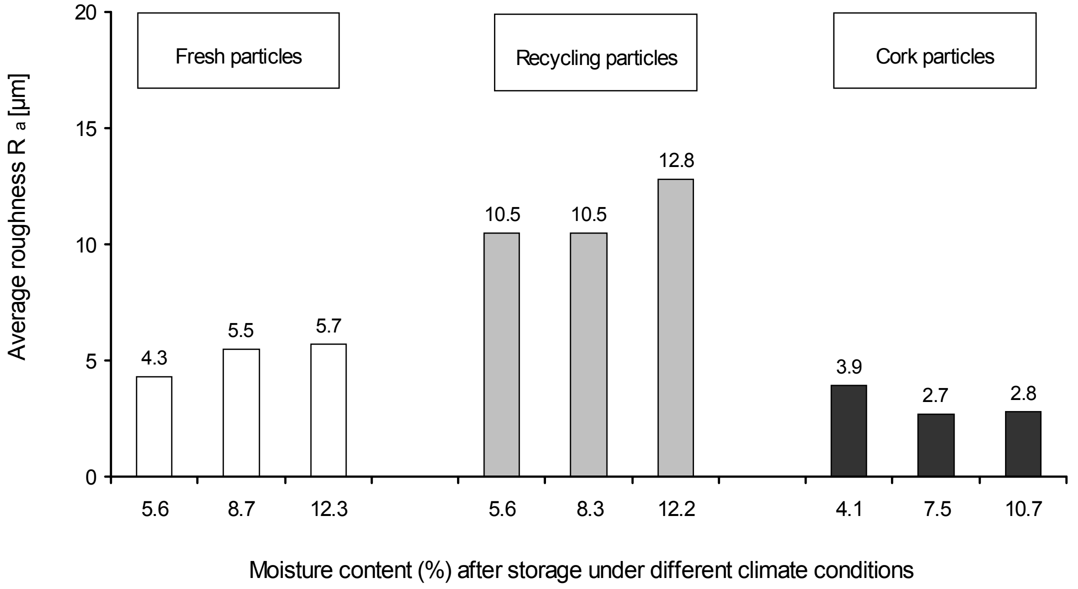


**Figure 21:** Average roughness $R_a$ (µm) of uncoated UF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

#### 5.1.1.2 Influence of raw material and climatic conditions on the surface roughness of uncoated TF-bonded particleboards as assessed by the contact method

For all uncoated TF-bonded particleboards (PB) the equilibrium moisture content was measured after storage under different climatic conditions (20°C / 30 % r.h., 20°C / 65 % r.h. and 20°C / 85 % r.h.). It can be seen from Figure 22 that the moisture content of all TF-bonded particleboards increased with higher relative humidity irrespective of the lignocellulosic raw material used for making the boards. TF-bonded particleboards made with fresh and recycled particles in the surface layers showed more or less the same rise in moisture content with increasing relative humidity during storage. For TF-bonded particleboards made with fresh and recycled particles the equilibrium moisture content after storage at 20°C / 30 % r.h. was about 6.3 %. After storage at 20°C / 65 % r.h. moisture content of both types of boards went higher to 10 %. The highest moisture contents (14.5 % and 14.7 %) were reached, when the particleboards were stored under a climate of 85 % relative humidity.

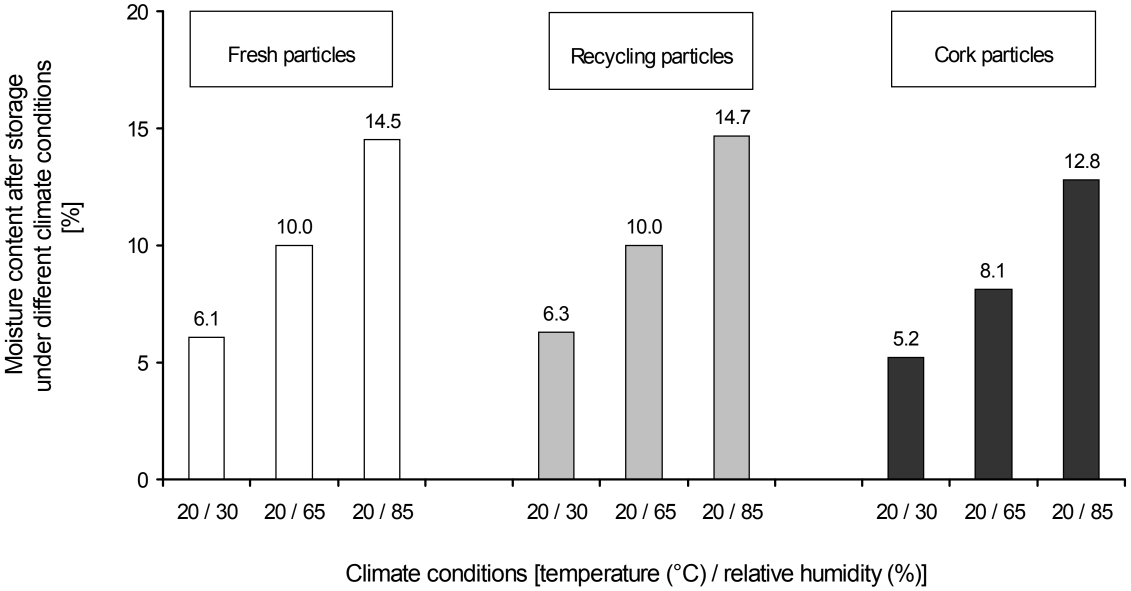


**Figure 22:** Equilibrium moisture content (E.M.C.) (%) of uncoated TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

The equilibrium moisture content of the uncoated TF-bonded particleboards with cork particles in the surface layer was compared to TF-particleboards made with fresh and recycled particles in general on a lower level. The equilibrium moisture content of uncoated TF-bonded PB with cork particles in the surface layer increased during storage of the boards under higher humidity from 5.2 % E.M.C. (20°C / 30 % r.h.) over 8.1 % E.M.C. (20°C / 65 % r.h.) to 12.8 % E.M.C. (20°C / 85 % r.h.).

Figure 23 shows an individual measurement of a roughness profile of an uncoated TF-bonded particleboard, made using fresh particles in the surface layer after reaching equilibrium moisture content (10.0 %) at climate 20°C / 65% relative humidity (variant 2).

PB-Measurement-no.: 224

| | | |
|---|---|---|
| $R_a$ | 5.7 | µm |
| $R_z$ | 31.8 | µm |
| $R_{max}$ | 45.2 | µm |

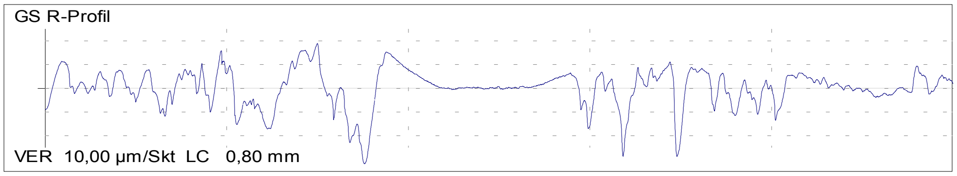


**Figure 23:** Individual measurement of a roughness profile of an uncoated TF-bonded particleboard, made using fresh particles in the surface layer after reaching equilibrium moisture content (10.0 %) at climate 20°C / 65% relative humidity (variant 2)

Figure 24 shows the influence of the raw material on the roughness of TF-bonded PB. TF-bonded PB with recycled particles showed the highest roughness of the surface ($R_a$ = 7.8 µm at 20ºC / 65% r.h.) in comparison with TF-bonded PB with fresh particles ($R_a$ = 6.0 µm at 20ºC / 65% r.h.). On the other hand TF-bonded PB with cork in the surface layers are comparatively of smooth surfaces ($R_a$ = 3.7 µm at 20ºC / 65% r.h.).

Figure 24 also shows that changes in climatic conditions impacts the roughness of the particleboards differently. The roughness value $R_a$ of TF-bonded particleboards with recycled particles increased due to increase in the moisture content. In case of TF-bonded particleboards made from fresh chips and those with cork particles in the surface no increase in roughness was found, on the contrary the $R_a$-values decreased slightly when the moisture content of the boards increased.

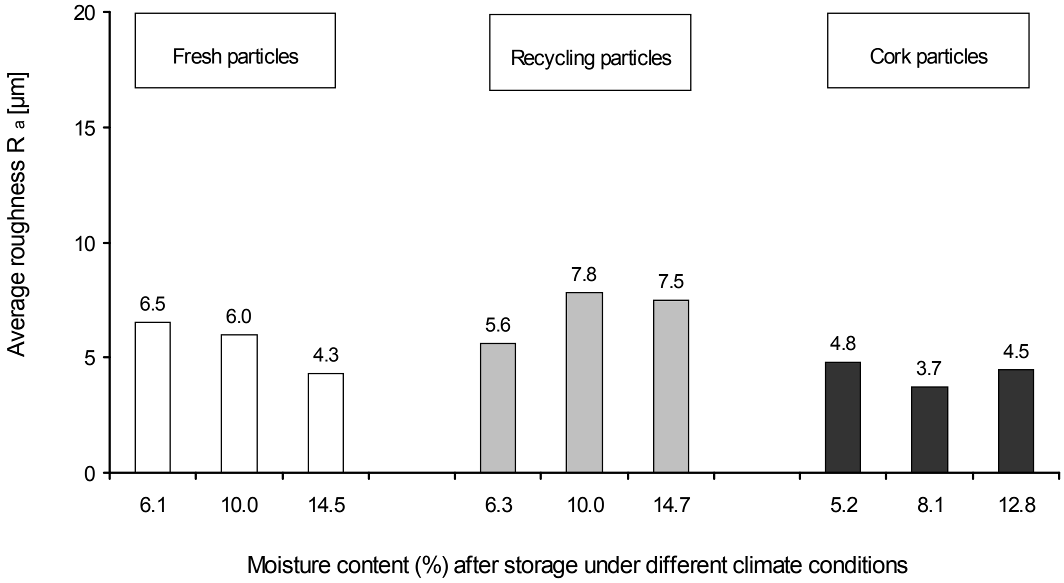


**Figure 24:** Average roughness $R_a$ (µm) of uncoated TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

#### 5.1.1.3 Influence of raw material and climatic conditions on the surface roughness of uncoated UF- and TF-bonded particleboards as assessed by the contact method

In the Figures 25 and 26 the results are summarized. As can be seen from Figure 25, in general, an increase in the equilibrium moisture content of the boards was measured, when the relative humidity increased from 30% r.h. over 65% r.h. to 85% r.h. Moreover, the influence of the type of adhesive on the moisture content of the manufactured particleboards was also obvious. TF-bonded PB showed higher equilibrium moisture content compared to UF-bonded PB.

As can be seen from Figure 26 particleboards made with recycled particles in the surface layer had the roughest surfaces (average roughness ($R_a$)) irrespective of the adhesive used.

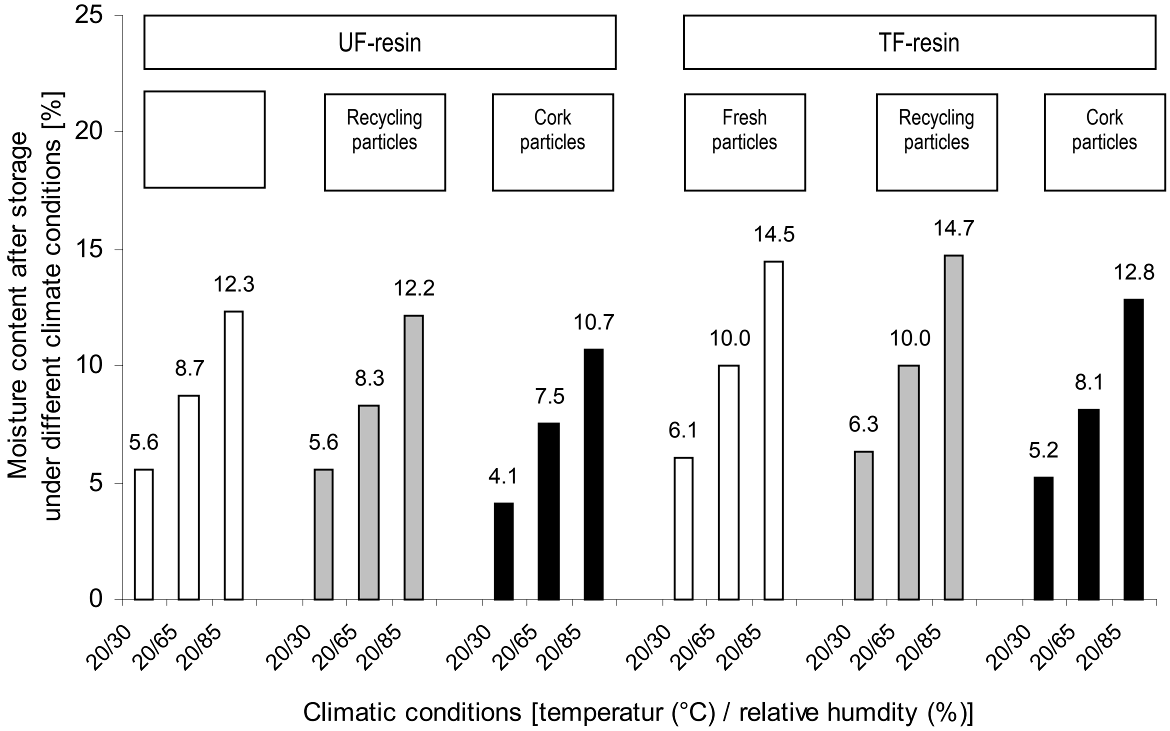


**Figure 25:** Equilibrium moisture content (E.M.C.) (%) of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

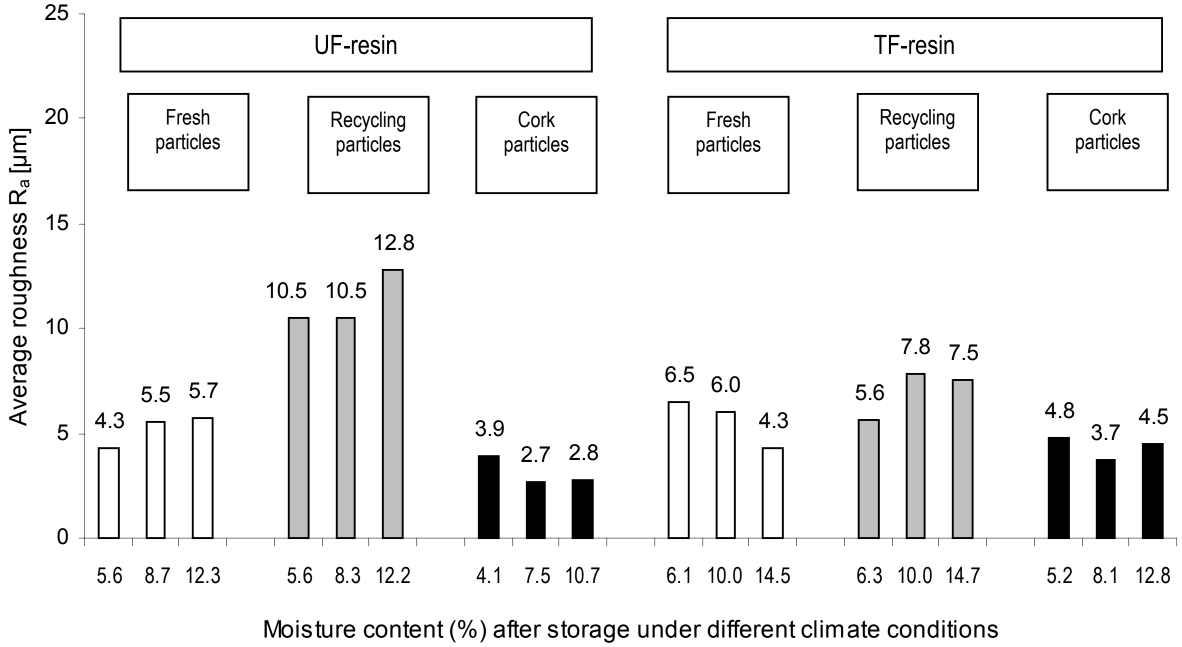


**Figure 26:** Average roughness $R_a$ (µm) of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

### 5.1.1.4 Statistical analysis of the results

Within the frame work of this study the grade of interaction between factors (independent variables) such as the type of raw material, type of adhesive, climatic conditions and responses (dependent variables) such as average roughness and moisture content of the particleboards was determined. Moreover, the average density of the particleboards was also measured. The data in chapter 5.1.1 were statistically analysed using two statistical tests (Anova analysis and Tukey's analysis). Table 15 helps to understand the preparation of data of the Anova analysis. The factors (independent variables) and responses (dependent variables) were:

Independent variables:

- Raw materials (fresh, recycled, cork particles)
- Adhesives (urea-formaldehyde-resin (UF-resin), tannin-formaldehyde resin (TF-resin)
- Climatic conditions (20°C/30% r.h., 20°C/65% r.h., 20°C/85% r.h.)

Dependent variables:

- Average roughness $R_a$ (µm)
- Moisture content (%)

Table 16 shows the results of the Anova analysis. The Anova analysis evaluates the influence of independent factors on the responses at two levels of significance, 0.05 % of statistical probability as significant and 0.01 % of statistical probability as highly significant. It can be seen from the table which factors under an independently or in interaction with other factors lead to significant differences in the values of the responses (properties of the uncoated particleboards). For a complete review of the statistical analysis done during the research work, see the appendix of this thesis.

#### Average roughness ($R_a$)

In a first step the influence of the factors raw material, adhesive and climatic conditions as well as the interaction between them on the average roughness ($R_a$) (response) of the uncoated particleboards was determined. As can bee seen from Table 16, only the factor raw material as a single factor has significant influence (0.0018) on the average surface roughness of the uncoated particleboards. There is also an interaction between the factors raw material and adhesive on the average roughness ($R_a$) (0.0177).

**Table 15:** Design of the Anova analysis, factors (independent variables) and responses (dependent variables) of the experiment

| Factors (independent variables) | | | Responses (dependent variables) | |
|---|---|---|---|---|
| Raw material | Type of adhesive | Climatic Conditions °C / rel. humidity % | Average roughness ($R_a$) µm | Moisture content % |
| Fresh particles | UF-resin | 20 / 30 | 4.3 | 5.6 |
| | | 20 / 65 | 5.5 | 8.7 |
| | | 20 / 85 | 5.7 | 12.3 |
| | TF-resin | 20 / 30 | 6.5 | 6.1 |
| | | 20 / 65 | 6.0 | 10.0 |
| | | 20 / 85 | 4.3 | 14.5 |
| Recycled particles | UF-resin | 20 / 30 | 10.5 | 5.6 |
| | | 20 / 65 | 10.5 | 8.3 |
| | | 20 / 85 | 12.8 | 12.2 |
| | TF-resin | 20 / 30 | 5.6 | 6.3 |
| | | 20 / 65 | 7.8 | 10.0 |
| | | 20 / 85 | 7.5 | 14.7 |
| Recycled cork | UF-resin | 20 / 30 | 3.9 | 4.1 |
| | | 20 / 65 | 2.7 | 7.5 |
| | | 20 / 85 | 2.8 | 10.7 |
| | TF-resin | 20 / 30 | 4.8 | 5.2 |
| | | 20 / 65 | 3.7 | 8.1 |
| | | 20 / 85 | 4.5 | 12.8 |

**Table 16:** Results of the Anova analysis. Grade of significance expressed as probability under two levels (0.05 % of probability as significant and 0.01 % of probability as high significance)

| | **Factors** (independent variables | | | **Interrelation between factors** (independent variables) | | |
|---|---|---|---|---|---|---|
| **Responses** (dependent variables) | Raw material | Adhesive | Climate | Raw material / Adhesive | Raw material / Climate | Adhesive / Climate |
| Average roughness ($R_a$) µm | 0.0018 | not significant | not significant | 0.0177 | not significant | not significant |
| Moisture content (%) | 0.0014 | 0.0005 | <0.0001 | not significant | not significant | 0.0246 |

The results (Table 16) also reveal, that there is no significant difference in average roughness ($R_a$) between particleboards of the same adhesive type due to change in the moisture content of the particleboards, though, higher relative humidity during storage does increase the equilibrium moisture content of the particleboards tremendously. As can be seen from Table 15, a change in relative humidity from 20ºC / 30 % relative humidity to 20ºC / 85 % relative humidity increases the moisture content of manufactured uncoated UF-bonded particleboards from fresh particles in the surface from 5.6 % to 12.3%.

Also, there is no significant difference in average roughness ($R_a$) between UF- and TF-bonded particleboards made with fresh particles. The same applies also for particleboards made with cork particles in the surface layer. However, statistical analysis showed that there is a significant difference in average roughness ($R_a$) between uncoated particleboards made from recycled particles due to changes in the adhesive (UF- or TF-resin). UF-bonded particleboards made from recycled particles in the surface layer showed higher roughness values compared to those made with a TF-resin.

The interaction between factors is explained through a Tukey´s statistical analysis. When the interaction between the adhesives (UF- and TF-resin) and the surface raw materials (fresh, recycled and cork particles) and the average roughness were statistically analysed, there were found significant differences. An example of the Tukey's statistical analysis is given below:

Tukey`s analysis of average surface roughness ($R_a$) for UF- and TF-bonded particleboards manufactured with different raw material in the surface layers (fresh particles, recycled particles and cork particles)

Tukey`s analysis for uncoated particleboards with fresh particles:

```
Tukey Group     Mean      N    adhesive

A              5.6000     3       TF-resin
A              5.1667     3       UF-resin
```

Tukey`s analysis for uncoated particleboards with recycled particles:

```
Tukey Group     Mean      N    adhesive

A              11.217     3       UF-resin
B               6.967     3       TF-resin
```

Tukey`s analysis for uncoated particleboards with cork particles:

```
Tukey Group     Mean      N    adhesive

A              4.3333     3      TF-resin
A              3.1333     3      UF-resin
```

*Means with the same letter are not significantly different.

Another Tukey's analysis was necessary to complete the explanation of the interrelation between the factors adhesives and raw materials on average surface roughness of the uncoated particleboards (see test results below). The following step was to analyse the interrelation between adhesives (UF- and TF-resin) and raw materials on the average roughness ($R_a$).

As can be seen from the results of the Tukey’s statistical test, UF-bonded particleboards made with recycled particles in the surface layer differ significantly in average roughness from those made with fresh and cork particles in the surface layer. For TF-bonded boards the statistical test shows, that they are not significantly different in their roughness in comparison with those made with fresh particles; also particleboards made with cork particles are not significantly different in their roughness in comparison to those made with fresh particles.

The results of the test reveal a high significant difference in average roughness between TF-bonded particleboards made with cork particles and recycling particles in the surface layer.

Tukey`s analysis of average surface roughness ($R_a$) for uncoated particleboards with fresh particles, recycled particles, and cork particles bonded with different adhesives (UF- and TF-resin):

Tukey`s analysis for uncoated UF-bonded particleboards:

```
Tukey Group    Mean       N    material

A            11.2167     3    recycled particles
B             5.1667     3    fresh particles
B             3.1333     3    cork particles
```

Tukey`s analysis for uncoated TF-bonded particleboards:

```
Tukey Group   Mean      N    material

A           6.9667     3    recycled particles
AB          5.6000     3    fresh particles
B           4.3333     3    cork particles
```

*Means with the same letter are not significantly different.

## Moisture content

According to the results, the climatic conditions exert a high influence on the moisture content of the particleboards as a single factor (< 0.0001). Other single factors are the raw material and the adhesive (0.0005 and 0.0014 respectively). The Anova test also showed a significant difference in the moisture contents of the boards due to climatic conditions and used adhesive.

A Tukey´s analysis compared the influence of both factors adhesives (UF- and TF-resin) and climate (20°C / 30 % r.h., 20°C / 65 % r.h., and 20°C / 85 % r.h.) on the moisture content of the particleboards. The results reveal that only at 20ºC / 85 % r.h. the use of UF- and TF-resin lead to significant differences in the moisture content of the particleboards. At lower relative humidity no significant difference in the moisture content on the boards was found. The higher moisture content of TF-bonded particleboards may be due to the presence of alkali in TF-resins.

Moreover, the uncoated UF- and TF-bonded particleboards made using cork particles in the surface layer are generally of lower moisture content than the corresponding boards made with fresh and recycled particles in the surface layer. This documents the influence of raw material on the equilibrium moisture content (E.M.C).

At last a statistical analysis was conducted about the influence of interaction between the factors adhesive and climatic conditions on the moisture content of the particleboards. The results reveal that between the used climate and the moisture content of the particleboards significant correlation exists irrespective of the type of adhesive used for making the boards.

### 5.1.2 Influence of raw material and type of adhesive on the surface roughness of uncoated particleboards as assessed by the non-contact method

An optical non-contact method (image analysis) was used to assess the roughness of the uncoated UF- and TF-bonded particleboards. Only boards stored at 20°C / 65 % relative humidity were tested. In Figure 27 different images from uncoated TF-bonded particleboards with different raw materials in the surface layers are shown. The pictures show clearly the structural differences between the particleboards made with fresh, recycled and cork particles in the surface layers.

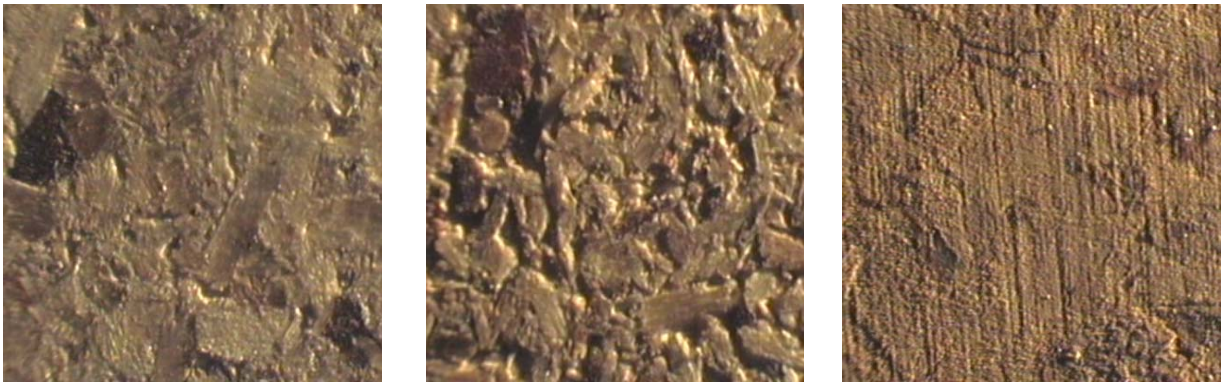


**Figure 27:** Images from uncoated TF-bonded particleboards, made using different raw materials in the surface layers (from left to right: fresh particles, recycled particles, cork particles). The boards were stored under 20°C / 65% relative humidity.

Figure 28 shows the results of calculation the standard deviation (SD) from the image analysis. Low standard deviation means a smooth surface, high standard deviation means rough surface. As can be seen from Figure 28 UF-bonded particleboards made with recycled particles showed the highest standard deviation value (SD-value) (51.8). The SD-value of UF-bonded particleboards with fresh particles was 48.5. The lowest SD-value was assessed for UF-bonded particleboards with cork particles in the surface layer (39.9).

For the tannin-formaldehyde bonded particleboards the situation was a little bit different. Here, particleboards with fresh particles show the highest SD-value (53.3) followed by the boards with recycled particles in the surface (SD = 49.9). Analogous to the UF-bonded particleboards also TF-bonded particleboards with cork particles in the surface layer showed the lowest SD-value (47.7). The reason why TF-bonded particleboards made with fresh particles showed a high roughness may be due to the fact that TF-resins contain alkali with a higher swelling power towards fresh particles compared to recycled particles.

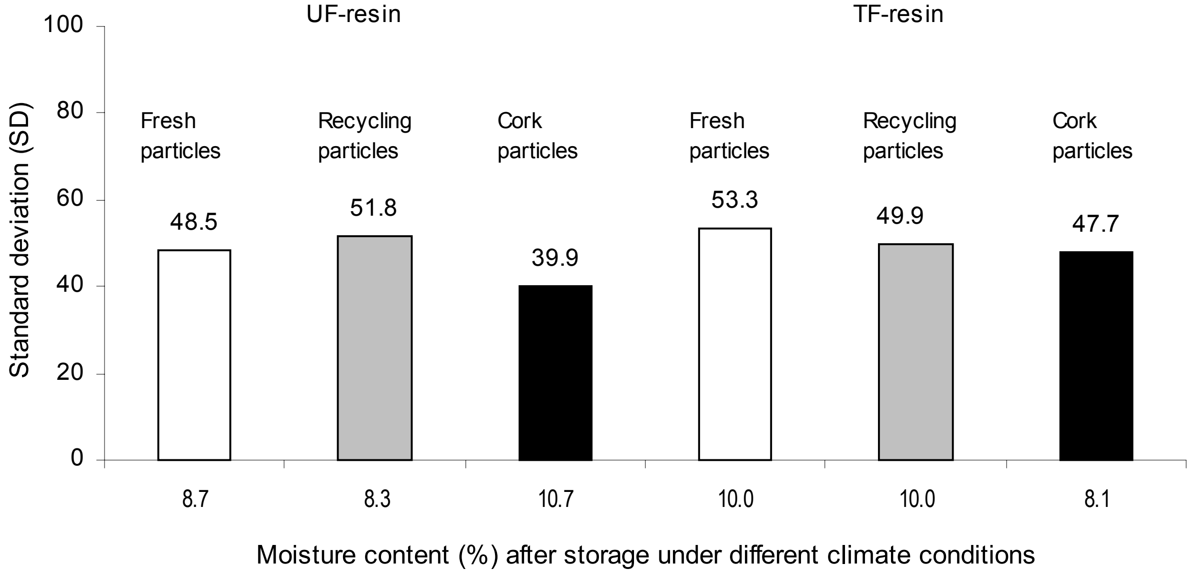
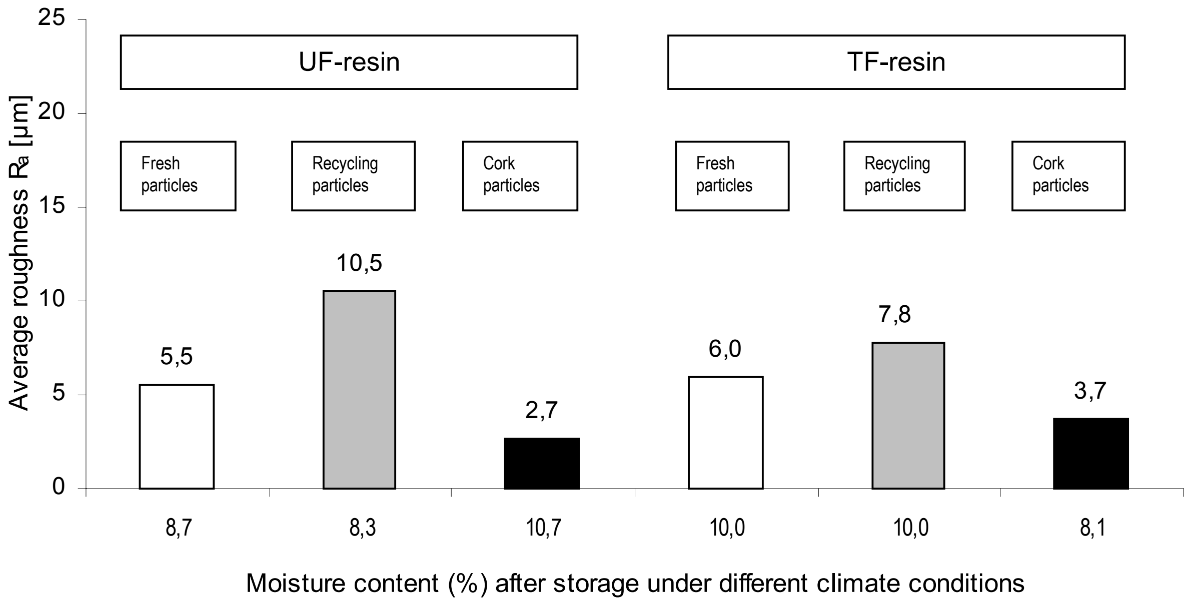


**Figure 28:** Standard deviation (SD) of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage at 20°C / 65% relative humidity. The Standard deviation (SD) was calculated from the gray level histogram of the surface image assessed by non-contact method (image analysis).

The biggest difference (about 16 %) between the SD-values of UF- and TF-bonded particleboards were found when cork particles in the surface layers were used (SD of UF-bonded PB = 39.9, SD of TF-bonded PB = 47.7).



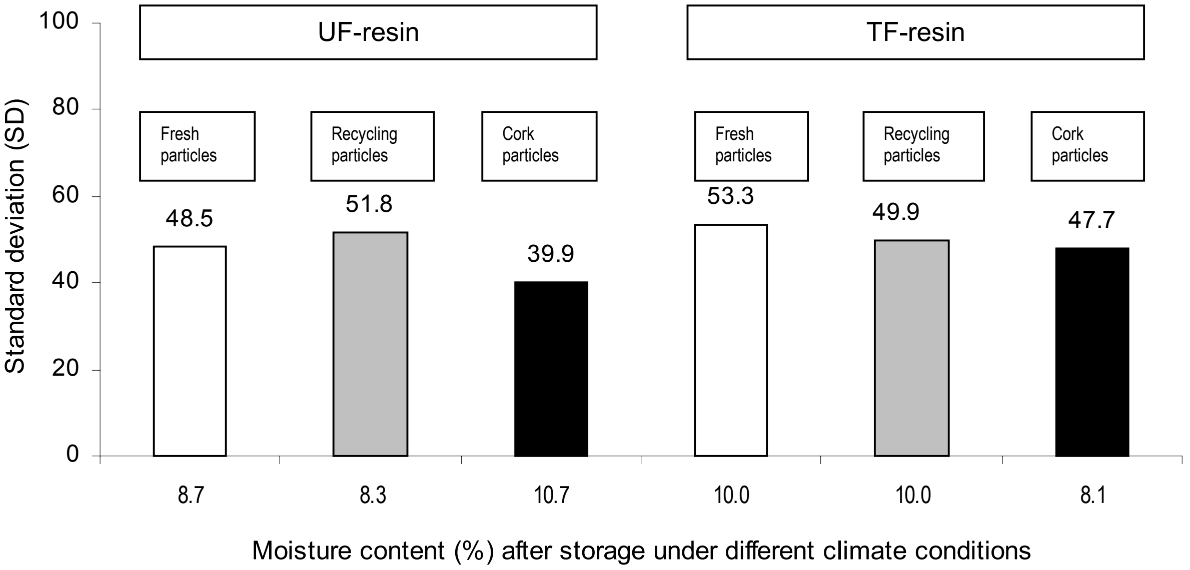


**Figure 29:** Average roughness $R_a$ (µm) (histogram above) and Standard deviation (SD) (histogram below) of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage at 20°C / 65% relative humidity. The average roughness $R_a$ was assessed by a contact method, the Standard deviation (SD) was assessed by a non-contact method (image analysis).

In the Figure 29 a general comparison between the results obtained from the contact method (perthometer method) and non-contact method (image analysis) is shown. Both methods show for UF- and TF-bonded particleboards with cork particles in the surface layer the lowest roughness values / standard deviations. For UF-bonded particleboards both methods showed the highest values for particleboards made with recycled particles in the surface layer followed by particleboards with fresh particles in the surface layer.

The correlations between both methods contact method and non-contact method were calculated for each adhesive (UF- and TF-resin). The results are given in Figure 29 below. As can be seen from Figure 29 for UF-bonded particleboards a coefficient of correlation ($r^2$) between both methods of $r^2 = 0.803$ was calculated. For TF-bonded particleboards the coefficient of correlation ($r^2$) was $r^2 = 0.395$.

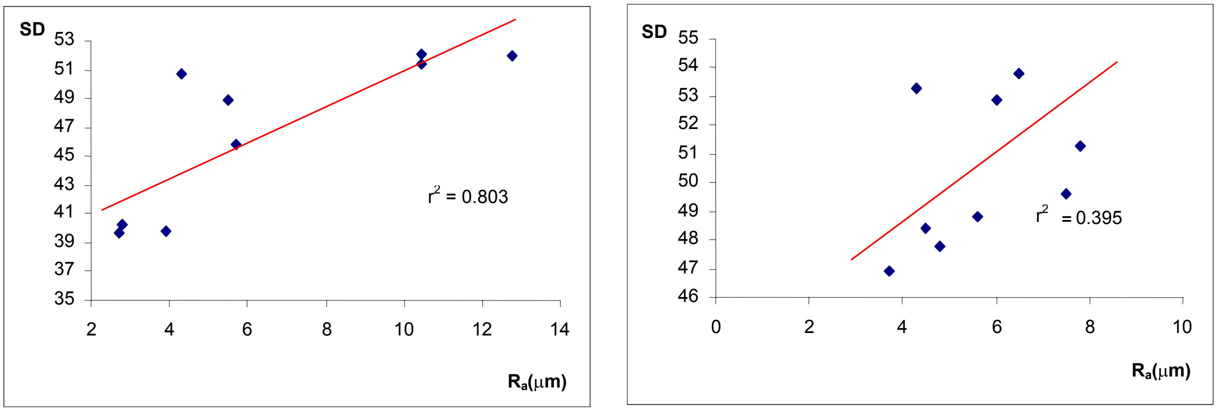


**Figure 30:** Correlation between a contact method (perthometer method) and a non-contact method (image analysis) for uncoated UF-bonded particleboards (left part of the Figure) and uncoated TF-bonded particleboards (right part of the Figure) after storage at 20°C / 65% relative humidity. The UF- and TF-bonded particleboards were made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles)

Non-contact method (Figure 29) shows for particleboards with recycled particles an intermediate surface (SD = 49.9) compared with particleboards with fresh particles (SD = 53.3) and cork particles (SD = 47.7). But this statement does not correlate high with the results of the contact method (indices of correlation $r^2 = 0.395$). A possible explanation for the low correlation of both methods when using TF-resins is the dark colour of the tannin. The darker a sample surface is, the more homogeneous appears the surface for image analysis. The principle of this optical technique considers a light source with a specific angle of inclination to assess the natural roughness of the sample in study. The standard deviation of the gray level in the digital image can be taken as an indicator of the roughness. This principle does not work well, the more dark a sample is. Therefore, it is difficult to assess the roughness of dark surfaces by using the optical image technique.

### 5.1.3 Influence of the raw material and the type of adhesive on the quality of finishing

As mentioned in chapter 4.3.1, uncoated UF- and TF-bonded particleboards made using different raw materials in the surface layers (fresh, recycled and cork particles) were transported to the Institute of Forest Technical Products at the University Austral de Chile, Valdivia, Chile. The particleboards were conditioned under 20°C and 65 % r.h. The particleboards were coated in a conditioned room (20°C / 65 % r.h.) with nitrocellulose paint by a conventional process. The amount of lacquer applied to the boards was kept constant of at 0.15 grams paint per cm² surface area. Thereafter, the coated boards were cut into samples according to the performance tests.

#### 5.1.3.1 Thickness of coating film

For each board the thickness of the coating film was measured. As can bee seen from the results in Table 17 coated UF- and TF-bonded particleboards, with fresh and cork particles in the surface layer, showed more or less the same thickness of the coating film; the values ranged from 115 µm to 130 µm. In comparison the coating film on UF- and TF-bonded particleboards with recycled particles was much thinner.

**Table 17:** Thickness of coating film (µm) of coated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measuring has been carried out under climate 20°C / 65% relative humidity

| Raw material in the surface layer | Binder | Climate °C / relative humidity % | Thickness of coating film µm |
|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 120<br>115 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 56<br>82 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 130<br>126 |

The values ranged from 56 µm (UF-bonded particleboards) to 82 µm (TF-bonded particleboards), although the amount of lacquer applied to all six particleboards was constant over the whole experiment (0.15 grams/cm²). The differences in thickness of the coating film between UF-bonded particleboards and TF-bonded particleboards may be due to a many reasons, e.g., the difference in the moisture content of the boards, hygroscopic effect of TF–resins, differences in the curing conditions and on homogenous application of the paint.

The results reveal that acid cured nitrocellulose lacquers has the same thickness on particleboard made from fresh particles and from cork. The thickness of the finishing in boards with recycled particles was much less that in the other two cases. This may be due to the high roughness of the surface of recycled boards and consequently to their higher porosity.

### 5.1.3.2 Surface roughness of uncoated and coated UF- and TF-bonded particleboards as assessed by the contact method

The average roughness $R_a$ of uncoated and coated UF- and TF-bonded particleboards was assessed by using a Mitutoyo apparatus SJ201p (contact method). The results are shown in Table 18.

**Table 18:** Average roughness $R_a$ (µm) of uncoated and coated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measuring has been carried out under climate 20°C / 65% relative humidity with a Mitutoyo apparatus SJ201p (contact method).

| Raw material in the surface layer | Binder | Climate °C / relative humidity % | Average roughness $R_a$ (uncoated) µm | Average roughness $R_a$ (coated) µm |
|---|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 5.2<br>5.6 | 2.6<br>4.1 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 11.2<br>7.0 | 5.7<br>2.5 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 3.1<br>4.3 | 1.7<br>1.6 |

As can be seen from the results in the Table 18, UF- and TF-bonded boards with recycled particles showed the highest average roughness values ($R_a$) (11.2 µm, 7.0 µm respectively). The $R_a$-values for uncoated UF- and TF-bonded particleboards with fresh particles ranged between 5.2 µm and 5.6 µm. Comparatively, low roughness values were found for uncoated particleboards with cork particles in the surface layer (3.1 µm and 4.3 µm respectively).

After lacquering the roughness of the coated surfaces of the particleboards were also assessed by contact method. As can be seen from Table 18 it seems that the roughness of the finishing (nitrocellulose paint) is significantly influenced by the surface-roughness of uncoated particleboards.

The influence of the surface roughness of uncoated particleboards on the surface roughness of the coated boards was assessed mathematically. Therefore, the correlation (coefficient of correlation ($r^2$) between the average roughness values $R_a$ of uncoated and coated particleboards was calculated. The results are shown in Figure 31. The calculated coefficient of correlation ($r^2$) was $r^2 = 0.7595$ (Figure 31). It becomes evident from the results, that the original roughness of the boards impacts the final roughness of the coated boards.

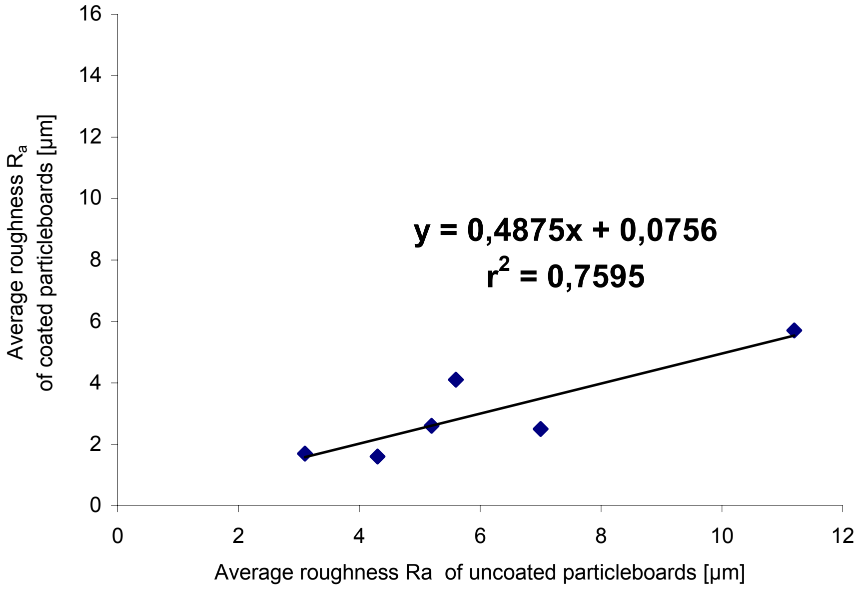


**Figure 31:** Correlation between the average roughness values ($R_a$) of uncoated and coated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measuring has been carried out at 20°C / 65% relative humidity with a Mitutoyo apparatus SJ201p (contact method).

### 5.1.3.3 Adherence strength of coated UF- and TF-bonded particleboards according to UNE-standard 48032

Adhesion plays an important role in the quality of the finishing. Coating systems need a substrate that permits primarily a mechanical link. Table 19 shows in general the influence of roughness on the adherence strength. Particleboards made with fresh and recycled particles showed higher roughness and therefore higher adherence strength compared to particleboards with cork particles, which had a relatively smooth surface.

The presence of a rough surfaces helps in the anchorage of the applied coating systems. A rough surface gives paints several possibilities to penetrate and create “fingers of resin”, insofar it helps in developing strong joins. On the other hand very high or too high roughness has negative aspects as high cost, mainly in coatings where an excessive volume of paint is necessary to give surfaces smooth appearances.

**Table 19:** Adherence strength and average roughness $R_a$ of coated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measurements have been carried out at 20°C and 65% relative humidity.

| Raw material in the surface layer | Binder | Climate<br>°C / relative humidity % | Adherence strength<br>Range of values<br>0 – 5 * | Average roughness $R_a$ (uncoated)<br>µm |
|---|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 4<br>4 | 5.2<br>5.6 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 4<br>4 | 11.2<br>7.0 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 2<br>2 | 3.1<br>4.3 |

(*The standard is an optical method. 6 grades of values are possible. The values range between 0 (which means total displace of the paint after the test) and 5 (which means no paint displacement, painted surface is unharmed).

### 5.1.3.4 Impact strength of coated UF- and TF-bonded particleboards according to UNE-standard 11019/6

Another surface property, which has been measured for the finished boards, was their impact strength. The results are compiled in Table 20. The results reveal that nitrocellulose finishing on boards made with fresh and recycled particles have a higher impact strength compared to finished boards with cork at the surface layer.

For particleboards with fresh and recycled particles the values for impact strength were more or less in the same level (4 – 5). This result is insofar interesting as coating film thickness on boards with recycled particles was about 50 % thinner compared to the coating film thickness on boards with fresh particles in their surface. This indicates that with in a certain range coating film thickness seems to have no significant influence on the impact strength of the coating system.

However, impact test caused higher damages in particleboards with a cork surfaces. The reason for this response can be explained by the significantly different elasto-mechanical properties of the cork particles compared to wood surfaces.

**Table 20:** Impact strength and thickness of coating film on UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measurements have been carried out at 20°C and 65% relative humidity.

| Raw material in the surface layer | Binder | Climate °C / relative humidity % | Impact strength Range of values 1 – 6 * | Thickness of coating film µm |
|---|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 4<br>5 | 120<br>115 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 5<br>5 | 56<br>82 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 3<br>3 | 130<br>126 |

(*The standard is an optical method. 6 grades of values are possible. The values range between 1 (which means high damage) and 6 (which means no damage, surface is unharmed).

### 5.1.3.5 Abrasion strength of coated UF- and TF-bonded particleboards according to EN-standard 438-2

The abrasion resistance of the finished surface layers of the particleboards was tested according to abrasion strength standard EN 438-2. The results are given in Table 21, also listed are the results of coating film thickness and average roughness $R_a$.

As can be seen from the Table 21 big differences were found between the particleboards types. UF- and TF-bonded particleboards made using with fresh particles in the surface layer have a much higher abrasion resistance (109 cycles and 118 cycles respectively) compared to UF- and TF-bonded particleboards with recycled particles (36 cycles and 53 respectively) and cork particles (36 cycles and 36 respectively).

**Table 21:** Abrasion resistance (cycles) and coating film thickness (µm) of coated and average roughness $R_a$ of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles. recycled particles and cork particles). The particleboards were coated with nitrocellulose paint. The measurements have been carried out at 20°C and 65% relative humidity

| Raw material in the surface layer | Binder | Climate °C / relative humidity % | Abrasion cycles | Thickness of coating film µm | Average roughness $R_a$ (uncoated) µm |
|---|---|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 109<br>118 | 120<br>115 | 5.2<br>5.6 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 36<br>53 | 56<br>82 | 11.2<br>7.0 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 35<br>36 | 130<br>126 | 3.1<br>4.3 |

From the results in Table 21 it seems that the relative thickness of the coating film on boards with fresh particles compared to boards with recycling particles are responsible for the higher abrasion resistance. Nevertheless, other different physical and chemical interactions between the different raw materials used and the nitrocellulose paint can be responsible for the difference of abrasion strength.

If UF- and TF-bonded particleboards with fresh and cork particles in the surface are compared, the results reveal, that abrasion strength of particleboards with fresh particles was about three times higher compared to boards with cork particles, though both type of boards showed more or less the same coating film thickness and also more or less similar average roughness of the uncoated surface.

This result can be ascribed to different chemical compositions of both raw materials. Cork has a relative high content of suberin, which is responsible for the general hydrophobic nature of cork. As a consequence, the adhesiveness of lacquer on cork surfaces is relatively poor and therefore the energy needed to remove the painted cork surface layer is much lower than that needed in the other cases.

It seems that not only the roughness of the surface but also the chemical interaction between the lacquer and surface is a very important factor for the adhesiveness of lacquer on the surface.

#### 5.1.3.6 Brightness test of coated UF- and TF-bonded particleboards according to EN-standard 48026

When a surface is distorted individual facets of the surface present different angles to the incident beam. The scale of texture necessary to break up specular reflection is related to the wavelength of light and to the angle of incidence. For angles up to about 45º degree, surface roughness on a scale and depth equal to the wavelength of light between 0.4 µm and 0.7 µm is enough to give at least a veiling effect on specular-reflection. (Lambourne and Strivens, 1999).

The results of measuring the brightness of the coated particleboards according to EN-standard 48026 are listed in Table 22. Also the values of average roughness $R_a$ of coated particleboards are given in the same Table. As it can be concluded from the results, finished UF- and TF-bonded particleboards with cork particles in the surface layer show a slightly higher brightness (28.1 % and 27.8 % respectively) compared to finished UF- and TF-bonded particleboards with fresh particles (27.6 % and 25.3 % respectively) and recycled particles (23.5 % and 26.9 % respectively).

**Table 22:** Brightness (%) and average roughness $R_a$ (µm) of coated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles). The particleboards were coated with nitrocellulose paint.

| Raw material in the surface layer | Binder | Climate °C / relative humidity % | Brightness % | Average roughness $R_a$ (coated) µm |
|---|---|---|---|---|
| Fresh particles | UF-resin<br>TF-resin | 20 / 65 | 27.6<br>25.3 | 2.6<br>4.1 |
| Recycled particles | UF-resin<br>TF-resin | 20 / 65 | 23.5<br>26.9 | 5.7<br>2.5 |
| Cork particles | UF-resin<br>TF-resin | 20 / 65 | 28.1<br>27.8 | 1.7<br>1.6 |

The results reveal that brightness is related directly to the average roughness of the coated surface. While the roughness of the coated surface decreases, as in the case of coated cork surfaces, the brightness increases. In case of coated particleboards with recycled particles it could be observed that brightness values were relatively low, due to the relatively higher roughness of the coated surface. However, more research work is needed to confirm the results. The brightness test showed that in general with increasing roughness the values of brightness decreases.

## 5.2 Medium density fiberboards (MDF)

### 5.2.1 Influence of raw material, type of adhesive and climatic conditions on the surface roughness of uncoated medium density fiberboards (MDF) as assessed by the contact method

#### 5.2.1.1 Influence of raw material and climatic conditions on the surface roughness of uncoated MUF-bonded medium density fiberboards (MDF) as assessed by the contact method

For uncoated MUF-bonded fiberboards the equilibrium moisture content (E.M.C.) was measured after storage under different climatic conditions (20°C / 30 % r.h., 20°C / 65 % r.h. and 20°C / 85 % r.h.). As Figure 31 shows, the moisture content of all MUF-bonded fiberboards increases with increasing relative humidity irrespective of the lignocellulosic raw material used in the manufacture of the boards. MUF-bonded fiberboards made with fresh and recycled fibers in the surface layers showed more or less the same rise in moisture content with increasing relative humidity during storage. For MUF-bonded fiberboards made with fresh and recycled fibers the equilibrium moisture content after storage at 20°C / 30 % r.h. was 3.0 % and 2.9 % respectively.

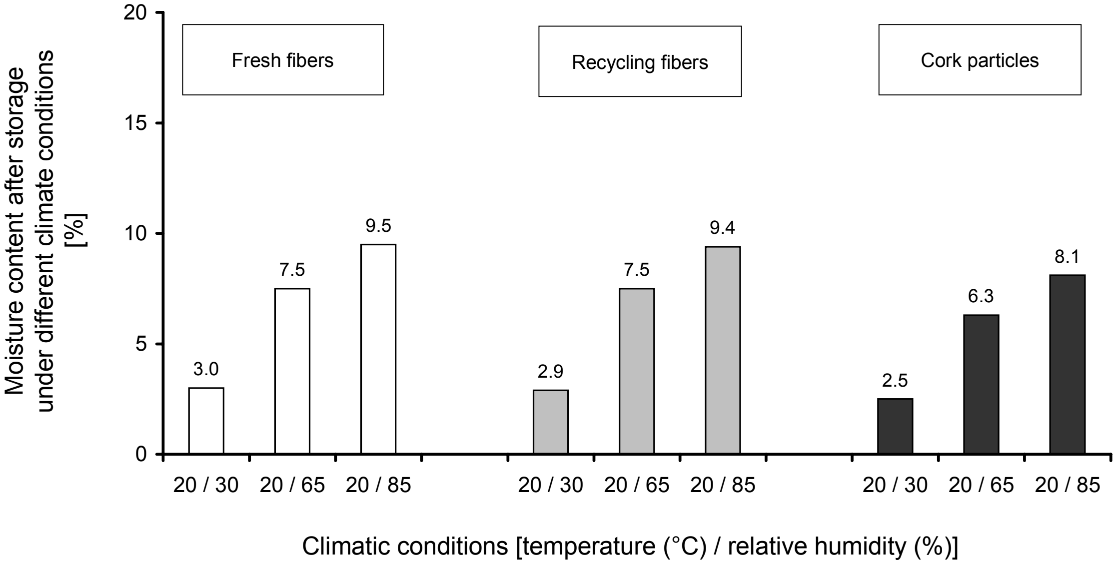


**Figure 31:** Equilibrium moisture content (E.M.C.) (%) of uncoated MUF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

After storage the boards at 20°C / 65 % r.h. the moisture content of both types of boards increased to 7.5 %. The highest moisture contents for both types of boards (9.5 % and 9.4 % respectively) were reached, when the fiberboards were stored under a climatic of 85 % relative humidity. Boards with recycled fibers in the surface showed a slightly lower equilibrium moisture content.

The equilibrium moisture content of the uncoated MUF-bonded fiberboards with cork particles in the surface layer was lower than that of MUF-bonded fiberboards made with fresh and recycled fibers. The equilibrium moisture content of uncoated MUF-bonded MDF with cork particles in the surface layer increased with increasing relative humidity from 2.5 % E.M.C. (20°C / 30 % r.h.) over 6.3 % E.M.C. (20°C / 65 % r.h.) to 8.1 % E.M.C. (20°C / 85 % r.h.).

Figure 32 shows an individual measurement of a roughness profile of a MUF-bonded uncoated MDF, manufactured with fresh fibers in the surface layer after reaching equilibrium moisture content (7.5 %) at climate 20°C / 65% relative humidity (variant 1). The profile describes the surface characteristics, e.g., average roughness ($R_a$), the mean peak-to-valley height ($R_z$), maximum-peak-to-valley height ($R_{max}$). $R_a$ was chosen in this work as the main parameter to describe the surfaces by the contact method.

MDF-Measurement-no.: B 1212

| | | |
|---|---|---|
| $R_a$ | 6.4 | µm |
| $R_z$ | 33.9 | µm |
| $R_{max}$ | 46.7 | µm |

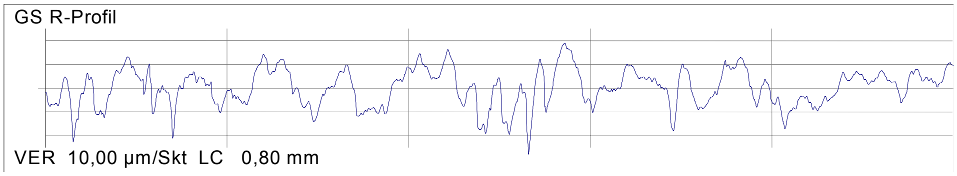


**Figure 32:** Individual measurement of a roughness profile of an uncoated MUF-bonded medium density fiberboard (MDF), made using with fresh fibers in the surface layer after reaching equilibrium moisture content (7.5%) at climate 20°C / 65% relative humidity (variant 1)

In Figure 33 the influence of the raw material and the moisture content on the roughness of MUF-bonded fiberboards are presented. As can be seen from Figure 33 MUF-bonded fiberboards with fresh fibers are of a higher roughness irrespective of the moisture content ($R_a$ = 6.5 µm at 20ºC/65% r.h.) in comparison to MDF with recycled fibers ($R_a$ = 4.4 µm at 20ºC/65% r.h.). On the other hand MUF-bonded MDF with cork particles on surface layers do have the smoothest surfaces ($R_a$ = 3.8 µm at 20ºC/65% r.h.).

Moreover, Figure 33 shows the general influence of different climatic conditions on the roughness of MUF-bonded MDF. The roughness of MUF-bonded fiberboards with fresh and recycled fibers increased with increasing moisture content.

The $R_a$-value of MUF-bonded MDF with fresh fibers increased with raising relative humidity in the region of 30% r.h. over 65% r.h. to 85% r.h. from 5.7 μm over 6.5 μm to 6.9 μm. In case of recycled fibers, $R_a$ increased from 4.2 μm to 4.8 μm.

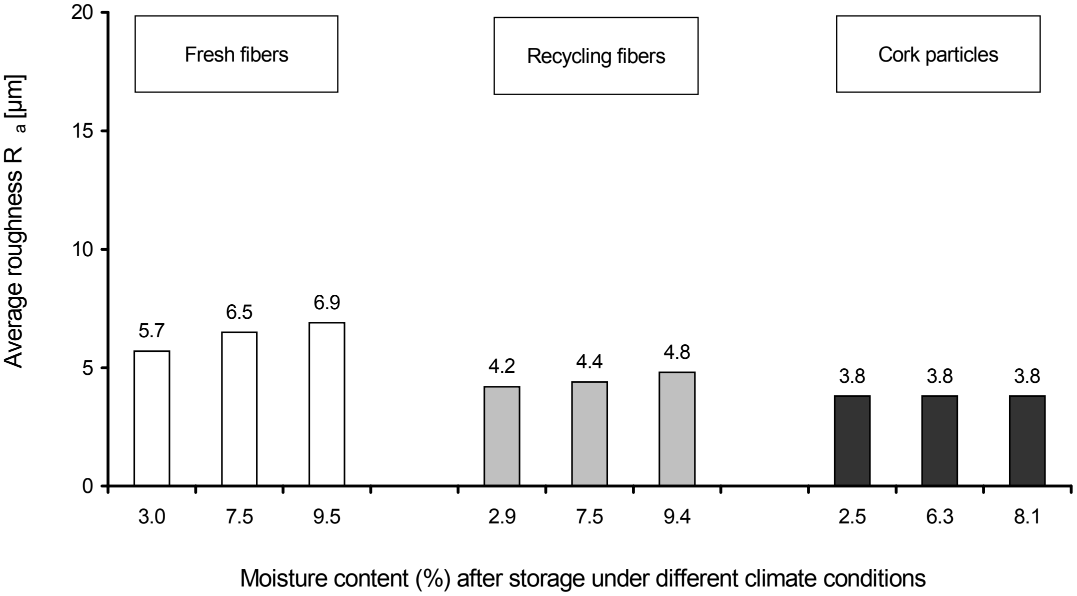


**Figure 33:** Average roughness $R_a$ (μm) of uncoated MUF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

Moreover, the results indicate: MUF-bonded MDF with cork particles in the surface layers display a quite different behaviour; there was no detectable increase in the roughness of the boards observed due to an increase in the moisture content of the boards.

#### 5.2.1.2 Influence of raw material and climatic conditions on the surface roughness of uncoated TF-bonded medium density fiberboards (MDF) as assessed by the contact method

For uncoated TF-bonded medium density fiberboards (MDF) the equilibrium moisture content was measured after storage under different climatic conditions (20°C / 30 % r.h., 20°C / 65 % r.h. and 20°C / 85 % r.h.). It can be seen from Figure 34 that the moisture content of all TF-bonded fiberboards increased with higher relative humidity irrespective of the lignocellulosic raw material used for making the boards. TF-bonded fiberboards made with fresh fibers in the surface layers showed in comparison to MDF with recycled fibers slightly higher moisture contents with increasing relative humidity during storage.

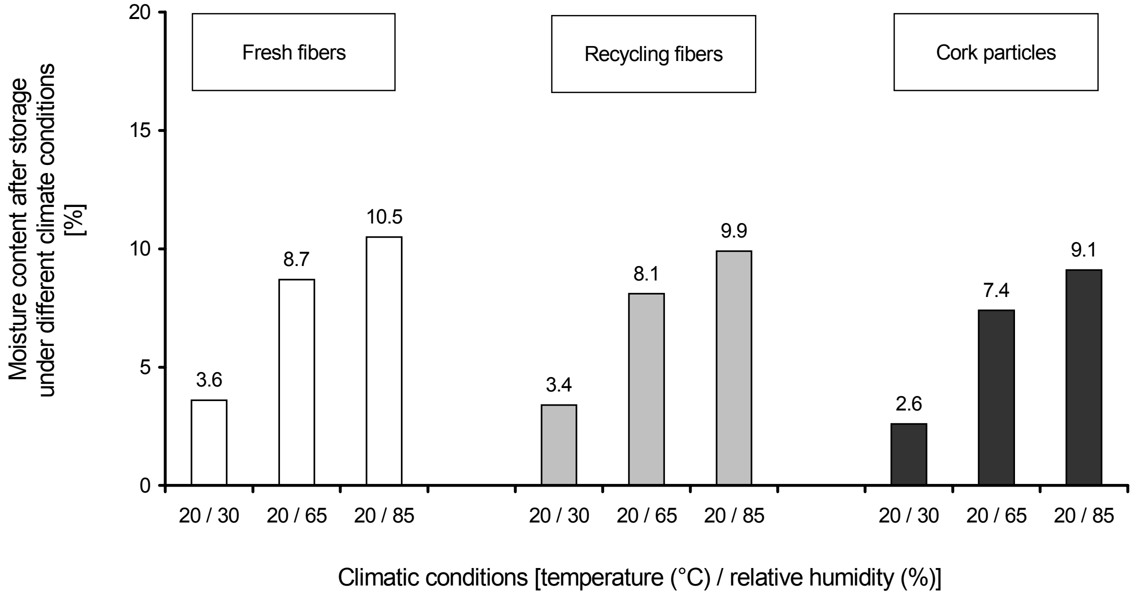


**Figure 34:** Equilibrium moisture content (E.M.C.) (%) of uncoated TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers, and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

The equilibrium moisture content of the uncoated TF-bonded fiberboards with cork particles in the surface layer are in general of lower values compared to TF-bonded MDF made with fresh and recycled fibers. The equilibrium moisture content of uncoated TF-bonded MDF with cork particles in the surface layer increased during storage of the boards under higher humidity from 2.6 % E.M.C. (20°C / 30 % r.h.) over 7.4 % E.M.C. (20°C / 65 % r.h.) to 9.1 % E.M.C. (20°C / 85 % r.h.).

Figure 35 shows an individual measurement of a roughness profile of an uncoated TF-bonded fiberboard, manufactured with fresh fibers in the surface layer after reaching equilibrium moisture content (8.7 %) at climate 20°C / 65% relative humidity (variant 2). In comparison with Figure 32 a smoother roughness profile can be seen in the picture below.

MDF-Measurement-no.: B2218

| | | |
|---|---|---|
| $R_a$ | 2.6 | µm |
| $R_z$ | 17.6 | µm |
| $R_{max}$ | 27.1 | µm |

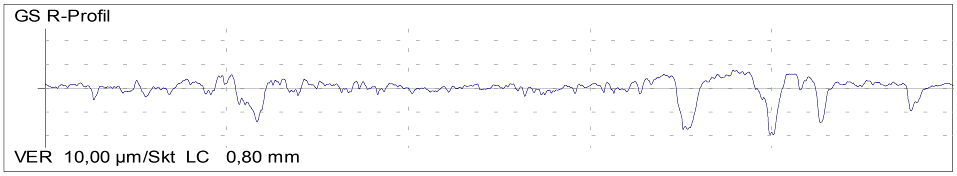


**Figure 35:** Individual measurement of a roughness profile of an uncoated TF-bonded medium density fiberboard (MDF), made using fresh fibers in the surface layer after reaching equilibrium moisture content (8.7 %) at climate 20°C / 65% relative humidity (variant 2)

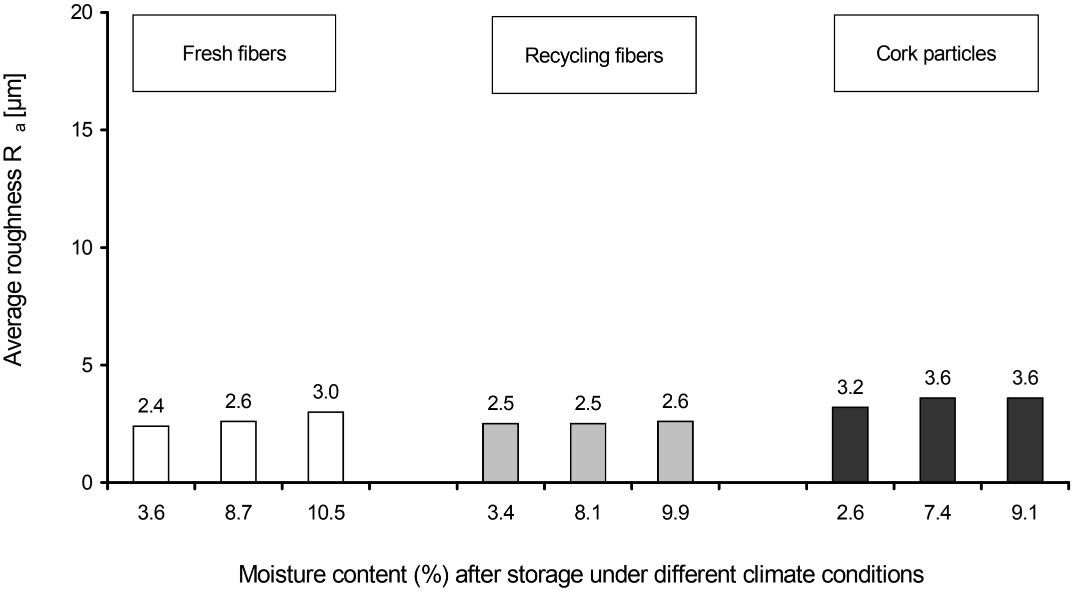


**Figure 36:** Average roughness $R_a$ (µm) of uncoated TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

Figure 36 shows the influence of the raw material on the roughness of TF-bonded MDF. TF-bonded MDF with fresh and recycled fibers presented a homogenous level of roughness on their surfaces. On the other hand TF-bonded MDF with cork on the surface layers presented a higher but also homogenous level of roughness. Figure 36 also shows that changes in the climatic conditions slightly influence the roughness of the TF-bonded MDF. Only for TF-bonded MDF with fresh fibers show a slight increase in roughness due to an increase in moisture content of the boards.

#### 5.2.1.3 Influence of raw material and climatic conditions on the surface roughness of uncoated MUF- and TF-bonded medium density fiberboards (MDF) as assessed by the contact method

In Figures 37 the results are summarized. In general, irrespective of the raw material used for making the fiberboards, an increase in the equilibrium moisture content of the boards was measured, as the humidity changed from 30% r.h. over 65% r.h. to 85% r.h. Moreover, the influence of the adhesive used on the moisture content of the manufactured fiberboards is also obvious. TF-bonded MDF are in general of higher equilibrium moisture content (E.M.C.) in comparison to MUF-bonded MDF.

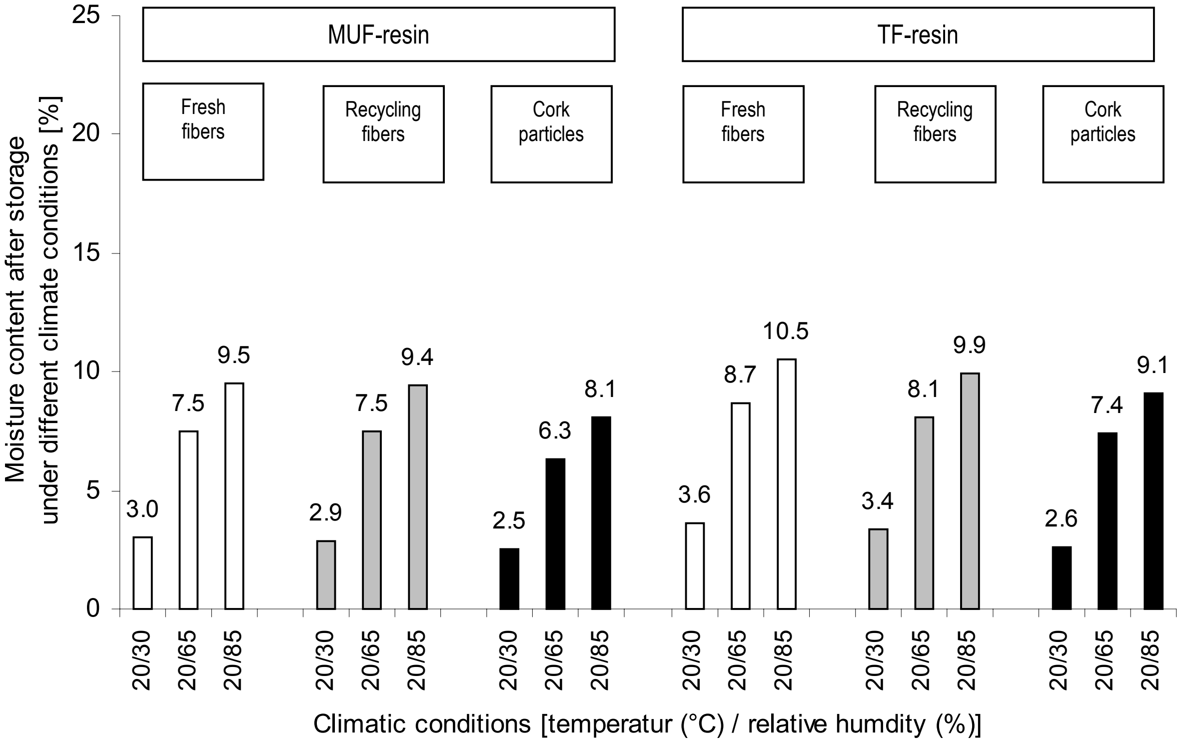


**Figure 37:** Equilibrium moisture content (E.M.C.) (%) of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

Figure 38 shows the roughness values $R_a$ for all fiberboards series. In general, TF-bonded boards have smoother surfaces compared to MUF-boards irrespective of the raw material used. MUF-bonded fiberboards increased their roughness with higher moisture content in the boards, however in case of TF-bonded MDF only a slight increase in the roughness was observed due to increase in the moisture content. A comparison between raw materials indicates that fresh fibers produce rougher surfaces than recycled fibers. On the other hand MUF- and TF-bonded MDF with cork in the surfaces showed no big changes in the roughness when the moisture content of the boards increased.

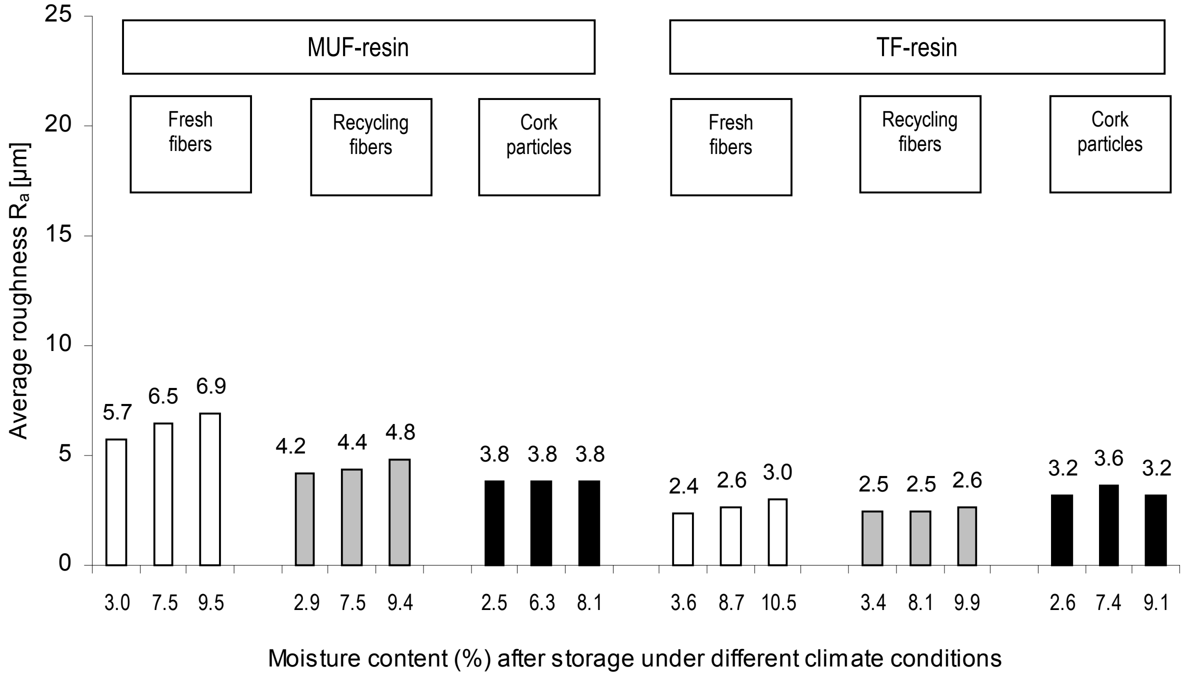


**Figure 38:** Average roughness $R_a$ (µm) of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

### 5.2.1.4 Statistical analysis of the results

Within the frame work of this study the grade of interaction between factors (independent variables) as the type of raw material, type of adhesive, climatic conditions and responses (dependent variables) of the uncoated fiberboards as average roughness and moisture content of uncoated fiberboards was determined. The collected data of chapter 5.2.1 were statistically analysed with two statistical tests (Anova analysis and Tukey's analysis). Table 23 helps to understand how the data of the Anova analysis were prepared. The factors (independent variables) and response (dependent variables) were:

Independent variables:

- Raw materials (fresh fibers, recycled fibers, cork particles)
- Adhesives (melamine-urea-formaldehyde-resin (MUF-resin), tannin-formaldehyde resin (TF-resin)
- Climatic conditions (20°C/30% r.h., 20°C/65% r.h., 20°C/85% r.h.)

Dependent variables:

- Average roughness $R_a$ (µm)
- Moisture content (%)

**Table 23:** Design of the Anova analysis, factors (independent variables) and responses (dependent variables) of the experiment

| Factors (independent variables) | | | Responses (dependent variables) | |
|---|---|---|---|---|
| Raw material | Type of adhesive | Climatic Conditions °C / rel. humidity % | Average roughness ($R_a$) µm | Moisture content % |
| Fresh fibers | MUF-resin | 20 / 30 | **5.7** | **3.0** |
| | | 20 / 65 | **6.5** | **7.5** |
| | | 20 / 85 | **6.9** | **9.5** |
| | TF-resin | 20 / 30 | 2.4 | 3.6 |
| | | 20 / 65 | 2.6 | 8.7 |
| | | 20 / 85 | 3.0 | 10.5 |
| Recycled fibers | MUF-resin | 20 / 30 | **4.2** | **2.9** |
| | | 20 / 65 | **4.4** | **7.5** |
| | | 20 / 85 | **4.8** | **9.4** |
| | TF-resin | 20 / 30 | 2.5 | 3.4 |
| | | 20 / 65 | 2.5 | 8.1 |
| | | 20 / 85 | 2.6 | 9.9 |
| Cork particles | MUF-resin | 20 / 30 | **3.8** | **2.5** |
| | | 20 / 65 | **3.8** | **6.3** |
| | | 20 / 85 | **3.8** | **8.1** |
| | TF-resin | 20 / 30 | 3.2 | 2.6 |
| | | 20 / 65 | 3.6 | 7.4 |
| | | 20 / 85 | 3.2 | 9.1 |

Table 24 shows the results of the Anova analysis. The Anova analysis evaluates the effects of factors on the responses at two levels of significance, 0.05 % of statistical probability as significant and 0.01 % of statistical probability as highly significant. It can be seen from the table which factor by itself or in interaction with other factors leads to significant differences in the values of the responses (properties of the uncoated fiberboards). For a complete review of the statistical analysis done during the research work, see the appendix of this thesis.

**Table 24:** Results of the Anova analysis. Grade of significance expressed as probability under two levels (0.05 % of probability as significant and 0.01 % of probability as highly significant).

| | **Factors** (independent variables | | | **Interrelation between factors** (independent variables) | | |
|---|---|---|---|---|---|---|
| **Responses** (dependent variables) | Raw material | Adhesive | Climate | Raw material / Adhesive | Raw material / Climate | Adhesive / Climate |
| Average roughness ($R_a$) µm | <0.0001 | 0.0008 | 0.0257 | 0.0002 | not significant | not significant |
| Moisture content (%) | 0.0011 | 0.0010 | <0.0001 | not significant | not significant | not significant |

## Average roughness ($R_a$)

According to Table 24 lignocellulosic raw material (<0.0001) is the most important factor which affects the roughness of MUF- and TF-bonded fiberboards. The test also indicated a significant interaction between raw material/adhesives. This interaction was analysed by Tukey`s analysis. A comparison between raw materials for each adhesive was done.

The results below show that roughness of MUF-bonded fiberboards made with fresh fibers is significantly different in comparison with MUF-bonded fiberboards made with recycled fibers and cork particles.

```
Tukey Group Mean       N    material

A           6.3533     3     Fresh
B           4.4500     3     Recycling
B           3.7967     3     Cork
```

*Means with the same letter are not significantly different.

Roughness of TF-bonded fiberboards made with cork particles is significantly different in comparison with TF-bonded fiberboards made with fresh and recycling fibers (see results below).

```
Tukey Group   Mean      N    material

A           3.3200     3     Cork
B           2.6900     3     Fresh
B           2.5367     3     Recycling
```

### Moisture content (%)

As far as the moisture content of the boards is concerned, the climatic conditions are dominating factors:

```
Tukey Group Mean       N    climate
A           9.4167     6      3
B           7.5833     6      2
C           3.0000     6      1
```

*Means with the same letter are not significantly different.

However, the adhesive and the raw material may also influence the moisture content significantly. Two more examples of Tukey`s analysis about the influence of the adhesives and raw materials on the moisture content of fiberboards are given below. It can be seen that the adhesive influences the moisture content of the boards. it can also be seen that the raw material influences the moisture content of fiberboards.

```
Tukey Group   Mean      N    adhesive

A           7.03333     9      TF
B           6.30000     9      MUF
```

*Means with the same letter are not significantly different.

```
Tukey Group   Mean      N    material

A           7.1333      6    Fresh
A           6.8667      6    Recycling
B           6.0000      6    Cork
```

*Means with the same letter are not significantly different.

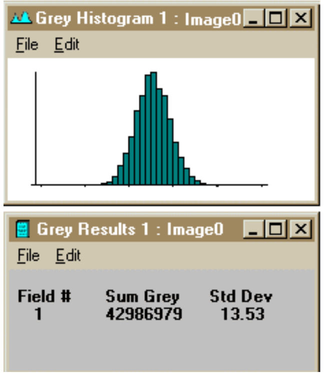
## 5.2.2 Influence of raw material, type of adhesive and climatic conditions on the surface roughness of uncoated medium density fiberboards (MDF) as assessed by the non-contact method

### 5.2.2.1 Influence of raw material and climatic conditions on the surface roughness of uncoated MUF-bonded medium density fiberboards (MDF) as assessed by the non-contact method

The surface roughness of the uncoated medium density fiberboards (MDF) was evaluated by the image analysis. The image analysis has the advantage that it is faster than the perthometer-method. One of the objectives of this thesis was to determine the correlation between both, contact and non-contact methods. In Figure 39 pictures from surfaces of uncoated MUF-bonded medium density fiberboards (MDF) taken by Leica Q500MC software are shown. The pictures were statistically analyzed and the standard deviation (SD) of the gray level histogram was determined.

**Figure 39:** Images from uncoated MUF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers (left), recycled fibers (middle) and cork particles (right)). The MDF were stored under 20°C / 65% relative humidity.

Figure 40 shows an example of a printout of a single measurement of surface roughness (SD-value) of an uncoated MUF-bonded MDF manufactured with recycled fibers assessed by image analysis. The gray level histogram is in the Figure as well as the calculated standard deviation (Std Dev 13.53) for the surface of the MDF.



```
Field #    Sum Grey     Std Dev
   1       42986979      13.53
```

**Figure 40:** Printout of a single measurement (SD-value) of an uncoated MUF-bonded MDF made using recycled fibers. Report of optical roughness: gray level histogram and value of standard deviation (Std Dev (SD)).

Figure 41 shows the effect of lignocellulosic raw material and the moisture content on the surface roughness (SD-values) of uncoated MUF-bonded medium density fiberboards (MDF). The results reveal that for uncoated MUF-bonded MDF image analysis can detect the effect of the moisture content on the surface roughness of the boards. Irrespective of the raw materials used the standard deviation (SD) increased when the moisture content of the boards becomes higher. In general, uncoated MUF-bonded MDF made with fresh fibers showed the highest SD-values.

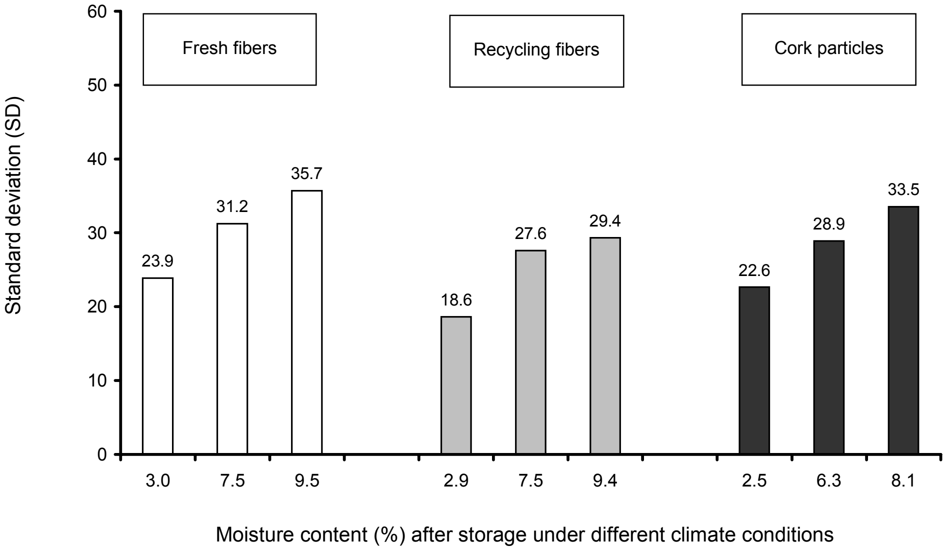


**Figure 41:** Standard deviation (SD) of uncoated MUF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

Moreover, the results indicate that the lowest SD-values were found in case of MUF-bonded MDF made with recycled fibers. The SD-values of MUF-bonded MDF with cork particles took an intermediate position.

#### 5.2.2.2 Influence of raw material and climatic conditions on the surface roughness of uncoated TF-bonded medium density fiberboards (MDF) as assessed by the non-contact method

Also surfaces of uncoated TF-bonded MDF were evaluated by the image analysis. In Figure 42 pictures of surfaces of TF-bonded fiberboards taken by Leica Q500MC software are shown. The pictures were analyzed and the standard deviation of the gray level histogram was determined. Image processing was used to determine roughness (SD-values) of the samples.

**Figure 42:** Images from uncoated TF-bonded medium density fiberboards (MDF), made using raw materials in the surface layers (fresh fibers (left), recycled fibers (middle) and cork particles (right)). The boards were stored under 20°C / 65% relative humidity.

Figure 43 shows the effect of lignocellulosic raw material and moisture content on the surface roughness (SD-values) of uncoated TF-bonded medium density fiberboards (MDF). The results are similar to those for uncoated MUF-bonded MDF. Also here image analysis can detect the effect of moisture content on the surface roughness of TF-bonded boards. TF-bonded MDF with fresh fibers showed in general the highest SD-values followed by TF-bonded MDF made with cork particles. The lowest SD-values were found for TF-bonded MDF with recycled fibers.

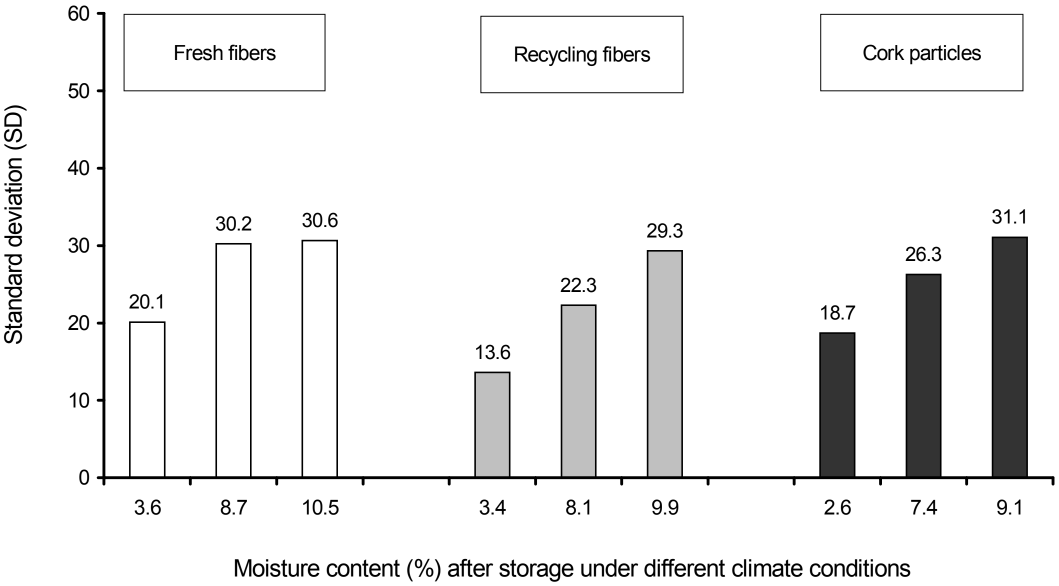


**Figure 43:** Standard deviation (SD) of uncoated TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

#### 5.2.2.3 Influence of raw material and climatic conditions on the surface roughness of uncoated MUF- and TF-bonded medium density fiberboards (MDF) as assessed by the non-contact method

In the Figure 44 the results are summarized. In general, irrespective of the raw material and adhesive used to make the boards, an increase in optical roughness (SD) of the boards could be seen, due to humidity increase from 30% r.h. over 65% r.h. to 85% r.h.

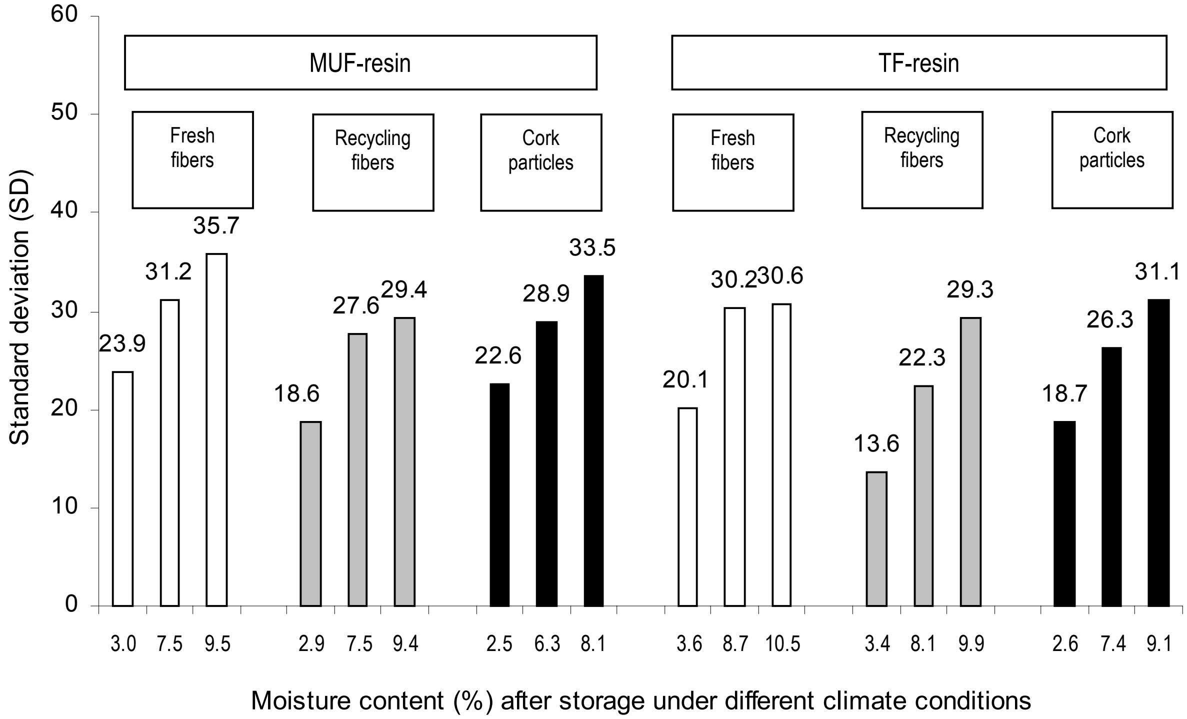


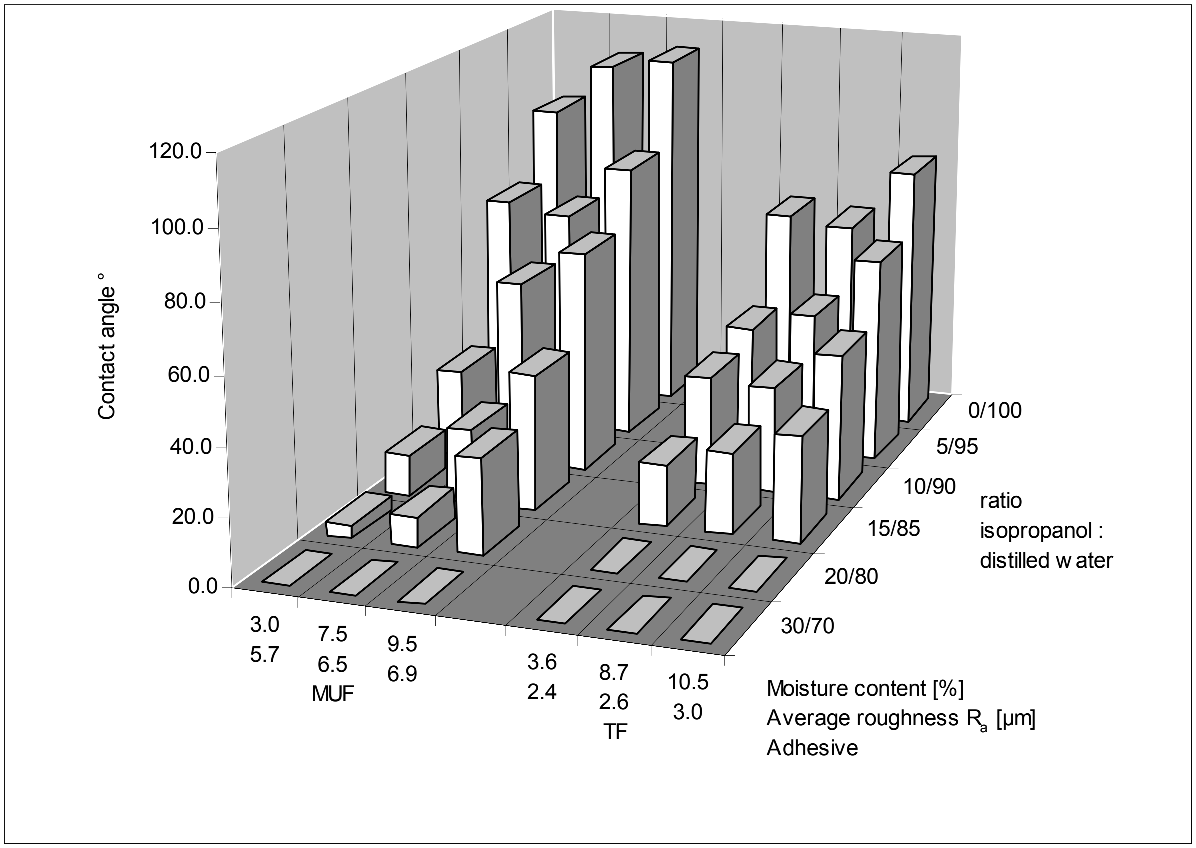
**Figure 44:** Standard deviation (SD) of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

### 5.2.3 Influence of raw material, climatic conditions, type of adhesive and surface roughness on the wettability of the medium density fibreboards (MDF)

This part of the thesis deals with the influence of raw material, climatic conditions, type of adhesive, surface roughness and isopropanol proportion on the wettability of uncoated MUF- and TF-bonded medium density fiberboards (MDF). The effect of different factors on wettability of MUF- and TF-bonded MDF, made using fresh fibers is shown at Figure 45. It shows that a high proportion of isopropanol in the isopropanol-water-solution increases the spreading of the test solution. This is due to the fact that isopropanol reduces surface tension of the liquid. Independent of the adhesive used an increase of the average roughness leads to higher contact angles or less wettability. The results show that roughness is the most important factor to determine the wettability of MDF, irrespective of the moisture content of the boards.

To Akbulut (2000) surface absorption characteristics decreased when the roughness of the wood-based panel samples increased (Shupe et al., 2001). Surface roughness is a result of raw material properties and manufacturing variables. Species, particle size, and geometry can be given as examples of some of the most important raw material characteristics; moisture content, amount of resin, press cycle, and sanding are the major manufacturing parameters that substantially affect the roughness characteristics of the boards (Hiziroglu and Graham, 1998; Westkämpfer, 1992).

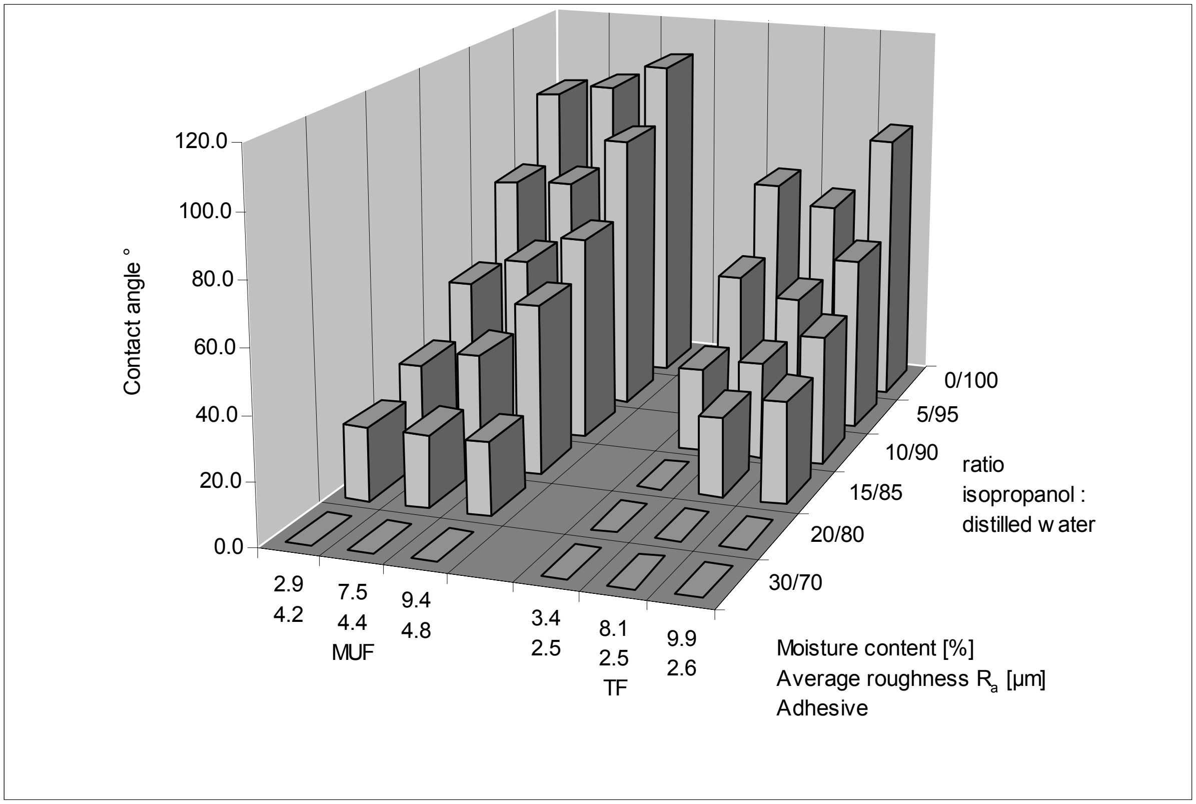
In general, TF-bonded MDF made using fresh fibers are of better wettability than MUF-bonded MDF.



| Raw material | Adhesive | $R_a$ [µm] | E.M.C. % | Contact angle ° at ratio isopropanol : distilled water | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 30 / 70 | 20 / 80 | 15 / 85 | 10 / 90 | 5 / 95 | 0 / 100 |
| fresh | MUF | 5.7 | 3.0 | 0.0 | 4.1 | 12.3 | 26.8 | 71.2 | 92.1 |
| fresh | MUF | 6.5 | 7.5 | 0.0 | 8.7 | 22.4 | 56.1 | 68.0 | 108.2 |
| fresh | MUF | 6.9 | 9.5 | 0.0 | 28.5 | 40.9 | 67.0 | 84.3 | 111.3 |
| fresh | TF | 2.4 | 3.6 | 0.0 | 0.0 | 18.5 | 32.8 | 37.3 | 63.9 |
| fresh | TF | 2.6 | 8.7 | 0.0 | 0.0 | 24.1 | 32.1 | 43.2 | 62.1 |
| fresh | TF | 3.0 | 10.5 | 0.0 | 0.0 | 31.4 | 43.6 | 62.3 | 80.7 |

**Figure 45:** Effect of average roughness ($R_a$), moisture content (%) and ratio of isopropanol on the wettability on MUF- and TF-bonded MDF, made using fresh fibers. For more detail see values in the table below the figure.

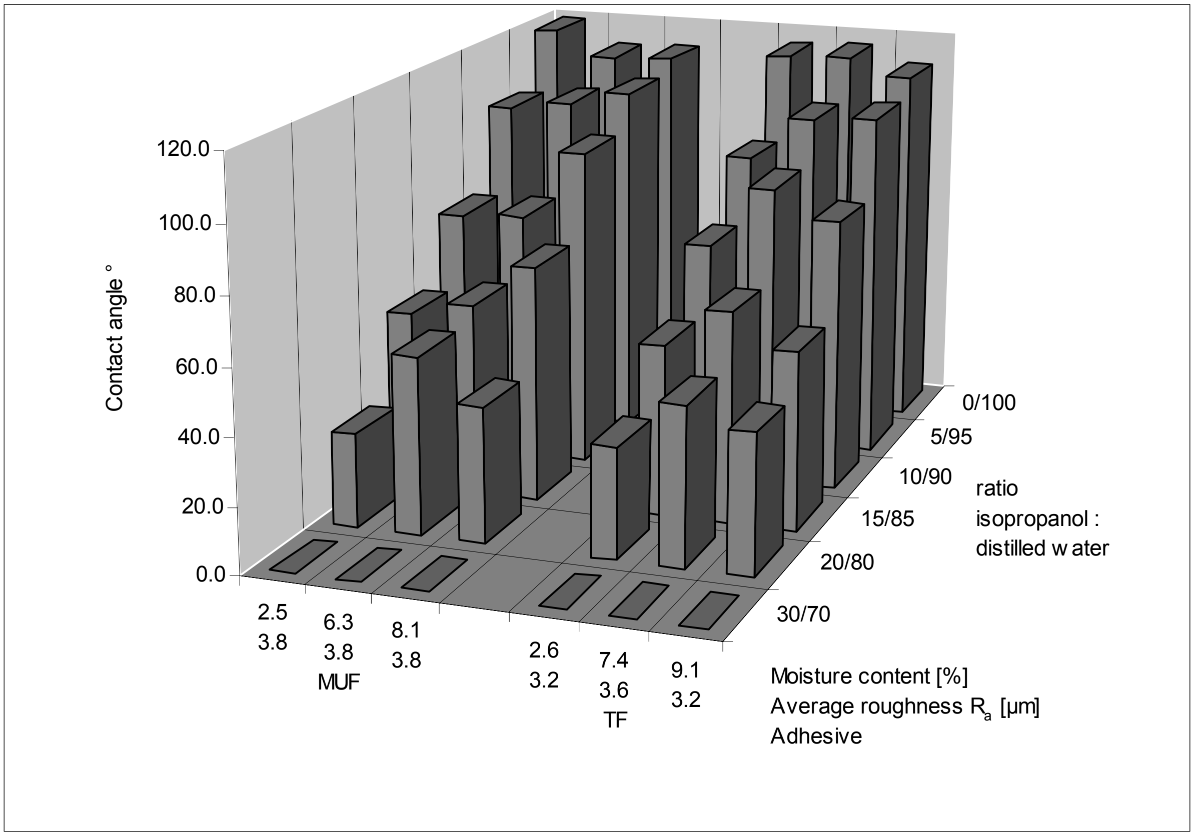
For MUF- and TF-bonded MDF, made using recycled fibers the results are shown in Figure 46. It was a better wettability for TF-bonded MDF than for MUF-bonded MDF when the ratio of isopropanol/destilled water increases. The wettability of TF-bonded MDF was higher than for MUF-bonded because the roughness in TF-bonded MDF was lower than for MUF-bonded MDF. This result is insofar interesting as before the experiment it was expected that higher moisture contents tends to reduce the wettability of the MDF.



| Raw material | Adhesive | $R_a$ [µm] | E.M.C. % | Contact angle ° at ratio isopropanol : distilled water | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 30 / 70 | 20 / 80 | 15 / 85 | 10 / 90 | 5 / 95 | 0 / 100 |
| recycling | MUF | 4.2 | 2.9 | 0.0 | 23.6 | 31.5 | 47.6 | 72.8 | 95.5 |
| recycling | MUF | 4.4 | 7.5 | 0.0 | 23.3 | 36.7 | 56.9 | 74.0 | 99.1 |
| recycling | MUF | 4.8 | 9.4 | 0.0 | 23.4 | 54.9 | 65.9 | 89.7 | 107.6 |
| recycling | TF | 2.5 | 3.4 | 0.0 | 0.0 | 0.0 | 26.8 | 46.9 | 69.2 |
| recycling | TF | 2.5 | 8.1 | 0.0 | 0.0 | 25.4 | 30.9 | 41.4 | 63.5 |
| recycling | TF | 2.6 | 9.9 | 0.0 | 0.0 | 32.7 | 41.4 | 56.4 | 88.0 |

**Figure 46:** Effect of average roughness ($R_a$), moisture content (%) and ratio of isopropanol on the wettability on MUF- and TF-bonded MDF, made using recycled fibers. For more detail see values in the table below the figure.

Finally, Figure 47 shows the wettability of MUF- and TF-bonded MDF with cork particles in the surface layer. In this case no clear tendency was found between both types of boards. The wettability was more or less on a same level.



| Raw material | Adhesive | $R_a$ [µm] | E.M.C. % | Contact angle ° at ratio isopropanol : distilled water | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 30 / 70 | 20 / 80 | 15 / 85 | 10 / 90 | 5 / 95 | 0 / 100 |
| cork | MUF | 3.8 | 2.5 | 0.0 | 28.2 | 53.3 | 74.3 | 100.3 | 118.5 |
| cork | MUF | 3.8 | 6.3 | 0.0 | 53.2 | 57.9 | 75.5 | 103.0 | 110.9 |
| cork | MUF | 3.8 | 8.1 | 0.0 | 40.6 | 71.3 | 96.8 | 107.5 | 111.7 |
| cork | TF | 3.2 | 2.6 | 0.0 | 33.3 | 51.5 | 71.7 | 90.0 | 115.0 |
| cork | TF | 3.6 | 7.4 | 0.0 | 47.6 | 63.4 | 90.5 | 103.5 | 116.1 |
| cork | TF | 3.2 | 9.1 | 0.0 | 42.0 | 53.7 | 82.1 | 105.2 | 110.7 |

**Figure 47:** Effect of average roughness ($R_a$), moisture content (%) and ratio of isopropanol on the wettability on MUF- and TF-bonded MDF, made using cork particles. For more detail see values in the table below the figure.

From Table 25 average roughness-values ($R_a$) and contact angles are compiled for all tested MUF- and TF-bonded MDF, made using different raw materials. As can be seen from the results, TF-bonded MDF, made using fresh and recycled fibers showed a better wettability than the corresponding MUF-bonded MDF. In case of MUF- and TF-bonded MDF with cork particles in the surface layers there were found no significant differences in the roughness nor the wettability. The better wettability of TF-bonded MDF observed in case of using fresh and recycled fibers doesn't seem to apply also for MDF with cork particles in the surface layers. This may be due to the extremly hydrophobic nature of cork, which over-compensates the influence of the TF-resin used. It must also be taken in consideration, that TF-resins increase the moisture of the board at high relative humidity levels.

**Table 25:** Design of the Anova analysis, factors (independent variables) and responses (dependent variables) of the experiment

| Factors (independent variables) | | | Responses (dependent variables) | |
|---|---|---|---|---|
| Raw material | Type of adhesive | Climatic conditions °C / rel. humidity % | Average roughness ($R_a$) µm | Contact angle (100% distilled water) % |
| Fresh fibers | UF-resin | 20 / 30 | 5.7 | 92.1 |
| | | 20 / 65 | 6.5 | 108.2 |
| | | 20 / 85 | 6.9 | 111.3 |
| | TF-resin | 20 / 30 | 2.4 | 63.9 |
| | | 20 / 65 | 2.6 | 62.1 |
| | | 20 / 85 | 3.0 | 80.7 |
| Recycled fibers | UF-resin | 20 / 30 | 4.2 | 95.5 |
| | | 20 / 65 | 4.4 | 99.1 |
| | | 20 / 85 | 4.8 | 107.6 |
| | TF-resin | 20 / 30 | 2.5 | 69.2 |
| | | 20 / 65 | 2.5 | 63.5 |
| | | 20 / 85 | 2.6 | 88.0 |
| Cork particles | UF-resin | 20 / 30 | 3.8 | 118.5 |
| | | 20 / 65 | 3.8 | 110.9 |
| | | 20 / 85 | 3.8 | 111.7 |
| | TF-resin | 20 / 30 | 3.2 | 115.0 |
| | | 20 / 65 | 3.6 | 116.1 |
| | | 20 / 85 | 3.2 | 110.7 |

## 5.3 Comparison between contact method and non-contact method

From the results shown in histogram Figure 48 it is possible to state, that in general, contact method as well as non-contact method show that uncoated TF-bonded MDF have a smoother surface than uncoated MUF-bonded MDF. Both methods detected, moreover, that uncoated MUF-bonded MDF with fresh fibers have the roughest surfaces. In general, the non-contact method seems more sensitive to change in the moisture content than the contact method.

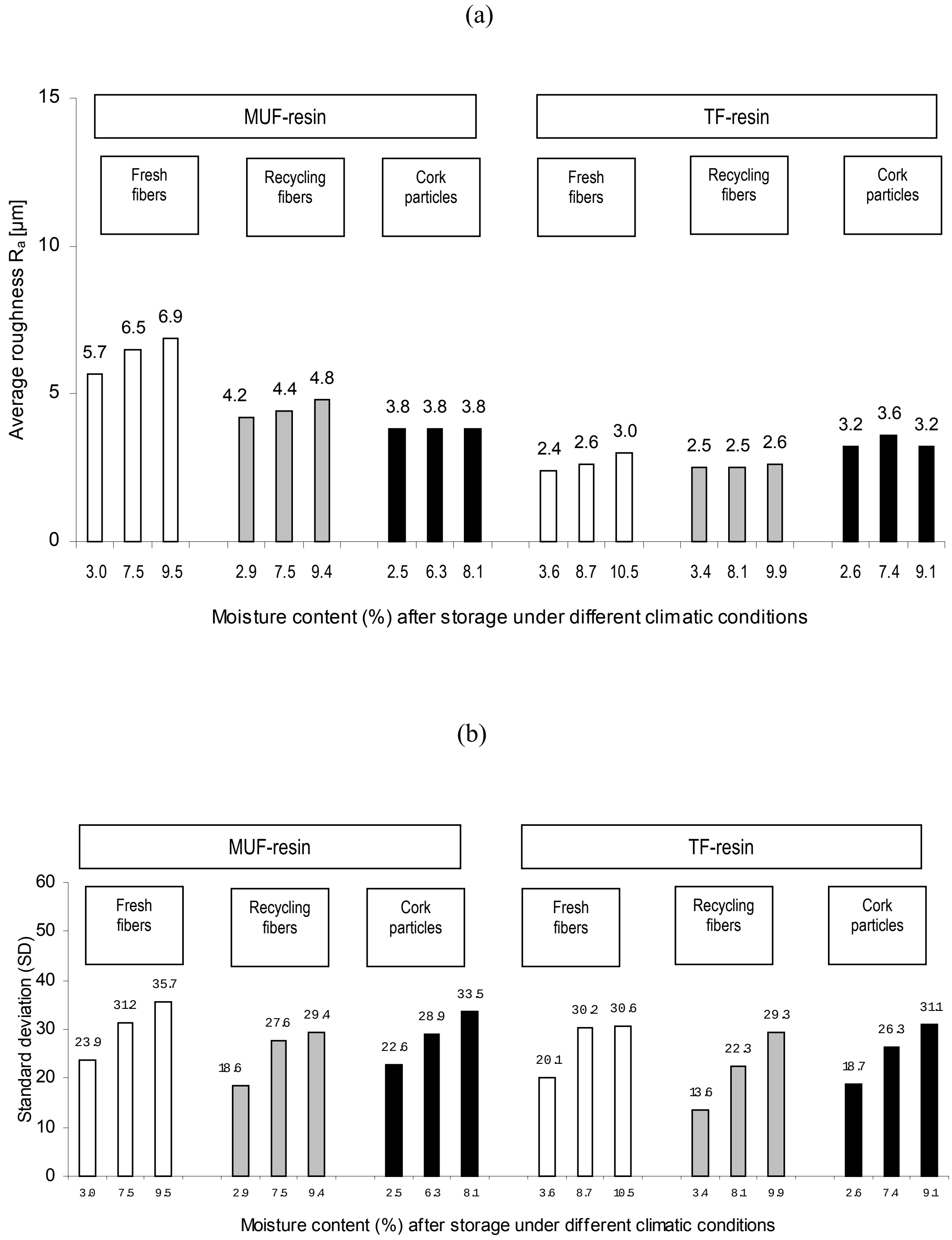


**Figure 48:** Average roughness $R_a$ (µm) (histogram above) and Standard deviation (SD) (histogram below) of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers. recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity). The average roughness $R_a$ was assessed by a contact method (48a), the Standard deviation (SD) was assessed by a non-contact method (48b) (image analysis).

With the data in Figure 48 for both methods (contact and non-contact method) a linear regression analysis was made. The results of the statistical analysis can be seen from Figure 49 (a) and (b). As can be seen from Figure 49 (a) for MUF-bonded MDF high correlation coefficients ($r^2$) between both methods could be found for all raw materials. The highest correlation coefficient ($r^2$) for both methods was found for MDF with fresh fibers ($r^2$= 0.9890) followed by MDF with cork particles ($r^2$= 0.8198) and MDF with recycled fibers ($r^2$= 0.7856) respectively.

In Figure 49 (b) the results for tannin-formaldehyde (TF-) bonded MDF are shown. It can be seen, that there was a low correlation coefficient ($r^2$) between $R_a$ and SD for uncoated TF-bonded MDF made with cork particles in the surface ($r^2$ = 0.0064). However, TF-bonded MDF with recycled fibers showed higher $r^2$ values ($r^2$ = 0.9489) compared to TF-bonded MDF made with fresh fibers ($r^2$ = 0.5993).

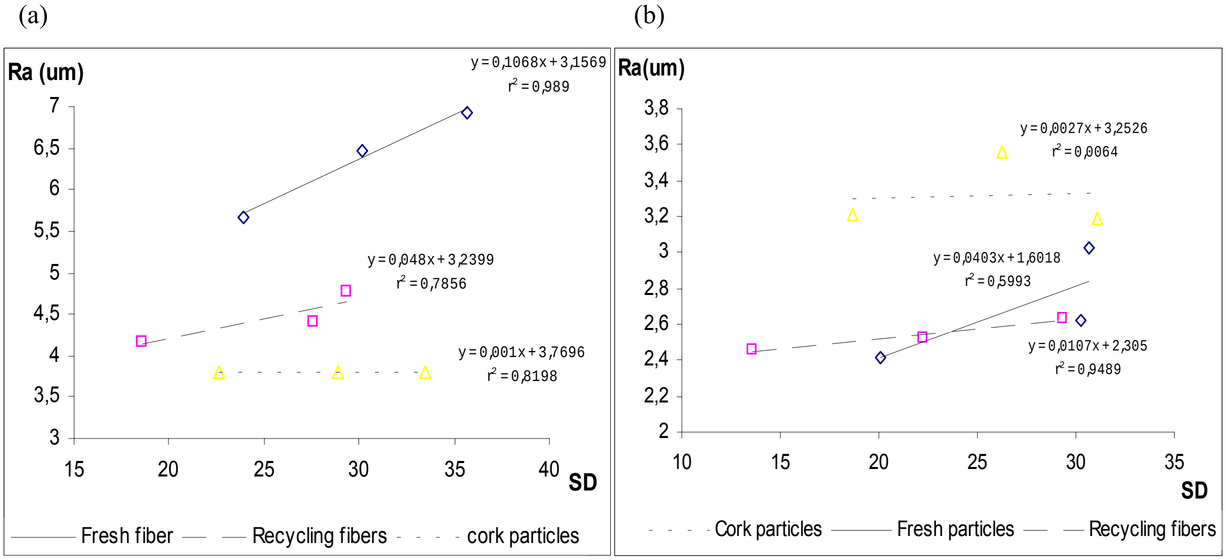


**Figure 49:** Correlation between average roughness ($R_a$) and standard deviation SD of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different lignocellulosic raw materials and stored under different climatic conditions. Figure 49 (a) shows the correlation coefficients for MUF-bonded MDF made with fresh and recycled fibers and cork particles, Figure 49 (b) shows the correlation coefficients for TF-bonded MDF made with fresh and recycled fibers and cork particles.

In medium density fiberboards (MDF) the surface roughness is affected by the adhesive and the lignocellulosic raw material used as well as by the processing conditions like sanding etc. As the sanding of the MDF was kept constant for all boards, mainly the type adhesive and the raw material were determining the roughness of the boards. The results reveal that non-contact method seems to be sensitive enough to detect subtle differences in roughness between samples.

## 5.4 General comparison of contact and non-contact method (image analysis)

One of the main objectives of this thesis was to compare the traditional contact method by perthometer with a non-contact method by image analysis. In Figure 50 a comparison is made between the contact method and the image analysis method for all tested particleboards and medium density fibreboards (MDF) boards under different climatic conditions. The contact method is expressed as $R_a$-values and the image analysis values are expressed as SD-values.

From Figure 50 it can be seen that the SD-values shift to the right side of the vertical reference line indicating a high sensitivity of the image analysis method towards change in the climatic conditions. In comparison there was no big change in the $R_a$-values of the board tested, there was no significant movement towards the horizontal reference line. In conclusion, both techniques seem to have different responses to changes in the board topography.

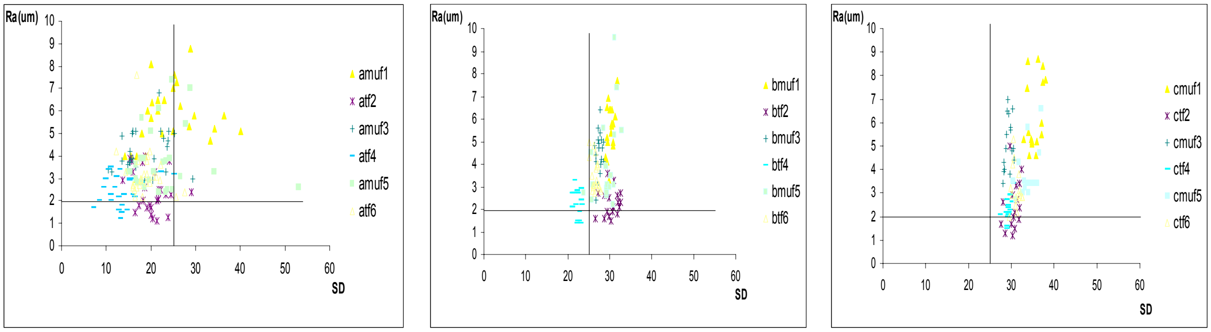

(a) (b) (c)

**Figure 50:** Effect of climatic conditions on the average roughness ($R_a$) and standard deviation (SD) of uncoated UF- and TF-bonded particleboards and MUF- and TF-bonded medium density fiberboards (MDF), made using different lignocellulosic raw materials. The boards were stored under different climatic conditions (from left to right 20°C / 30% relative humidity (a), 20°C / 65% relative humidity (b) and 20°C / 85% relative humidity (c)).

# 6 Summary

The growth of wood composites has been immense over the past 50 years. At the dawn of the 20th century plywood and fiberboards were developed, in the forties the invention of particleboards (PB) was a major breakthrough. In the past three decades other wood-based composites were developed such as oriented strand boards (OSB), laminated veneer lumber (LVL), and laminated strand lumber (LSL). In Europe, particleboards and medium density fiberboards (MDF) are, nowadays, the most important wood-based panels.

In the early days of the industry in Europe, mainly round timber from thinning operations in the forest was used as a raw material for wood-based panels; in the last decades, however, the raw material in the most developed countries within Europe, especially in Germany, has changed due to many reasons dramatically: Environmental regulations forced the use of waste wood in the last few years. In 1995 about 3.5 % of the raw material used in the particleboard industry in Germany was waste wood. At the turn of the century nearly 20 % of the lignocellulosic raw material in the particleboard industry were from recovered wood.

Recently, a number of methods have also been developed to recycle wood-based panels, some of them have reached industrial application as they are economically feasible. The challenge for the future will be to produce increasingly better performing, more consistent, environmentally friendly products at lower cost and using increasing amounts of recycled material in the process.

In Germany, nearly seventy percent of the particleboards (PB) and more than ninety percent of all medium density fiberboards are used in the furniture industry, where the surface properties of particleboards and fiberboards are of a primary importance. In particular, adhesion issues of paints and overlays depend to high extent on the surface properties of the boards. Under different climatic conditions the physical and chemical characteristics of board surfaces many change noticeably depending e.g., on the wood species (raw materials) used in the boards as well as on the binders applied. In many publications the hygroscopic behaviour of wood is covered, however so far only sporadic data are available on the influence of climatic conditions on the physical properties of the surface in different wood-based panels bonded with different adhesives.

One of the most important surface properties of wood-based panels is their roughness. It can be defined as the measure of the fine irregularities of a surface. In case of painted or overlaid composite boards irregularities may have a negative impact on the adhesion of paints and overlays and thus on the quality of the final product. The surface roughness is primarily a function of the raw material properties. Other factors like type and amount of resin, press cycle, sanding and moisture content of the boards may also affect the roughness and other surface properties.

The common technique used to characterize roughness of surfaces of e.g., metals, woods and wood-based panels is the so called contact method according to DIN 4768. One of the main disadvantages of this method is the relatively long time necessary to perform several measurements. Moreover, it is very restricted because one measurement is tracing only a short and small single-line. Therefore, in the last decades a lot of research work has been carried out to develop alternative and more efficient non-contact methods. One main principle of non-contact methods is measuring the intensity of light reflected from the surface of a tested sample and to evaluate the reflected light by means of optical sensors. Optical sensors measuring surface roughness have the advantage of high speed and the possibility to collect many data from a relatively large sample area.

The main objective of this study was, therefore, to evaluate the influence of the surface roughness of particleboards and medium density fiberboards on their performance towards coating. Within the framework of the study, different aspects pertaining to surface properties of particleboards (PB) and medium density fiberboards (MDF) were studied. These include:

- effect of fresh particles and recycling particles from UF-bonded boards, fresh fibers and recycling fibers from UF-bonded boards and recycling cork particles on the surface properties of wood-based panels bonded with an urea-formaldehyde resin (UF-resin), a melamine-urea-formaldehyde resin (MUF-resin) and a tannin-formaldehyde resin (TF-resin),

- effect of storage under three climatic conditions (20ºC / 30 % relative humidity, 20ºC / 65 % relative humidity and 20ºC / 85 % relative humidity) on the surface roughness of wood-based panels,

- influence of surface roughness of different uncoated particleboards on their performance towards coating using different methods of testing and appearance,

- effect of surface roughness on the wettability of uncoated medium density fiberboards (MDF) stored under different climatic conditions,
- comparison of contact and non-contact methods to measure surface roughness of wood-based panels.

In the first part of the research work three layer particleboards were produced with different raw materials in the surface and by using different binders. The raw materials used for the surfaces of the chipboards were industrially produced fresh particles, recycled particles from industrially produced UF-bonded particleboards and recycled cork particles. The recycled particles were produced by a dry process in the laboratories of the Institute of Wood Biology and Wood Technology. For preparation of particleboards a commercial urea-formaldehyde resin (UF-resin) and a tannin-formaldehyde resin (TF-resin) were used. After production, the particleboards were conditioned about four weeks prior to evaluating their surfaces at three different climatic conditions. These were 20ºC / 30 % relative humidity, 20ºC / 65 % relative humidity and 20ºC / 85 % relative humidity. After reaching equilibrium moisture content at the above mentioned climates the surface roughness was measured by the contact method (Perthometer (S4P)) and by the non-contact method (image analysis, Leica Q500MC and JVC-CCD camera).

The most important parameter determined was the average roughness ($R_a$). It is the average distance from the profile to the mean line. The results for the different boards are shown in Table 1.

As can be seen from Table 1 the moisture content of all UF- and TF-bonded particleboards increased with increasing relative humidity irrespective of the lignocellulosic raw material and the binder used in making the boards. UF- and TF-bonded particleboards made with fresh and recycled particles in the surface layers showed more or less the same rise in moisture content with increasing relative humidity during storage. The equilibrium moisture content of the uncoated UF- and TF-bonded particleboards made using cork particles in the surface layer was, however, lower than that of UF-particleboards made with fresh and recycled particles in the surface. TF-bonded uncoated particleboards showed, in general, higher equilibrium moisture content compared to UF-bonded uncoated particleboards. This may be due to the alkaline nature of used tannin formaldehyde resins.

**Table 1:** Average roughness $R_a$ (µm) and equilibrium moisture content (E.M.C.) (%) of uncoated UF- and TF-bonded particleboards, made using different raw materials in the surface layers (fresh particles, recycled particles and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

| Independent variables | | | Dependent variables | |
|---|---|---|---|---|
| Raw material | Type of adhesive | Climatic Conditions °C / rel. humidity % | Moisture content % | Average roughness ($R_a$) µm |
| Fresh particles | UF-resin | 20 / 30 | 5.6 | 4.3 |
| | | 20 / 65 | 8.7 | 5.5 |
| | | 20 / 85 | 12.3 | 5.7 |
| | TF-resin | 20 / 30 | 6.1 | 6.5 |
| | | 20 / 65 | 10.0 | 6.0 |
| | | 20 / 85 | 14.5 | 4.3 |
| Recycled particles | UF-resin | 20 / 30 | 5.6 | 10.5 |
| | | 20 / 65 | 8.3 | 10.5 |
| | | 20 / 85 | 12.2 | 12.8 |
| | TF-resin | 20 / 30 | 6.3 | 5.6 |
| | | 20 / 65 | 10.0 | 7.8 |
| | | 20 / 85 | 14.7 | 7.5 |
| Recycled cork | UF-resin | 20 / 30 | 4.1 | 3.9 |
| | | 20 / 65 | 7.5 | 2.7 |
| | | 20 / 85 | 10.7 | 2.8 |
| | TF-resin | 20 / 30 | 5.2 | 4.8 |
| | | 20 / 65 | 8.1 | 3.7 |
| | | 20 / 85 | 12.8 | 4.5 |

Moreover, Table 1 relates also the general influence of different climatic conditions with the roughness of uncoated UF- and TF-bonded particleboards. The average roughness (Ra) of uncoated UF-bonded particleboards, made using fresh and recycled particles increased with increasing moisture content. The same tendency applies also to uncoated TF-bonded particleboards, made using recycled particles. Interestingly, cork particles showed a quite different behaviour as no detectable increase in the roughness of the boards due to increase in the moisture content of the boards was measured irrespective of the adhesive used. As can also be seen from Table 1 particleboards made with recycled particles in the surface layer had the highest roughness in the surface (average roughness ($R_a$)) irrespective of the adhesive used.

An Anova statistical test was used to complement and confirm the results. The statistical analysis confirmed that the dependent variables (equilibrium moisture content and average roughness) are not only under the influence of an individual factor but a result of interaction of factors inducing significant differences in the dependent variables.

In the second step of the research work, uncoated UF- and TF-bonded particleboards were conditioned under climate 20°C and 65 % relative humidity and coated with nitrocellulose paint by a conventional process. The amount of lacquer applied to the boards surface area was kept constant. The surfaces of the coated particleboards were evaluated through several UNE standards to evaluate the effects of surface properties on the quality of the finishing. The following tests were made on the conditioned coated particleboards samples: adherence strength (UNE-standard 48032), speculate brightness (UNE-standard 48026), impact strength (UNE-standard 11019/6), abrasion strength (EN-standard 438-2, article 6).

The results reveal that, in general, higher values of roughness of uncoated particleboards lead to thinner coating films on the surface. The original roughness of the uncoated board surface impacts also the final roughness of the coated boards. Particleboards made with fresh and recycled particles showed higher values of average roughness ($R_a$) and higher adherence strength to the coating compared to particleboards with cork particles, which had a relatively smooth surface. From the results of the abrasion test it can be concluded that not only the roughness of the surface but also interaction between the lacquer and surface seems to be a very important factor determining the strength of adhesiveness between lacquer and the surface. Moreover, the results reveal that boards made with fresh and recycled particles have a higher impact strength compared to finished boards with cork particles in the surface layer. This result is insofar interesting as the coating film on boards with recycled particles was about 50 % thinner compared to that on boards with fresh and cork particles in their surface layers. This may be due to the significantly different elasto-mechanical properties of the cork particles compared to wood surfaces.

In the third part of the research work medium density fiberboards (MDF) were made using different raw materials in the surface layers as well as different binders. The raw materials for the surfaces of the MDF were industrially produced fresh fibers (thermo-mechanical pulp, TMP) and recycling fibers generated from industrially produced UF-bonded fiberboards. In another set of experiments recycled cork particles were used in the surface layers. Nowadays, medium density fiberboards (MDF) coated with a surface layer of cork are commercially available.

The recycled fibers were produced by a thermo-hydrolytic process in the laboratories of the Institute of Wood Biology and Wood Technology. For preparation of medium density fiberboards (MDF) a commercial melamine-urea-formaldehyde resin (MUF-resin) and a tannin-formaldehyde resin (TF-resin) were used as binders. One layer MDF were made with the fresh and the recycled fibers as well as three layers MDF with recycled cork particles in the surface layer and fresh fibers in the core layer.

After pressing, trimming and sanding the MDF the boards were conditioned in a first step at a climate of 20°C / 30% relative humidity until the boards reached equilibrium moisture content (E.M.C). The surface roughness of the MDF was then measured using the contact method (Perthometer (S4P)) and the non-contact method (image analysis, Leica Q500MC and JVC-CCD camera). Thereafter, boards were conditioned at 20ºC and 65% rel. humidity to a higher E.M.C. until the boards reached equilibrium moisture content. Thereafter, the same surface parameters were measured again. In the last step of the experiment the MDF were stored at 20°C and 85% rel. humidity and the surface roughness was also evaluated. In Table 2 the results of this part of the research work are listed.

**Table 2:** Average roughness $R_a$ (μm) and equilibrium moisture content (E.M.C.) (%) of uncoated MUF- and TF-bonded medium density fiberboards (MDF), made using different raw materials in the surface layers (fresh fibers, recycled fibers and cork particles) after storage under different climatic conditions (20°C / 30% relative humidity, 20°C / 65% relative humidity and 20°C / 85% relative humidity)

| Independent variables | | | Dependent variables | |
|---|---|---|---|---|
| Raw material | Type of adhesive | Climatic Conditions °C / rel. humidity % | Moisture content % | Average roughness ($R_a$) μm |
| Fresh fibers | MUF-resin | 20 / 30 | 3.0 | 5.7 |
| | | 20 / 65 | 7.5 | 6.5 |
| | | 20 / 85 | 9.5 | 6.9 |
| | TF-resin | 20 / 30 | 3.6 | 2.4 |
| | | 20 / 65 | 8.7 | 2.6 |
| | | 20 / 85 | 10.5 | 3.0 |
| Recycled fibers | MUF-resin | 20 / 30 | 2.9 | 4.2 |
| | | 20 / 65 | 7.5 | 4.4 |
| | | 20 / 85 | 9.4 | 4.8 |
| | TF-resin | 20 / 30 | 3.4 | 2.5 |
| | | 20 / 65 | 8.1 | 2.5 |
| | | 20 / 85 | 9.9 | 2.6 |
| Cork particles | MUF-resin | 20 / 30 | 2.5 | 3.8 |
| | | 20 / 65 | 6.3 | 3.8 |
| | | 20 / 85 | 8.1 | 3.8 |
| | TF-resin | 20 / 30 | 2.6 | 3.2 |
| | | 20 / 65 | 7.4 | 3.6 |
| | | 20 / 85 | 9.1 | 3.2 |

As the results reveal equilibrium moisture content of all MUF- and TF-bonded medium density fibreboards (MDF) increased with increasing relative humidity irrespective of the lignocellulosic raw material used in the manufacture of the fiberboards. Moreover, the influence of the adhesive used on the moisture content of the manufactured fiberboards is also obvious. TF-bonded MDF are in general of higher equilibrium moisture content (E.M.C.) in comparison to MUF-bonded MDF. This again may be due to the alkaline nature of the used TF-resin.

In general, TF-bonded MDF have within the same set of experiments smoother surfaces (lower average surface roughness ($R_a$)) compared to MUF-bonded MDF irrespective of the raw material used. As it can also be deduced from the results, MUF-bonded fiberboards increased their roughness with higher moisture content in the boards, however in case of TF-bonded MDF only a slight increase in the roughness was observed due to increase in the moisture content. A comparison between the raw materials indicates that fresh fibers lead to rougher surfaces than recycled fibers. Moreover, MUF- and TF-bonded MDF with cork in the surfaces showed no big changes in the roughness with increasing moisture content of the boards.

The results were also statistically analysed by an Anova statistical test. The statistical analysis confirmed that the dependent variables (equilibrium moisture content and average roughness) are a complex function of interactions between many variables.

In further research work, the wettability of the MDF surfaces was measured using different mixtures of distilled water and isopropanol. It was found that a high proportion of isopropanol in the isopropanol-water-solution increases the spreading of the test solution on the surface of the boards. This is due to the fact that isopropanol reduces surface tension of the liquid. As can be seen from the results, TF-bonded MDF, made using fresh and recycled fibers showed a better wettability than the corresponding MUF-bonded MDF. This may be due to the hygroscopic nature of the alkaline medium used in TF-resins. In case of MUF- and TF-bonded MDF with cork particles in the surface layers no significant differences in the roughness nor in the wettability were measured. The better wettability of TF-bonded MDF observed in case of using fresh and recycled fibers doesn’t seem to apply for MDF with cork particles in the surface layers. This may be due to the extremly hydrophobic nature of cork, which seems to overcompensate the influence of the alkali in TF-resin used. The whole results show that roughness is one of the most important factors on the wettability of MDF surfaces, irrespective of the moisture content of the boards.

Within the frame work of the research conducted a comparison was made between both methods (contact method and non-contact method) for all uncoated particle- and medium density fibreboards (MDF). The data of average roughness ($R_a$) obtained by contact method were correlated with values of the standard deviation (SD) of the gray level histogram assessed by non-contact method.

For uncoated UF-bonded particleboards a coefficient of correlation ($r^2$) of $r^2 = 0.803$ between both methods was found. For uncoated TF-bonded particleboards the coefficient of correlation ($r^2$) was $r^2 = 0.395$. Moreover, uncoated MUF-bonded MDF showed high correlation coefficients ($r^2$) between both methods for all raw materials (fresh fibers ($r^2 = 0.9890$), cork particles ($r^2 = 0.8198$) and recycled fibers ($r^2 = 0.7856$) respectively). For uncoated TF-bonded MDF the following correlation coefficients ($r^2$) between $R_a$ and SD were found (cork particles ($r^2 = 0.0064$), fresh fibers ($r^2 = 0.5993$) and recycled fibers ($r^2 = 0.9489$).

A possible explanation for the lower coefficients of correlation between both methods when using TF-resins is the dark colour of the tannin. The darker a sample surface is, the more homogeneous appears the surface for image analysis. This principle does not work well, the darker a sample is. Therefore, it is difficult to assess the roughness of dark surfaces by using the optical image technique.

Finally, the traditional contact method (perthometer method) was compared with a non-contact method (image analysis). The comparison was made between both methods by testing all particleboards and medium density fibreboards (MDF) under different climatic conditions. The results show the high sensitivity of the non-contact method (image analysis) towards changes in the climatic conditions. In comparison, there was no big change in the $R_a$-values of the tested boards due to change in the climatic conditions. In general, however, both techniques lead to more or less similar characterization of the roughness of particleboards and medium density fiberboard (MDF) surfaces.

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# 8 Appendix

# Anova Procedure for Particleboards

```
                                      The SAS System   10:48 Wednesday, March 27, 2002 134
                                   The ANOVA Procedure
                                 Class Level Information
                       Class         Levels    Values
                       adhesivo           2    MUF TF
                       material           3    Cork Fresh Reciclin
                       clima              3    1 2 3

                               Number of observations    18
                                      The SAS System   10:48 Wednesday, March 27, 2002 135
                                   The ANOVA Procedure
Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     317171.8333      24397.8333    1240.57    <.0001

   Error                        4         78.6667         19.6667

   Corrected Total             17     317250.5000

                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.999752      0.693465      4.434712         639.5000

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1        264.5000        264.5000      13.45    0.0214
   material                     2     314230.3333     157115.1667    7988.91    <.0001
   clima                        2        217.0000        108.5000       5.52    0.0708
   adhesivo*material            2       1129.0000        564.5000      28.70    0.0042
   adhesivo*clima               2        196.3333         98.1667       4.99    0.0818
   material*clima               4       1134.6667        283.6667      14.42    0.0121
                                      The SAS System   10:48 Wednesday, March 27, 2002 136
                                   The ANOVA Procedure
Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     138.3433333      10.6417949     311.47    <.0001

   Error                        4       0.1366667       0.0341667

   Corrected Total             17     138.4800000

                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.999013      2.772634      0.184842        6.666667




Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1       2.4200000       2.4200000      70.83    0.0011
   material                     2       4.2133333       2.1066667      61.66    0.0010
   clima                        2     131.0833333      65.5416667    1918.29    <.0001
   adhesivo*material            2       0.1200000       0.0600000       1.76    0.2835
   adhesivo*clima               2       0.2633333       0.1316667       3.85    0.1167
   material*clima               4       0.2433333       0.0608333       1.78    0.2950
                                      The SAS System   10:48 Wednesday, March 27, 2002 137
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```
                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     31.12775556      2.39444274      83.90    0.0003

   Error                        4      0.11415556      0.02853889

   Corrected Total             17     31.24191111


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.996346      4.379064      0.168935         3.857778


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     18.32142222     18.32142222     641.98    <.0001
   material                     2      3.97941111      1.98970556      69.72    0.0008
   clima                        2      0.59767778      0.29883889      10.47    0.0257
   adhesivo*material            2      7.64067778      3.82033889     133.86    0.0002
   adhesivo*clima               2      0.10814444      0.05407222       1.89    0.2637
   material*clima               4      0.48042222      0.12010556       4.21    0.0964
                                      The SAS System   10:48 Wednesday, March 27, 2002 138
                                   The ANOVA Procedure

Dependent Variable: angulo

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     6627.878333      509.836795      16.73    0.0074

   Error                        4      121.886667       30.471667

   Corrected Total             17     6749.765000


                   R-Square     Coeff Var      Root MSE    angulo Mean

                   0.981942      5.763127      5.520115       95.78333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     1915.805000     1915.805000      62.87    0.0014
   material                     2     2928.573333     1464.286667      48.05    0.0016
   clima                        2      314.230000      157.115000       5.16    0.0781
   adhesivo*material            2     1025.320000      512.660000      16.82    0.0113
   adhesivo*clima               2       57.143333       28.571667       0.94    0.4635
   material*clima               4      386.806667       96.701667       3.17    0.1447









                                          The SAS System   10:48 Wednesday, March 27, 2002 139
                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   19.66667
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        5.8043


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo
```

```
                          A       643.333      9    TF

                          B       635.667      9    MUF
                                    The SAS System   10:48 Wednesday, March 27, 2002 140

                                 The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for humedad

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.034167
                     Critical Value of Studentized Range  3.92650
                     Minimum Significant Difference        0.2419


              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    adhesivo

                          A       7.03333      9    TF

                          B       6.30000      9    MUF
                                    The SAS System   10:48 Wednesday, March 27, 2002 141

                                 The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.028539
                     Critical Value of Studentized Range  3.92650
                     Minimum Significant Difference        0.2211


              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    adhesivo

                          A       4.86667      9    MUF

                          B       2.84889      9    TF
                                    The SAS System   10:48 Wednesday, March 27, 2002 142

                                 The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   30.47167
                     Critical Value of Studentized Range  3.92650
                     Minimum Significant Difference        7.2249


              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    adhesivo

                          A       106.100      9    MUF

                          B        85.467      9    TF
                                    The SAS System   10:48 Wednesday, March 27, 2002 143

                                 The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad
```

```
NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   19.66667
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        9.1252

              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    material

                          A       735.333      6    Fresh
                          A
                          A       730.500      6    Reciclin

                          B       452.667      6    Cork
                                    The SAS System   10:48 Wednesday, March 27, 2002 144

                                 The ANOVA Procedure

                   Tukey's Studentized Range (HSD) Test for humedad

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.

                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.034167
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        0.3803

              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    material

                          A        7.1333      6    Fresh
                          A
                          A        6.8667      6    Reciclin

                          B        6.0000      6    Cork
                                    The SAS System   10:48 Wednesday, March 27, 2002 145

                                 The ANOVA Procedure

                  Tukey's Studentized Range (HSD) Test for rugosida

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.028539
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        0.3476


              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    material

                          A       4.52167      6    Fresh

                          B       3.55833      6    Cork
                          B
                          B       3.49333      6    Reciclin
                                    The SAS System   10:48 Wednesday, March 27, 2002 146

                                 The ANOVA Procedure

                   Tukey's Studentized Range (HSD) Test for angulo

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   30.47167
                     Critical Value of Studentized Range  5.04026
```

```
                     Minimum Significant Difference        11.359


              Means with the same letter are not significantly different.


             Tukey Grouping          Mean      N    material

                          A       113.817      6    Cork

                          B        87.150      6    Reciclin
                          B
                          B        86.383      6    Fresh
                                    The SAS System   10:48 Wednesday, March 27, 2002 147

                                 The ANOVA Procedure

                  Tukey's Studentized Range (HSD) Test for densidad

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   19.66667
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        9.1252






             Means with the same letter are not significantly different.


              Tukey Grouping          Mean      N    clima

                           A       643.667      6    2
                           A
                           A       639.667      6    3
                           A
                           A       635.167      6    1
                                    The SAS System   10:48 Wednesday, March 27, 2002 148

                                 The ANOVA Procedure

                   Tukey's Studentized Range (HSD) Test for humedad

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.034167
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        0.3803


             Means with the same letter are not significantly different.


              Tukey Grouping          Mean      N    clima

                           A        9.4167      6    3

                           B        7.5833      6    2

                           C        3.0000      6    1
                                    The SAS System   10:48 Wednesday, March 27, 2002 149

                                 The ANOVA Procedure

                  Tukey's Studentized Range (HSD) Test for rugosida

NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.028539
                     Critical Value of Studentized Range  5.04026
                     Minimum Significant Difference        0.3476
```

```
                Means with the same letter are not significantly different.

                   Tukey Grouping          Mean      N    clima

                                A       4.06000      6    3
                                A
                           B    A       3.89500      6    2
                           B
                           B            3.61833      6    1










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                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   30.47167
                       Critical Value of Studentized Range  5.04026
                       Minimum Significant Difference        11.359


               Means with the same letter are not significantly different.


                Tukey Grouping          Mean      N    clima

                             A       101.667      6    3
                             A
                             A        93.317      6    2
                             A
                             A        92.367      6    1
                                      The SAS System   10:48 Wednesday, March 27, 2002 151
------------------------------------- material=Cork --------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information

                             Class         Levels    Values

                             adhesivo           2    MUF TF

                             material           1    Cork


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 152
------------------------------------- material=Cork --------------------------------------
                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      6.00000000      6.00000000       1.57    0.2791

   Error                        4     15.33333333      3.83333333

   Corrected Total              5     21.33333333


                  R-Square     Coeff Var      Root MSE    densidad Mean
```

```
                  0.281250      0.432524      1.957890         452.6667

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      6.00000000      6.00000000       1.57    0.2791




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------------------------------------- material=Cork --------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   3.833333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        4.4385


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       453.667      3    MUF
                            A
                            A       451.667      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 154

------------------------------------- material=Fresh -------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                             Class         Levels    Values

                             adhesivo           2    MUF TF

                             material           1    Fresh


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 155

------------------------------------- material=Fresh -------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     1350.000000     1350.000000       5.32    0.0824

   Error                        4     1015.333333      253.833333

   Corrected Total              5     2365.333333


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.570744      2.166657      15.93215         735.3333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     1350.000000     1350.000000       5.32    0.0824
```

```
                                          The SAS System   10:48 Wednesday, March 27, 2002 156

------------------------------------- material=Fresh -------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   253.8333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        36.118


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        750.33      3    TF
                            A
                            A        720.33      3    MUF
                                      The SAS System   10:48 Wednesday, March 27, 2002 157

----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                            Class         Levels    Values

                            adhesivo           2    MUF TF

                            material           1    Reciclin


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 158

----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      37.5000000      37.5000000       0.25    0.6423

   Error                        4     596.0000000     149.0000000

   Corrected Total              5     633.5000000


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.059195      1.670986      12.20656         730.5000


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     37.50000000     37.50000000       0.25    0.6423




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----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
```

```
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                        149
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        27.672


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       733.000      3    MUF
                            A
                            A       728.000      3    TF
                                          The SAS System   10:48 Wednesday, March 27, 2002 160

------------------------------------- adhesivo=MUF -------------------------------------

                                       The ANOVA Procedure

                                     Class Level Information

                       Class         Levels    Values

                       adhesivo           1    MUF

                       material           3    Cork Fresh Reciclin


                               Number of observations    9
                                          The SAS System   10:48 Wednesday, March 27, 2002 161

------------------------------------- adhesivo=MUF -------------------------------------

                                       The ANOVA Procedure

Dependent Variable: densidad

                                                Sum of
   Source                      DF          Squares     Mean Square    F Value    Pr > F

   Model                        2      149298.6667      74649.3333     453.64    <.0001

   Error                        6         987.3333        164.5556

   Corrected Total              8      150286.0000


                 R-Square     Coeff Var      Root MSE    densidad Mean

                 0.993430      2.018026      12.82792         635.6667


   Source                      DF         Anova SS     Mean Square    F Value    Pr > F

   material                     2      149298.6667      74649.3333     453.64    <.0001




                                              The SAS System   10:48 Wednesday, March 27, 2002 162

------------------------------------- adhesivo=MUF -------------------------------------

                                       The ANOVA Procedure

                              Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   164.5556
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        32.136


                Means with the same letter are not significantly different.
```

```
               Tukey Grouping          Mean      N    material

                            A        733.00      3    Reciclin
                            A
                            A        720.33      3    Fresh

                            B        453.67      3    Cork
                                      The SAS System   10:48 Wednesday, March 27, 2002 163

-------------------------------------- adhesivo=TF --------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           1    TF

                       material           3    Cork Fresh Reciclin

                               Number of observations    9
                                      The SAS System   10:48 Wednesday, March 27, 2002 164

-------------------------------------- adhesivo=TF --------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     166060.6667      83030.3333     779.22    <.0001

   Error                        6        639.3333        106.5556

   Corrected Total              8     166700.0000

                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.996165      1.604545      10.32258         643.3333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     166060.6667      83030.3333     779.22    <.0001


                                          The SAS System   10:48 Wednesday, March 27, 2002 165

-------------------------------------- adhesivo=TF --------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   106.5556
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        25.859


                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    material

                            A       750.333      3    Fresh
                            A
                            A       728.000      3    Reciclin

                            B       451.667      3    Cork
                                      The SAS System   10:48 Wednesday, March 27, 2002 166
```

```
------------------------------------- material=Cork --------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              material           1    Cork

                              clima              3    1 2 3


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 167
------------------------------------- material=Cork --------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2      6.33333333      3.16666667       0.63    0.5896

   Error                        3     15.00000000      5.00000000

   Corrected Total              5     21.33333333


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.296875      0.493977      2.236068         452.6667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   clima                        2      6.33333333      3.16666667       0.63    0.5896




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------------------------------------- material=Cork --------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   3
                       Error Mean Square                          5
                       Critical Value of Studentized Range  5.90960
                       Minimum Significant Difference        9.3439


               Means with the same letter are not significantly different.


                Tukey Grouping          Mean      N    clima

                             A       454.000      2    1
                             A
                             A       452.500      2    3
                             A
                             A       451.500      2    2
                                      The SAS System   10:48 Wednesday, March 27, 2002 169
------------------------------------- material=Fresh -------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                              Class         Levels    Values

                              material           1    Fresh
```

```
                              clima              3    1 2 3

                               Number of observations    6

                                      The SAS System   10:48 Wednesday, March 27, 2002 170
------------------------------------- material=Fresh -------------------------------------
                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2      906.333333      453.166667       0.93    0.4844

   Error                        3     1459.000000      486.333333

   Corrected Total              5     2365.333333

                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.383174      2.999044      22.05297         735.3333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   clima                        2     906.3333333     453.1666667       0.93    0.4844


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------------------------------------- material=Fresh -------------------------------------
                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   3
                       Error Mean Square                   486.3333
                       Critical Value of Studentized Range  5.90960
                       Minimum Significant Difference        92.153


               Means with the same letter are not significantly different.


                Tukey Grouping          Mean      N    clima

                             A        747.50      2    3
                             A
                             A        740.00      2    2
                             A
                             A        718.50      2    1
                                      The SAS System   10:48 Wednesday, March 27, 2002 172
----------------------------------- material=Reciclin ------------------------------------
                                   The ANOVA Procedure


                                 Class Level Information

                            Class         Levels    Values

                            material           1    Reciclin

                            clima              3    1 2 3


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 173
----------------------------------- material=Reciclin ------------------------------------
                                   The ANOVA Procedure
```

```
Dependent Variable: densidad

                                           Sum of
   Source                     DF          Squares     Mean Square    F Value    Pr > F

   Model                       2     439.0000000     219.5000000       3.39    0.1701

   Error                       3     194.5000000      64.8333333

   Corrected Total             5     633.5000000


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.692976      1.102247      8.051915         730.5000


   Source                     DF        Anova SS     Mean Square    F Value    Pr > F

   clima                       2     439.0000000     219.5000000       3.39    0.1701



                                           The SAS System   10:48 Wednesday, March 27, 2002 174

----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   3
                       Error Mean Square                   64.83333
                       Critical Value of Studentized Range  5.90960
                       Minimum Significant Difference        33.647


               Means with the same letter are not significantly different.


                Tukey Grouping          Mean      N    clima

                             A       739.500      2    2
                             A
                             A       733.000      2    1
                             A
                             A       719.000      2    3
                                       The SAS System   10:48 Wednesday, March 27, 2002 175

---------------------------------------- clima=1 -----------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       material           3    Cork Fresh Reciclin

                       clima              1    1


                               Number of observations    6
                                       The SAS System   10:48 Wednesday, March 27, 2002 176

---------------------------------------- clima=1 -----------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                     DF          Squares     Mean Square    F Value    Pr > F

   Model                       2     98674.33333     49337.16667     206.00    0.0006

   Error                       3       718.50000       239.50000

   Corrected Total             5     99392.83333
```

```
                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.992771      2.436492      15.47579         635.1667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     98674.33333     49337.16667     206.00    0.0006



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---------------------------------------- clima=1 -----------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   3
                       Error Mean Square                      239.5
                       Critical Value of Studentized Range  5.90960
                       Minimum Significant Difference        64.669


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    material

                            A        733.00      2    Reciclin
                            A
                            A        718.50      2    Fresh

                            B        454.00      2    Cork
                                     The SAS System   10:48 Wednesday, March 27, 2002 178
---------------------------------------- clima=2 -----------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                       Class         Levels    Values

                       material           3    Cork Fresh Reciclin

                       clima              1    2


                               Number of observations    6
                                     The SAS System   10:48 Wednesday, March 27, 2002 179
---------------------------------------- clima=2 -----------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     110784.3333      55392.1667     520.93    0.0002

   Error                        3        319.0000        106.3333

   Corrected Total              5     111103.3333


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.997129      1.602041      10.31181         643.6667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     110784.3333      55392.1667     520.93    0.0002
```

```
                                           The SAS System   10:48 Wednesday, March 27, 2002 180

---------------------------------------- clima=2 -----------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   3
                       Error Mean Square                   106.3333
                       Critical Value of Studentized Range  5.90960
                       Minimum Significant Difference         43.09


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    material

                            A        740.00      2    Fresh
                            A
                            A        739.50      2    Reciclin

                            B        451.50      2    Cork
                                      The SAS System   10:48 Wednesday, March 27, 2002 181

---------------------------------------- clima=3 -----------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                       Class         Levels    Values

                       material           3    Cork Fresh Reciclin

                       clima              1    3


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 182

---------------------------------------- clima=3 -----------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     105906.3333      52953.1667     251.76    0.0005

   Error                        3        631.0000        210.3333

   Corrected Total              5     106537.3333


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.994077      2.267255      14.50287         639.6667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     105906.3333      52953.1667     251.76    0.0005



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---------------------------------------- clima=3 -----------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad
```

```
  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   3
                     Error Mean Square                   210.3333
                     Critical Value of Studentized Range  5.90960
                     Minimum Significant Difference        60.603


               Means with the same letter are not significantly different.


              Tukey Grouping          Mean      N    material

                           A        747.50      2    Fresh
                           A
                           A        719.00      2    Reciclin

                           B        452.50      2    Cork
                                         The SAS System   10:48 Wednesday, March 27, 2002 184

------------------------------------- material=Cork -------------------------------------

                                      The ANOVA Procedure

                                    Class Level Information

                              Class         Levels    Values

                              adhesivo           2    MUF TF

                              material           1    Cork


                                Number of observations    6
                                         The SAS System   10:48 Wednesday, March 27, 2002 185

------------------------------------- material=Cork -------------------------------------

                                      The ANOVA Procedure

Dependent Variable: rugosida

                                                 Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      0.34081667      0.34081667      15.73    0.0166

   Error                        4      0.08666667      0.02166667

   Corrected Total              5      0.42748333


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.797263      4.136656      0.147196         3.558333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      0.34081667      0.34081667      15.73    0.0166




                                              The SAS System   10:48 Wednesday, March 27, 2002 186

------------------------------------- material=Cork -------------------------------------

                                      The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   4
                     Error Mean Square                   0.021667
                     Critical Value of Studentized Range  3.92650
                     Minimum Significant Difference        0.3337
```

```
                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    adhesivo

                            A        3.7967      3    MUF

                            B        3.3200      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 187
------------------------------------- material=Fresh --------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information

                             Class         Levels    Values

                             adhesivo           2    MUF TF

                             material           1    Fresh

                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 188
------------------------------------- material=Fresh --------------------------------------
                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     20.13001667     20.13001667      80.18    0.0009

   Error                        4      1.00426667      0.25106667

   Corrected Total              5     21.13428333

                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.952482      11.08143      0.501066         4.521667

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     20.13001667     20.13001667      80.18    0.0009



                                          The SAS System   10:48 Wednesday, March 27, 2002 189
------------------------------------- material=Fresh --------------------------------------
                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.251067
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        1.1359


                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    adhesivo

                            A        6.3533      3    MUF

                            B        2.6900      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 190
```

```
----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                            Class         Levels    Values

                            adhesivo           2    MUF TF

                            material           1    Reciclin

                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 191
----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      5.49126667      5.49126667     104.86    0.0005

   Error                        4      0.20946667      0.05236667

   Corrected Total              5      5.70073333

                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.963256      6.550696      0.228838         3.493333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      5.49126667      5.49126667     104.86    0.0005




                                           The SAS System   10:48 Wednesday, March 27, 2002 192
----------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.052367
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        0.5188


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        4.4500      3    MUF

                            B        2.5367      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 193
-------------------------------------- adhesivo=MUF --------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           1    MUF

                       material           3    Cork Fresh Reciclin
```

```
                               Number of observations    9
                                      The SAS System   10:48 Wednesday, March 27, 2002 194
-------------------------------------- adhesivo=MUF ---------------------------------------
                                   The ANOVA Procedure
Dependent Variable: rugosida
                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F
   Model                        2     10.58606667      5.29303333      31.58    0.0007
   Error                        6      1.00553333      0.16758889
   Corrected Total              8     11.59160000

                  R-Square     Coeff Var      Root MSE    rugosida Mean
                  0.913253      8.411840      0.409376         4.866667

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F
   material                     2     10.58606667      5.29303333      31.58    0.0007



                                          The SAS System   10:48 Wednesday, March 27, 2002 195
-------------------------------------- adhesivo=MUF ---------------------------------------
                                   The ANOVA Procedure
                    Tukey's Studentized Range (HSD) Test for rugosida
  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.

                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   0.167589
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        1.0255

                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    material
                            A        6.3533      3    Fresh
                            B        4.4500      3    Reciclin
                            B
                            B        3.7967      3    Cork
                                      The SAS System   10:48 Wednesday, March 27, 2002 196
-------------------------------------- adhesivo=TF ----------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information
                       Class         Levels    Values
                       adhesivo           1    TF
                       material           3    Cork Fresh Reciclin

                               Number of observations    9
                                      The SAS System   10:48 Wednesday, March 27, 2002 197
-------------------------------------- adhesivo=TF ----------------------------------------
```

```
                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2      1.03402222      0.51701111      10.52    0.0109

   Error                        6      0.29486667      0.04914444

   Corrected Total              8      1.32888889


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.778110      7.781471      0.221685         2.848889


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2      1.03402222      0.51701111      10.52    0.0109



                                          The SAS System   10:48 Wednesday, March 27, 2002 198

------------------------------------- adhesivo=TF --------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   0.049144
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        0.5554


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    material

                            A        3.3200      3    Cork

                            B        2.6900      3    Fresh
                            B
                            B        2.5367      3    Reciclin
                                      The SAS System   10:48 Wednesday, March 27, 2002 199

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                             Class         Levels    Values

                             adhesivo           2    MUF TF

                             material           1    Cork


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 200

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

Dependent Variable: angulo

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      0.08166667      0.08166667       0.01    0.9402

   Error                        4     51.16666667     12.79166667
```

```
   Corrected Total              5     51.24833333

                R-Square     Coeff Var      Root MSE    angulo Mean

                0.001594      3.142373      3.576544       113.8167

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      0.08166667      0.08166667       0.01    0.9402
```

```
                                 The SAS System   10:48 Wednesday, March 27, 2002 201
------------------------------------- material=Cork -------------------------------------
                              The ANOVA Procedure

                   Tukey's Studentized Range (HSD) Test for angulo

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                       higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   12.79167
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        8.1079


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       113.933      3    TF
                            A
                            A       113.700      3    MUF
                             The SAS System   10:48 Wednesday, March 27, 2002 202
------------------------------------- material=Fresh ------------------------------------
                              The ANOVA Procedure


                            Class Level Information

                        Class         Levels    Values

                        adhesivo           2    MUF TF

                        material           1    Fresh


                          Number of observations    6
                             The SAS System   10:48 Wednesday, March 27, 2002 203
------------------------------------- material=Fresh ------------------------------------
                              The ANOVA Procedure

Dependent Variable: angulo

                                        Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     1834.001667     1834.001667      17.34    0.0141

   Error                        4      422.966667      105.741667

   Corrected Total              5     2256.968333


                R-Square     Coeff Var      Root MSE    angulo Mean

                0.812595      11.90401      10.28308       86.38333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     1834.001667     1834.001667      17.34    0.0141
```

```
                                          The SAS System   10:48 Wednesday, March 27, 2002 204

------------------------------------ material=Fresh ------------------------------------

                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   105.7417
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        23.311


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       103.867      3    MUF

                            B        68.900      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 205

---------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                            Class         Levels    Values

                            adhesivo           2    MUF TF

                            material           1    Reciclin


                               Number of observations    6
                                      The SAS System   10:48 Wednesday, March 27, 2002 206

---------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

Dependent Variable: angulo

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     1107.041667     1107.041667      10.91    0.0299

   Error                        4      405.933333      101.483333

   Corrected Total              5     1512.975000


                   R-Square     Coeff Var      Root MSE    angulo Mean

                   0.731699      11.55926      10.07389       87.15000


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     1107.041667     1107.041667      10.91    0.0299




                                          The SAS System   10:48 Wednesday, March 27, 2002 207

---------------------------------- material=Reciclin ------------------------------------

                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo
```

```
  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   101.4833
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        22.837


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       100.733      3    MUF

                            B        73.567      3    TF
                                      The SAS System   10:48 Wednesday, March 27, 2002 208

-------------------------------------- adhesivo=MUF --------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           1    MUF

                       material           3    Cork Fresh Reciclin


                               Number of observations    9
                                      The SAS System   10:48 Wednesday, March 27, 2002 209

-------------------------------------- adhesivo=MUF --------------------------------------

                                   The ANOVA Procedure

Dependent Variable: angulo

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     274.6466667     137.3233333       2.54    0.1589

   Error                        6     324.5733333      54.0955556

   Corrected Total              8     599.2200000


                   R-Square     Coeff Var      Root MSE    angulo Mean

                   0.458340      6.932109      7.354968       106.1000


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     274.6466667     137.3233333       2.54    0.1589




                                           The SAS System   10:48 Wednesday, March 27, 2002 210

-------------------------------------- adhesivo=MUF --------------------------------------

                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   54.09556
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        18.425
```

```
                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    material

                            A       113.700      3    Cork
                            A
                            A       103.867      3    Fresh
                            A
                            A       100.733      3    Reciclin
                                      The SAS System   10:48 Wednesday, March 27, 2002 211

-------------------------------------- adhesivo=TF ---------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           1    TF

                       material           3    Cork Fresh Reciclin


                               Number of observations    9
                                      The SAS System   10:48 Wednesday, March 27, 2002 212

-------------------------------------- adhesivo=TF ---------------------------------------

                                   The ANOVA Procedure

Dependent Variable: angulo

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     3679.246667     1839.623333      19.87    0.0023

   Error                        6      555.493333       92.582222

   Corrected Total              8     4234.740000


                   R-Square     Coeff Var      Root MSE    angulo Mean

                   0.868825      11.25815      9.621966       85.46667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     3679.246667     1839.623333      19.87    0.0023


                                          The SAS System   10:48 Wednesday, March 27, 2002 213

-------------------------------------- adhesivo=TF ---------------------------------------

                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for angulo

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   92.58222
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        24.104


                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    material

                            A       113.933      3    Cork

                            B        73.567      3    Reciclin
                            B
                            B        68.900      3    Fresh
```

# Anova Procedure for Medium Density Fiberboards (MDF)

```
                                      The SAS System    09:38 Thursday, April 25, 2002 120

                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           2    TF UF

                       material           3    Cork Fresh Recyclin

                       clima              3    1 2 3


                               Number of observations    18

                                      The SAS System    09:38 Thursday, April 25, 2002 121

                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     4991.722222      383.978632      25.36    0.0034

   Error                        4       60.555556       15.138889

   Corrected Total             17     5052.277778


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.988014      0.555354      3.890873         700.6111


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     1549.388889     1549.388889     102.34    0.0005
   material                     2      648.444444      324.222222      21.42    0.0073
   clima                        2      821.777778      410.888889      27.14    0.0047
   adhesivo*material            2     1869.777778      934.888889      61.75    0.0010
   adhesivo*clima               2       69.777778       34.888889       2.30    0.2159
   material*clima               4       32.555556        8.138889       0.54    0.7187

                                      The SAS System    09:38 Thursday, April 25, 2002 122

                                   The ANOVA Procedure

Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     183.7505556      14.1346581     170.18    <.0001

   Error                        4       0.3322222       0.0830556

   Corrected Total             17     184.0827778

                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.998195      3.188374      0.288194        9.038889

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1       8.9605556       8.9605556     107.89    0.0005
   material                     2       8.5077778       4.2538889      51.22    0.0014
   clima                        2     164.2077778      82.1038889     988.54    <.0001
   adhesivo*material            2       0.1144444       0.0572222       0.69    0.5532
   adhesivo*clima               2       1.7877778       0.8938889      10.76    0.0246
   material*clima               4       0.1722222       0.0430556       0.52    0.7299

                                      The SAS System    09:38 Thursday, April 25, 2002 123

                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                       13     127.6184722       9.8168056       9.81    0.0201
```

```
   Error                        4       4.0022222       1.0005556

   Corrected Total             17     131.6206944


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.969593      16.48055      1.000278         6.069444


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      3.42347222      3.42347222       3.42    0.1380
   material                     2     90.37194444     45.18597222      45.16    0.0018
   clima                        2      0.35111111      0.17555556       0.18    0.8452
   adhesivo*material            2     26.11194444     13.05597222      13.05    0.0177
   adhesivo*clima               2      1.39111111      0.69555556       0.70    0.5507
   material*clima               4      5.96888889      1.49222222       1.49    0.3540

                                      The SAS System    09:38 Thursday, April 25, 2002 124

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF

                              material           1    Cork


                               Number of observations    6

                                      The SAS System    09:38 Thursday, April 25, 2002 125

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

Dependent Variable: densidad

                                             Sum of
   Source                      DF           Squares     Mean Square    F Value    Pr > F

   Model                        1     104.1666667     104.1666667       1.09    0.3549

   Error                        4     381.3333333      95.3333333

   Corrected Total              5     485.5000000


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.214555      1.409946      9.763879         692.5000


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     104.1666667     104.1666667       1.09    0.3549




                                          The SAS System    09:38 Thursday, April 25, 2002 126

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   95.33333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        22.134


                Means with the same letter are not significantly different.
```

```
               Tukey Grouping         Mean      N    adhesivo

                            A      696.667      3    TF
                            A
                            A      688.333      3    UF
                                     The SAS System    09:38 Thursday, April 25, 2002 127

------------------------------------ material=Fresh ------------------------------------

                                  The ANOVA Procedure

                                Class Level Information

                             Class         Levels    Values

                             adhesivo           2    TF UF

                             material           1    Fresh

                              Number of observations    6
                                     The SAS System    09:38 Thursday, April 25, 2002 128

------------------------------------ material=Fresh ------------------------------------

                                  The ANOVA Procedure

Dependent Variable: densidad

                                          Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      793.500000      793.500000       9.82    0.0351

   Error                        4      323.333333       80.833333

   Corrected Total              5     1116.833333


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.710491      1.271974      8.990736         706.8333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     793.5000000     793.5000000       9.82    0.0351




                                         The SAS System    09:38 Thursday, April 25, 2002 129

------------------------------------ material=Fresh ------------------------------------

                                  The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                         higher Type II error rate than REGWQ.


                      Alpha                                   0.05
                      Error Degrees of Freedom                   4
                      Error Mean Square                   80.83333
                      Critical Value of Studentized Range  3.92650
                      Minimum Significant Difference        20.382


                Means with the same letter are not significantly different.


               Tukey Grouping         Mean      N    adhesivo

                            A      718.333      3    UF

                            B      695.333      3    TF
                                     The SAS System    09:38 Thursday, April 25, 2002 130

---------------------------------- material=Recyclin ----------------------------------
```

```
                                   The ANOVA Procedure

                                 Class Level Information

                            Class         Levels    Values

                            adhesivo           2    TF UF

                            material           1    Recyclin

                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 131
----------------------------------- material=Recyclin ------------------------------------
                                   The ANOVA Procedure

Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     2521.500000     2521.500000      36.02    0.0039

   Error                        4      280.000000       70.000000

   Corrected Total              5     2801.500000


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.900054      1.190975      8.366600         702.5000


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     2521.500000     2521.500000      36.02    0.0039




                                           The SAS System    09:38 Thursday, April 25, 2002 132
----------------------------------- material=Recyclin ------------------------------------
                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                         70
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        18.967


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A       723.000      3    UF

                            B       682.000      3    TF
                                      The SAS System    09:38 Thursday, April 25, 2002 133
-------------------------------------- adhesivo=TF ---------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information

                       Class         Levels    Values

                       adhesivo           1    TF

                       material           3    Cork Fresh Recyclin
```

```
                              Number of observations    9
                                     The SAS System    09:38 Thursday, April 25, 2002 134
-------------------------------------- adhesivo=TF --------------------------------------
                                  The ANOVA Procedure

Dependent Variable: densidad

                                              Sum of
   Source                      DF           Squares     Mean Square    F Value    Pr > F

   Model                        2        394.666667      197.333333       1.67    0.2652

   Error                        6        709.333333      118.222222

   Corrected Total              8       1104.000000


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.357488      1.572759      10.87300         691.3333


   Source                      DF          Anova SS     Mean Square    F Value    Pr > F

   material                     2       394.6666667     197.3333333       1.67    0.2652




                                         The SAS System    09:38 Thursday, April 25, 2002 135
-------------------------------------- adhesivo=TF --------------------------------------
                                  The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   118.2222
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        27.238


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    material

                            A       696.667      3    Cork
                            A
                            A       695.333      3    Fresh
                            A
                            A       682.000      3    Recyclin
                                     The SAS System    09:38 Thursday, April 25, 2002 136
-------------------------------------- adhesivo=UF --------------------------------------
                                  The ANOVA Procedure


                                Class Level Information

                       Class         Levels    Values

                       adhesivo           1    UF

                       material           3    Cork Fresh Recyclin


                              Number of observations    9
                                     The SAS System    09:38 Thursday, April 25, 2002 137
-------------------------------------- adhesivo=UF --------------------------------------
                                  The ANOVA Procedure
```

```
Dependent Variable: densidad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     2123.555556     1061.777778      23.14    0.0015

   Error                        6      275.333333       45.888889

   Corrected Total              8     2398.888889


                  R-Square     Coeff Var      Root MSE    densidad Mean

                  0.885225      0.954253      6.774134         709.8889


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     2123.555556     1061.777778      23.14    0.0015



                                           The SAS System    09:38 Thursday, April 25, 2002 138

------------------------------------- adhesivo=UF ---------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for densidad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   45.88889
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference         16.97


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    material

                            A       723.000      3    Recyclin
                            A
                            A       718.333      3    Fresh

                            B       688.333      3    Cork
                                      The SAS System    09:38 Thursday, April 25, 2002 139

---------------------------------------- clima=1 ----------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF

                              clima              1    1


                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 140

---------------------------------------- clima=1 ----------------------------------------

                                   The ANOVA Procedure

Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      0.88166667      0.88166667       1.61    0.2729

   Error                        4      2.18666667      0.54666667

   Corrected Total              5      3.06833333
```

```
                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.287344      13.48393      0.739369        5.483333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      0.88166667      0.88166667       1.61    0.2729


                                           The SAS System    09:38 Thursday, April 25, 2002 141
---------------------------------------- clima=1 ----------------------------------------
                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for humedad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.546667
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        1.6761


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        5.8667      3    TF
                            A
                            A        5.1000      3    UF
                                      The SAS System    09:38 Thursday, April 25, 2002 142
---------------------------------------- clima=2 ----------------------------------------
                                   The ANOVA Procedure


                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF

                              clima              1    2


                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 143
---------------------------------------- clima=2 ----------------------------------------
                                   The ANOVA Procedure

Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      2.16000000      2.16000000       2.74    0.1732

   Error                        4      3.15333333      0.78833333

   Corrected Total              5      5.31333333


                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.406524      10.12792      0.887881        8.766667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      2.16000000      2.16000000       2.74    0.1732
```

```
                                         The SAS System    09:38 Thursday, April 25, 2002 144

--------------------------------------- clima=2 ----------------------------------------

                                  The ANOVA Procedure

                      Tukey's Studentized Range (HSD) Test for humedad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.788333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        2.0128


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        9.3667      3    TF
                            A
                            A        8.1667      3    UF
                                    The SAS System    09:38 Thursday, April 25, 2002 145

--------------------------------------- clima=3 ----------------------------------------

                                  The ANOVA Procedure


                                Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF

                              clima              1    3


                               Number of observations    6
                                    The SAS System    09:38 Thursday, April 25, 2002 146

--------------------------------------- clima=3 ----------------------------------------

                                  The ANOVA Procedure

Dependent Variable: humedad

                                              Sum of
   Source                      DF          Squares     Mean Square    F Value    Pr > F

   Model                        1       7.70666667      7.70666667       8.14    0.0462

   Error                        4       3.78666667      0.94666667

   Corrected Total              5      11.49333333


                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.670534      7.561927      0.972968        12.86667


   Source                      DF          Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1       7.70666667      7.70666667       8.14    0.0462




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--------------------------------------- clima=3 ----------------------------------------

                                  The ANOVA Procedure

                      Tukey's Studentized Range (HSD) Test for humedad
```

```
  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.

                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.946667
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        2.2057


                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    adhesivo

                            A       14.0000      3    TF

                            B       11.7333      3    UF
                                      The SAS System    09:38 Thursday, April 25, 2002 148
-------------------------------------- adhesivo=TF ---------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           1    TF

                              clima              3    1 2 3

                               Number of observations    9
                                      The SAS System    09:38 Thursday, April 25, 2002 149
-------------------------------------- adhesivo=TF ---------------------------------------
                                   The ANOVA Procedure

Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2      99.8688889      49.9344444      56.82    0.0001

   Error                        6       5.2733333       0.8788889

   Corrected Total              8     105.1422222

                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.949846      9.620772      0.937491        9.744444

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   clima                        2     99.86888889     49.93444444      56.82    0.0001




                                          The SAS System    09:38 Thursday, April 25, 2002 150
-------------------------------------- adhesivo=TF ---------------------------------------
                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for humedad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.

                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   0.878889
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        2.3485
```

```
               Means with the same letter are not significantly different.

                Tukey Grouping          Mean      N    clima

                             A       14.0000      3    3

                             B        9.3667      3    2

                             C        5.8667      3    1
                                      The SAS System    09:38 Thursday, April 25, 2002 151
-------------------------------------- adhesivo=UF ---------------------------------------
                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           1    UF

                              clima              3    1 2 3

                               Number of observations    9
                                      The SAS System    09:38 Thursday, April 25, 2002 152
-------------------------------------- adhesivo=UF ---------------------------------------
                                   The ANOVA Procedure

Dependent Variable: humedad

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     66.12666667     33.06333333      51.48    0.0002

   Error                        6      3.85333333      0.64222222

   Corrected Total              8     69.98000000

                   R-Square     Coeff Var      Root MSE    humedad Mean

                   0.944937      9.616652      0.801388        8.333333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   clima                        2     66.12666667     33.06333333      51.48    0.0002


                                          The SAS System    09:38 Thursday, April 25, 2002 153
-------------------------------------- adhesivo=UF ---------------------------------------
                                   The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for humedad

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   6
                       Error Mean Square                   0.642222
                       Critical Value of Studentized Range  4.33902
                       Minimum Significant Difference        2.0076


               Means with the same letter are not significantly different.

                Tukey Grouping          Mean      N    clima

                             A       11.7333      3    3

                             B        8.1667      3    2

                             C        5.1000      3    1
```

```
                                      The SAS System    09:38 Thursday, April 25, 2002 154

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF

                              material           1    Cork


                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 155

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      2.16000000      2.16000000       5.63    0.0765

   Error                        4      1.53333333      0.38333333

   Corrected Total              5      3.69333333


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.584838      16.58409      0.619139         3.733333


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      2.16000000      2.16000000       5.63    0.0765




                                          The SAS System    09:38 Thursday, April 25, 2002 156

------------------------------------- material=Cork -------------------------------------

                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.383333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        1.4036


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        4.3333      3    TF
                            A
                            A        3.1333      3    UF
                                      The SAS System    09:38 Thursday, April 25, 2002 157

------------------------------------- material=Fresh ------------------------------------

                                   The ANOVA Procedure


                                 Class Level Information

                              Class         Levels    Values

                              adhesivo           2    TF UF
```

```
                              material           1    Fresh

                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 158
------------------------------------- material=Fresh -------------------------------------
                                   The ANOVA Procedure

Dependent Variable: rugosida

                                           Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1      0.28166667      0.28166667       0.30    0.6153

   Error                        4      3.80666667      0.95166667

   Corrected Total              5      4.08833333

                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.068895      18.12138      0.975534         5.383333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1      0.28166667      0.28166667       0.30    0.6153



                                          The SAS System    09:38 Thursday, April 25, 2002 159
------------------------------------- material=Fresh -------------------------------------
                                   The ANOVA Procedure

                    Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                          higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   0.951667
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        2.2115


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        5.6000      3    TF
                            A
                            A        5.1667      3    UF
                                      The SAS System    09:38 Thursday, April 25, 2002 160
----------------------------------- material=Recyclin ------------------------------------
                                   The ANOVA Procedure


                                 Class Level Information

                            Class         Levels    Values

                            adhesivo           2    TF UF

                            material           1    Recyclin


                               Number of observations    6
                                      The SAS System    09:38 Thursday, April 25, 2002 161
----------------------------------- material=Recyclin ------------------------------------
                                   The ANOVA Procedure
```

```
Dependent Variable: rugosida

                                         Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        1     27.09375000     27.09375000      17.00    0.0146

   Error                        4      6.37333333      1.59333333

   Corrected Total              5     33.46708333


                  R-Square     Coeff Var      Root MSE    rugosida Mean

                  0.809564      13.88385      1.262273         9.091667


   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   adhesivo                     1     27.09375000     27.09375000      17.00    0.0146




                                          The SAS System    09:38 Thursday, April 25, 2002 162

----------------------------------- material=Recyclin -----------------------------------

                                    The ANOVA Procedure

                     Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                       Alpha                                   0.05
                       Error Degrees of Freedom                   4
                       Error Mean Square                   1.593333
                       Critical Value of Studentized Range  3.92650
                       Minimum Significant Difference        2.8615


                Means with the same letter are not significantly different.


               Tukey Grouping          Mean      N    adhesivo

                            A        11.217      3    UF

                            B         6.967      3    TF
                                     The SAS System    09:38 Thursday, April 25, 2002 163

-------------------------------------- adhesivo=TF --------------------------------------

                                    The ANOVA Procedure

                                  Class Level Information

                       Class         Levels    Values

                       adhesivo           1    TF

                       material           3    Cork Fresh Recyclin


                              Number of observations    9
                                     The SAS System    09:38 Thursday, April 25, 2002 164

-------------------------------------- adhesivo=TF --------------------------------------

                                    The ANOVA Procedure

Dependent Variable: rugosida

                                         Sum of
   Source                      DF         Squares     Mean Square    F Value    Pr > F

   Model                        2     10.40666667      5.20333333       5.07    0.0513

   Error                        6      6.15333333      1.02555556

   Corrected Total              8     16.56000000
```

```
               R-Square     Coeff Var      Root MSE    rugosida Mean

               0.628422      17.97687      1.012697         5.633333

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     10.40666667      5.20333333       5.07    0.0513




                                         The SAS System    09:38 Thursday, April 25, 2002 165

-------------------------------------- adhesivo=TF --------------------------------------

                                   The ANOVA Procedure

                  Tukey's Studentized Range (HSD) Test for rugosida

  NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                        higher Type II error rate than REGWQ.


                    Alpha                                   0.05
                    Error Degrees of Freedom                   6
                    Error Mean Square                   1.025556
                    Critical Value of Studentized Range  4.33902
                    Minimum Significant Difference        2.5369


              Means with the same letter are not significantly different.


                Tukey Grouping          Mean      N    material

                         A        6.9667      3    Recyclin
                         A
                    B    A        5.6000      3    Fresh
                    B
                    B             4.3333      3    Cork
                                     The SAS System    09:38 Thursday, April 25, 2002 166

-------------------------------------- adhesivo=UF --------------------------------------

                                   The ANOVA Procedure

                                 Class Level Information

                    Class         Levels    Values

                    adhesivo           1    UF

                    material           3    Cork Fresh Recyclin

                          Number of observations    9
                                     The SAS System    09:38 Thursday, April 25, 2002 167

-------------------------------------- adhesivo=UF --------------------------------------

                                   The ANOVA Procedure

Dependent Variable: rugosida

                                            Sum of
   Source                      DF          Squares     Mean Square    F Value    Pr > F

   Model                        2     106.0772222      53.0386111      57.24    0.0001

   Error                        6       5.5600000       0.9266667

   Corrected Total              8     111.6372222


               R-Square     Coeff Var      Root MSE    rugosida Mean

               0.950196      14.79713      0.962635         6.505556

   Source                      DF        Anova SS     Mean Square    F Value    Pr > F

   material                     2     106.0772222      53.0386111      57.24    0.0001
```

```
------------------------------------- adhesivo=UF -------------------------------------

                              The ANOVA Procedure

                  Tukey's Studentized Range (HSD) Test for rugosida

 NOTE: This test controls the Type I experimentwise error rate, but it generally has a
                         higher Type II error rate than REGWQ.


                     Alpha                                   0.05
                     Error Degrees of Freedom                   6
                     Error Mean Square                   0.926667
                     Critical Value of Studentized Range  4.33902
                     Minimum Significant Difference        2.4115


                Means with the same letter are not significantly different.

               Tukey Grouping          Mean      N    material

                            A       11.2167      3    Recyclin

                            B        5.1667      3    Fresh
                            B
```

## Curriculum vitae

### Personal data

| | |
|---|---|
| Forename, surname: | Aldo Evandro Rolleri Saavedra |
| Date of birth: | 10.09.1966 |
| Place of birth: | Tome, Chile |
| Parents: | Italo Rolleri, Ines Saavedra |
| Family status: | married |
| Nationality: | Chilean |

### Education

| | |
|---|---|
| 1971 - 1983: | Instituto de Humanidades Alfredo Silva Santiago (elementary school, junior high school and secondary school), Concepción, Chile |
| 1985 – 1992: | Student at the Faculty of Forestry, University Austral de Chile, Valdivia, Chile |
| 1992: | graduated with the degree of Forestry engineer |
| 1999 – 2001: | Student at the University Politecnica de Valencia, Spain |
| 2001: | graduated with the degree of Master in design and products engineering |
| 2000 – 2003: | Ph. D. student at the Faculty of Forest Sciences and Forest Ecology, Institute of wood biology and wood technology, Georg-August-University Göttingen, Germany |

### Professional experience

| | |
|---|---|
| 1993 – 1999: | Assistance researcher at the Institute of technology and wood products, Faculty of Forestry, University Austral de Chile, Valdivia, Chile |