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Use of radiofrequency heating to glue wood products with polyvinyl acetate adhesives

Adhesive layers perpendicular to the electric field

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Aim and introduction to the Handbook

1. Aim and introduction to the Handbook

The present handbook wants to be a practical guide for operators using radiofrequency heating to glue wood and wood-based substrates (for instance, a panel to a veneer, or several panels among them) by using polyvinyl acetate (PVAc) adhesives.

In wood industry several heating techniques are commonly used in order to speed up the process of product setting, among them hot-pressing, which has been extensively treated in specific handbooks and practical guides.

However, in addition to hot-pressing, commonly used heating techniques include systems based on the transformation of electromagnetic energy in heat. In turn, these latter include radiofrequency-based technologies and are associated with electromagnetic radiation interacting with dielectric materials, which are able to absorb this type of radiation (the principles at the basis of this process are introduced in Chapter 2).

Differently from hot-pressing, only a few handbooks deal with the use of radiofrequency for bonding wood-based materials, and very few of them with the specific use of PVAc glues.

Therefore, the present handbook wants to contribute in filling this gap (which is mostly of practical, more than theoretical, type), giving useful information to industries and enterprises using PVAc glues in their processes, to help in the completion of the complex frame of knowledge already present in this sector. Accordingly, the handbook will show that all types of PVAc dispersions can be virtually processed with radiofrequencies to produce heat able to promote water evaporation. It is worthwhile evidencing that in commercially available PVAc adhesives there is no need of post-adding salts or similar compounds to increase the dispersion electrical conductivity.

Depending on the specific manufacture process, three different radiofrequency systems are used in wood industry (Figure 1.1):

- normal (or perpendicular) heating,
- parallel heating,
- punctual heating.

In the first case (normal heating), both the substrate and the adhesive layer are positioned perpendicular to the electric field (and hence the metal plates connected to the radiofrequency generator are parallel to the adhesive layers). For instance, this type of process is used in veneering and plywood manufacture.

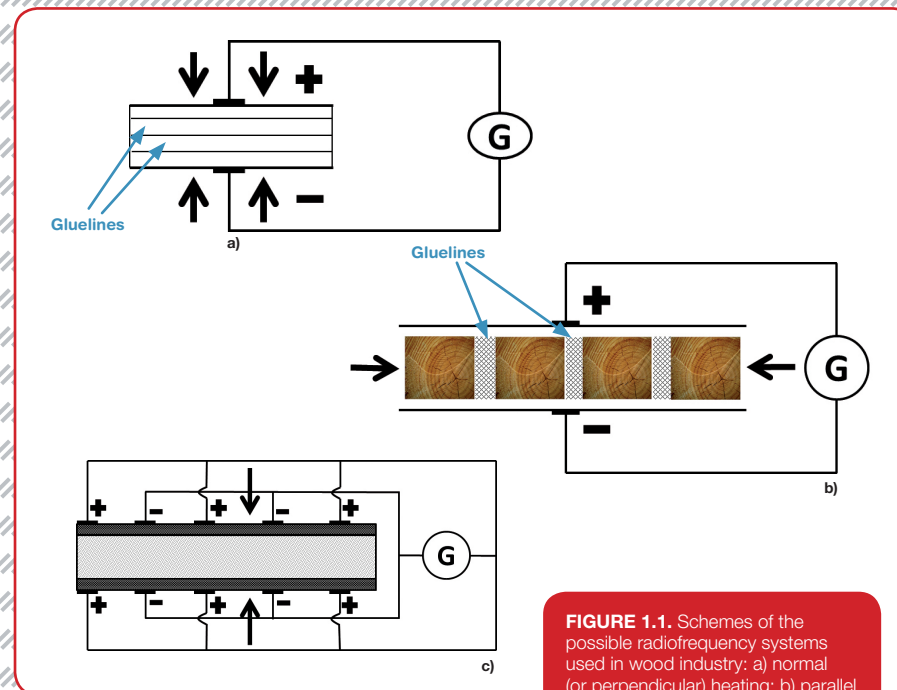


FIGURE 1.1. Schemes of the possible radiofrequency systems used in wood industry: a) normal (or perpendicular) heating; b) parallel heating; c) punctual heating.

In parallel heating, the electromagnetic field is parallel to the glue lines (and hence metal plates are perpendicular to adhesive layers). This process is mostly used in solid wood panels manufacture.

In punctual heating, the radiofrequency is only applied in selected areas, and not on the whole bondline. This allows the gluing of large surfaces or of parts where the geometry is not regular, and it is mostly used in panels edge gluing. In the present handbook only the normal radiofrequency heating is considered.

Radiofrequency heating is advantageous over alternative methods, such as hot-pressing, in accelerating the adhesive drying because of the higher efficiency of the technique, which is able to selectively heat the glue line when still wet. On the other hand, only a relatively limited temperature increase in a dry substrate is induced (in practice, it is only warmed after the bondline has set). The theoretical reasons of such a behaviour will be also explained in Chapter 2. In hot-pressing systems, the substrates to be glued (for instance, panels) need to be also heated before glue lines can be dried. This is due the fact that heat

passes by convection from hot plates to adjacent layers, and from these ones to the underneath ones. In contrast, in the case of radiofrequency heating, radiation is able to deeply penetrate within the glued assembly, directly drying gluelines without firstly heating the supports as well. The dramatic rate increase of bondline temperature in radiofrequency heating compared to hot-pressing will be considered in Chapter 3.

In fact, as it will be detailed in the following chapters, experimental tests on assemblies glued with PVAc adhesives put in evidence a dramatic decrease in pressing times necessary to reach suitable performances when passing from the room temperature bonding procedure to hot pressing and finally to radiofrequency heating. Instead, proper mechanical characteristics are reached independently on the considered drying procedure. This confirms that, generally speaking, the various processes only affect the time needed for drying, and not the overall adhesive performance. The aspects related to the effects of radiofrequency heating on the mechanical characteristics of PVAc-glued assemblies, together with the evaluation of the glue amount and of substrate moisture content on the final joints properties, are considered in Chapters 4-6. Moreover, the effect of radiofrequency heating in determining the failure pattern in bonded joints is considered in Chapter 7. In this specific case, the term “failure pattern” practically refers to the quantity of wood fibres (as opposite to the visible glue layer) that is broken after the joint opening owing to failure. In addition, in order to appreciably reduce pressing times by also keeping comparable (or even better) mechanical performances related to bonds tested in both normal and even wet conditions (this latter aspect is expressly considered in Chapter 8), the higher efficiency of radiofrequency heating also allows appreciable savings in terms of power consumption during the bonding process. This aspect will be explained in Chapter 9. Finally, a brief outline about the questions concerning the protection issues related to the use of radiofrequency heating is reported in Chapter 10.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The present handbook wants to fill the gap of practical knowledge for industries and enterprises using polyvinyl acetate dispersions to glue wood and wood-based products
- Only normal radiofrequency heating (both substrate and adhesive layer positioned perpendicular to the electric field) is considered

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

PVAc: Polyvinyl Acetate Dispersion

2.

Principles at the basis of radiofrequency heating

2. Principles at the basis of radiofrequency heating

GENERAL PRINCIPLES

The field of application of radiofrequency intended for wood adhesives is based on the dielectric heating induced by electromagnetic waves. In fact, the interaction of materials with electromagnetic radiation can be differentiated according to three different processes: absorption, transmission, and reflection (Figure 2.1). Materials able to absorb radiation are called dielectrics, and those showing intense absorption can develop high quantities of heat under irradiation (which means that they appreciably increase internal temperature). On the opposite, in materials whose surface is able to reflect radiation, only a limited (or even negligible) part of energy is absorbed and therefore they do not highlight any temperature increase. Electrically conductive materials, such as metals, belong to this latter type (and hence they show surface reflection), whereas polyvinyl acetate (PVAc) dispersions evidence absorption by irradiation.

The dielectric characteristic of materials are usually related to the presence of polar groups in their molecular structure. These groups constitute electrical dipoles. Of course, the example of water molecules is the easiest to understand: water molecules are natural electrical dipoles (owing to the different electronegativity between oxygen and hydrogen atoms). However, dipoles may be either a natural feature of dielectric materials or be induced by intense electric field, which is able to distort the interatomic distances in molecules, thus producing temporary dipoles in selected materials.

In general, polar substances strongly interact with radiofrequency, whereas completely apolar compounds sharpen weak interactions with electromagnetic radiation.

If such dipoles have sufficient freedom to move, they tend to align with an existing (externally generated) electric field, through molecular rotation (complete or partial, depending on the molecular mobility). In fact, the applied electric field aligns the randomly oriented dipoles in a direction opposite to that of the same electric field (Figure 2.2). Of course, if the electric field varies its intensity and direction with time, the dipole orientation will also tend to vary accordingly. However, if the variation frequency is sufficiently low, dipoles follow these variations keeping well-aligned to the electric field: in this case, the irradiated material will be transparent to radiation. On the other hand, a very quick inversion of the electric field causes the chaotic, not-aligned with

FIGURE 2.1. Schematic drawing evidencing the possible interaction between different materials and electromagnetic radiation. From left to right: absorption, transmission, reflection.

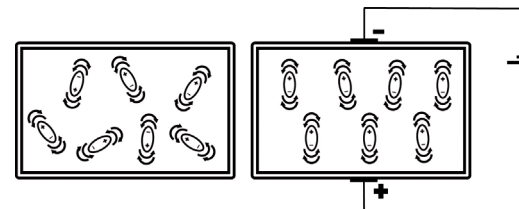
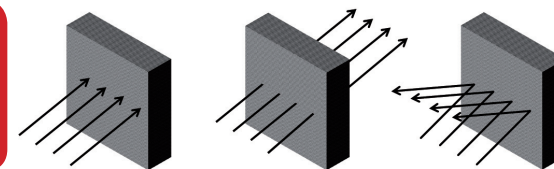


FIGURE 2.2. Schematic drawing representing the molecular rotations and movements in dielectrics due to the presence of an alternating, externally applied, electric field. These continuous movements cause heating in the material.

the electric field, rotation (complete or partial) of electrical dipoles. As a consequence, an internal friction is produced among polar molecules, which is able to produce direct and uniform heating of the interested material. In that way, energy associated to the electric field is transformed in kinetic energy and therefore in heat.

ELECTRICAL PARAMETERS

To quantify this phenomenon in electromagnetic fields, a series of parameters are usually considered. These parameters include the *dielectric constant*, ϵ' , the *dielectric loss*, ϵ'' , and the *loss factor*, usually referred as $\tan \delta$: ϵ' is related to the amount of energy (supplied by the electric field) stored in the material, due to the ordered configuration represented by the dipoles aligned with the electric field; in contrast, ϵ'' is a measure of the energy that can be dissipated by the same material (usually in form of heat, as described in previous section); $\tan \delta$ is the ratio between ϵ'' and ϵ' :

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

2.1

By definition, a high value of the ratio indicates a higher dissipated energy compared to the stored one. Therefore, $\tan \delta$ is a direct measurement of the ability of a material to absorb energy by irradiation. This parameter is associated to the relaxation time of the material molecules immersed within the electric field, and it is perhaps the most important parameter to be considered for dielectric heating.

As it can be easily imagined, $\tan \delta$ depends on both molecular mass and volume of the material, on the nature of its constituting functional groups, but also on the frequency of the alternating electric field. At the same time, it also strongly depends on both temperature (which affects the kinetic energy of molecules) and moisture content (which increases the presence of dipoles within materials). Considering that the loss factor is dependent upon the conditions under which it is measured, data available on handbooks should be viewed just as an indication (Table 2.1).

In general, a loss factor between approximately 0.01 and 1 denotes a material able to appropriately heat in an alternating electric field. If $\tan \delta$ is too low, heating takes place slowly and heat losses could even prevent the attainment of the desired temperature. If the loss factor is too high, the material would arc to the work electrode.

Water based polyvinyl acetate (PVAc) dispersions used as wood adhesives are widely processed with dielectric heating systems. In fact, the adhesive loss factor, $\tan \delta$, for PVAc dispersions is higher (thanks to the presence of considerable amounts of water) than that for sufficiently dry wood and wood-based materials and, as a consequence, the interaction of electromagnetic radiation with a PVAc-glued assembly (substrate – adhesive – substrate), induces an easier heat dissipation into the PVAc glue compared to the substrate.

Material	Loss tangent x 10 ³	Frequency	Remarks
Water	40	1 MHz	
	5	100 MHz	distilled
	157	3 GHz	
	157	3 GHz	distilled
Cellulose paper fibres	5	50 Hz	calculated
Paper fibres	50	1 MHz	
Paper pressboard	8	50 Hz	dry
Walnut, 0% m.c.	35	10 MHz	
Walnut, 17% m.c.	140	10 MHz	
Beech, 16% m.c.	60-80	1 MHz/100 MHz	d=0.62
Birch, 10% m.c.	40-80	1 MHz/100 MHz	d=0.63
Mahogany	25	1 MHz/3 GHz	
Scots pine, 15% m.c.	60-95	1 MHz/100 MHz	d=0.61
Polyethylene	0.2-0.3	50 Hz/3 GHz	
Polypropylene	0.5	50 Hz/1 MHz	
Polystyrene	0.2-0.5	50 Hz/1 GHz	
Polyamides (e.g. Nylon)	20	50 Hz/100 MHz	
Polymethylmethacrylate	60-6	50 Hz/100 MHz	
Polyvinyl chloride	20-10	50 Hz/100 MHz	unplasticized
	60	1 MHz/10 MHz	plasticized
Melamine resin	40	3 GHz	
Phenolic resin	50	1 MHz	fabric filled
	30-80	1 MHz/1 GHz	paper filled
Urea resin	30	1 MHz	paper filled
Polyvinyl acetate	50	1 MHz/10 MHz	plasticized

TABLE 2.1. Loss tangent values (at 20°C) of selected materials. In the table, *m.c.* stands for moisture content, *d* stands for density.

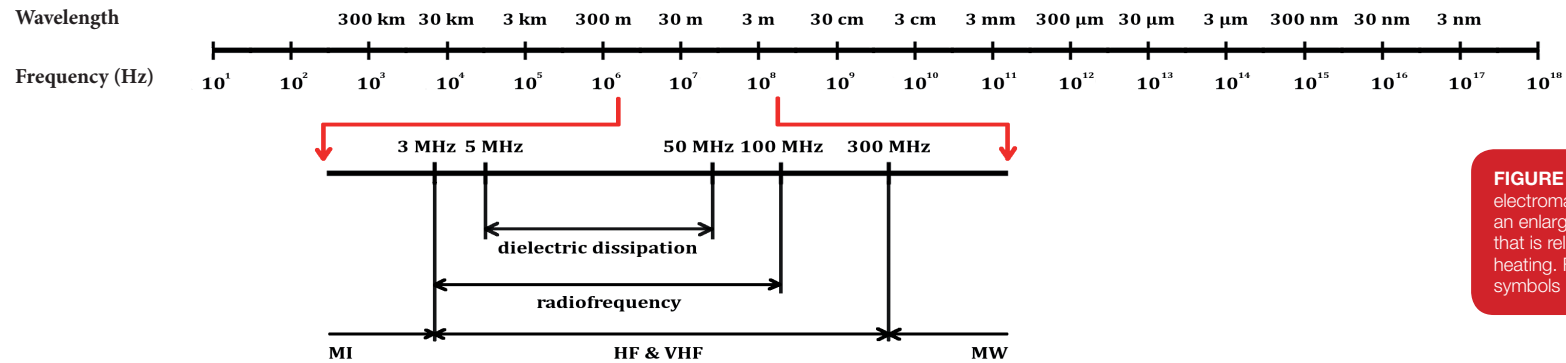


FIGURE 2.3. The electromagnetic spectrum with an enlargement of the range that is relevant for dielectric heating. For the meaning of symbols refer to the text.

INDUSTRIAL GENERATORS

In the industry, all frequency ranges are generally used, this choice depending on the specific material to be heated. For instance, magnetic induction (MI) (frequency in the range 50 Hz – 3 MHz) is normally used in Iron, Steel and Electronics industry, while microwaves (MW) (frequency above 300 MHz and below 300 GHz) are mainly used in Paper manufacture, Food processing and Coating industry.

On the other hand, high (and very high) frequency heating (HF and VHF, frequency in the range 3 MHz – 300 MHz) is used in Plastic or Textile and in the Wood industries. More in detail, for applications in wood and wood-based products radiofrequency heating is widely adopted. This term generally refers to the frequency range between 3 – 100 MHz; however, the *dielectric dissipation* usually refers to frequency in the range 5 – 50 MHz, and it is the most largely adopted in wood industry (Figure 2.3). Industrial systems based on dielectric dissipation are composed by (Figure 2.4):

- a power unit (or generator),
- an applicator device.

The *power unit* is able to increase both voltage and frequency of the avail-

able on-line power. In the past this was mostly accomplished through triode oscillators using vacuum tubes. However, they are costly and have limited life. Nowadays, solid-state power amplifiers are an increasingly widespread technology.

The *applicator device* is normally constituted by two faced metal surfaces between which the substrates to be bonded (for instance wood panels to be veneered) are positioned. In such a way, a plane electrical condenser (or, more correctly, a capacitor) is constituted (Figure 2.5). Capacitors are devices where electric charges are accumulated in the constituting plates, which are able to generate electric fields in the space in between. Wave guides are used to transfer the generated energy to the applicator, whereas an hydraulic press device is used to keep the assembly under pressure during heating. It clearly appears from above that the field intensity (which is proportional to the applied voltage) is able to appreciably affect dielectric heating.

At the same time, for the electrode configuration considered in the present handbook (bonding plane perpendicular to the electric field), also the volume of the specific dielectric material to be heated represents a factor of importance.

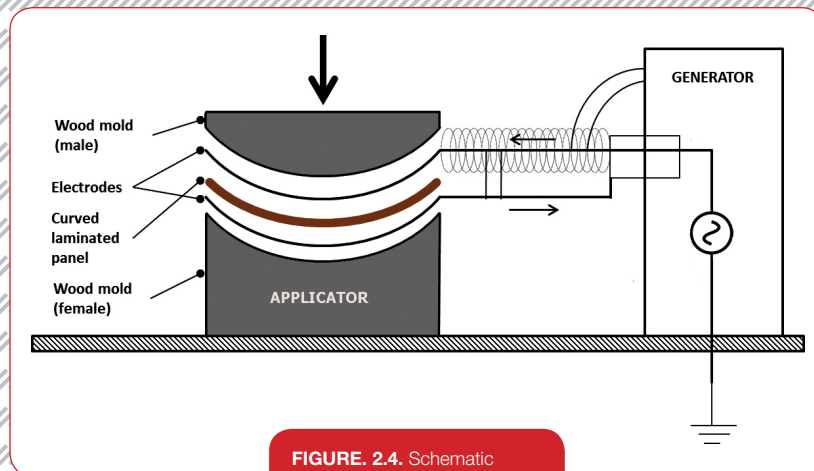


FIGURE 2.4. Schematic example of industrial systems used for dielectric heating.

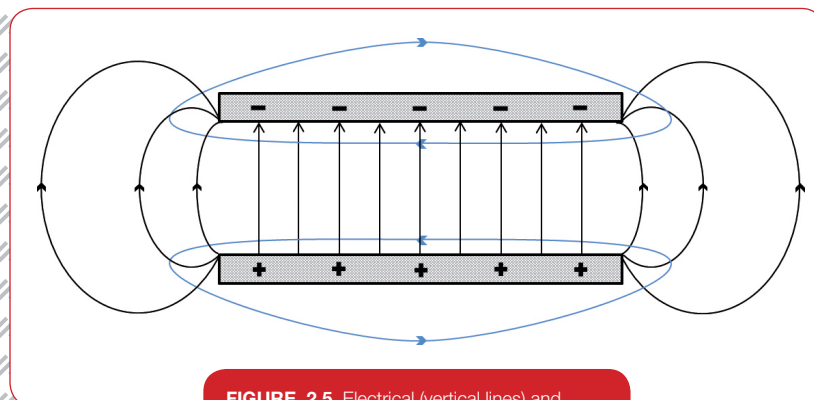


FIGURE 2.5. Electrical (vertical lines) and magnetic (horizontal, closed lines) field lines in a plane capacitor. The electric field is constant and homogeneously distributed between the plates, whereas it is distorted (and even strongly distorted) close to the capacitor edges.

The unit energy (that is, energy for unit volume) supplied by the electromagnetic generator to materials is:

$$E = Q \cdot V \quad 2.2$$

where V is the voltage (expressed in Volt) and Q is the electric charge density value (usually expressed in C/cm^3 or C/m^3). From the basic knowledge of electric fields, it is known that the electric charge is given by the product between electric current and time (this expression comes from the same definition of electric current):

$$Q = \frac{A \cdot t}{Vol} \quad 2.3$$

where Vol is the volume interested by the electric field. For instance, in the case of plane capacitors, Vol is the volume between the two condenser plates (where the electric field is developed).

In the case of radiofrequency generators, the same expression 2.3 can be put in the following form:

$$Q = \frac{\text{Anodic current} \cdot \text{Exposure time}}{\text{Assembly volume}} \quad 2.4$$

which represents the electric charge density (proportional to the unit energy, according to expression 2.2) supplied by the radiofrequency generator to an assembly to be glued (Q is usually expressed in C/cm^3).

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The presence of dipoles (which can be either already present in the molecular structure or induced by the externally applied electric field) is responsible for the dielectric characteristics of materials
- Heating is due to molecular friction among the dipoles
- PVAc dispersions dissipate energy much easily compared to sufficiently dry wood-based materials

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

HF: High Frequency - **MI:** Magnetic Induction - **MW:** MicroWaves - **PVAc:** Polyvinyl Acetate Dispersion - **VHF:** Very High Frequency

3.

**Effect of
radiofrequency
exposure
on the glue
line
temperature**

3. Effect of radiofrequency exposure on the glueline temperature

Heating by radiofrequency is a very effective heating system when polar substances (such as water-based emulsions) are used. In the practice, this means that, when temperature is measured as a function of time, it increases much more quickly in joints heated under radiofrequency than in those heated with traditional hot-pressing. This also implies that radiofrequency dramatically decreases the time needed for drying assemblies.

Figure 3.1 shows the glueline temperature vs. time curves for three different 10 mm-thick assemblies glued with Vinavil 2252 M and heated under:

- radiofrequency (RF, green curve);
- hot-pressing with press plates set at 80°C (blue curve);
- hot-pressing with press plates set at 100°C (red curve).

For such measurements, temperature was measured by means of an IR thermometer (mod. OPTRIS LS-PLUS), pointing on a spot of more than 1 mm on the external edge of assembled thin boards, in correspondence of the glue-line. In fact, the use of an online temperature measurement with a thermocouple was prevented by its metallic nature, which reflected the radiation.

Figure 3.1 puts in evidence that:

- in hot-pressed assemblies the glueline temperature is always lower than the press-plates (in the case of both 80°C and 100°C) even after prolonged exposure, whereas glueline temperature during RF exposure reaches higher values;
- the time needed to reach a same temperature level (let's say 70°C) is much shorter with RF irradiation (approx. 1 min) compared to both hot-pressing at 80°C (6 min) and 100°C (3.5 min).

Of course, heating time becomes longer when thicker assemblies have to be prepared. For instance, Figure 3.2 shows the temperature-time curves for 40 mm-thick assemblies (the same colours and combinations as for Figure 3.1 were used). In this case, the time needed to reach 70°C (the same temperature as set before) were: 2.5 min for RF and 30 min for hot-pressing at 100°C, whereas assemblies hot-pressed at 80°C did not reach that temperature even after 60 min heating.

The heating efficiency is lower in thicker joints due to the increased contri-

FIGURE 3.1. Comparison among temperature vs. time curves for assemblies dried under radiofrequency (RF) and hot-pressing (press plates set at 80°C and 100°C). Global assembly thickness: 10 mm.

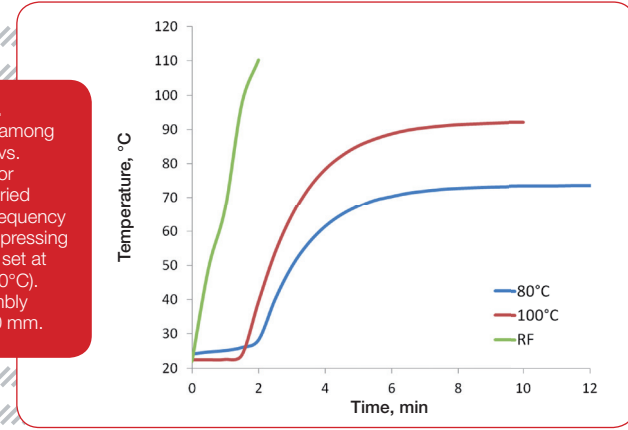


FIGURE 3.2. Temperature vs. time curves for assemblies dried under radiofrequency (RF) and hot-pressing (press plates set at 80°C and 100°C). Global assembly thickness: 40 mm.

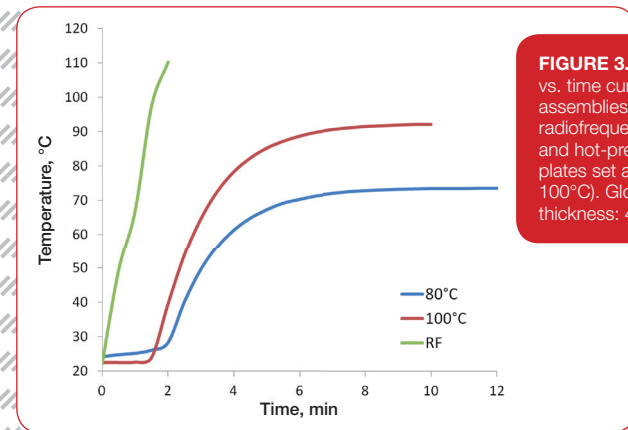
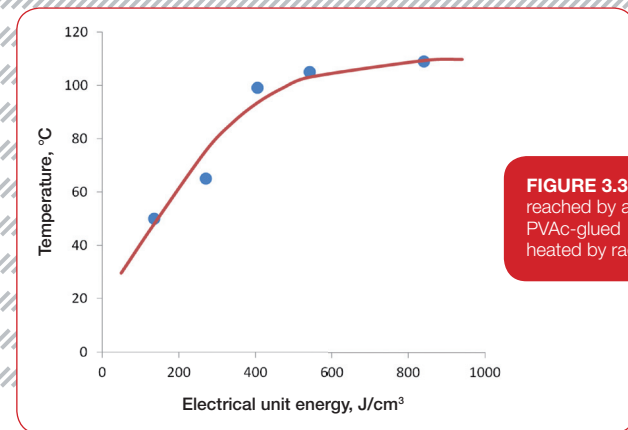


FIGURE 3.3. Temperature reached by a 10 mm-thick PVAc-glued assembly heated by radiofrequency.



bution of the wood-based material constituting the substrate (which in hot-pressing acts in practice as a thermal insulator).

However, the same two figures also underline how the final heating effect of radiofrequency is the same (in acceptable pressing times) also in thick joints: in fact, the same final temperature of 110°C was attained in both cases shown in Figure 3.1 and Figure 3.2.

In addition to the geometrical size of assemblies, the efficiency of radiofrequency heating also depends on the amount of energy supplied to the joints by means of the power unit (generator). Figure 3.3 shows the curve of glue-line temperature reached by a 10 mm-thick assembly glued with PVAc with varying energy levels supplied by the RF generator. In the practice, these energy levels are changed by regulating either the anodic current or the exposure time of assemblies to RF (see expressions 2.2 and 2.4).

It can be seen from Figure 3.3 that the glue-line temperature continuously increases by increasing energy up to approx.¹ 400-500 J/cm³, when its increase rate practically stops (that is, a constant value is reached): this value corresponds to the dispersion boiling. Although this behaviour can be considered as general for PVAc dispersions, nevertheless the specific plateau value depends on the particular used product (it can vary according to solid content, chemical composition etc.). It could be argued, basing on the above considerations, that drying times can be reduced appreciably by increasing the heating supplied to the joints by means of RF. This is true. On the other hand, this occurrence also shows consequences on the bond performances, as it will be better explained in next chapters.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- Temperature increases very quickly under radiofrequency
- Radiofrequency dramatically decreases the time needed for drying assemblies prepared with PVAc
- Longer heating time with thicker assemblies, even in the case of radiofrequency (owing to the increased contribution of the wood-based material, which also dissipates energy)

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

IR: InfraRed Thermometer - **PVAc:** Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency

¹ Considering that also the support is able to absorb energy (due to its moisture content), this value strongly depends on the specific conditions used in the practice (for instance, the material to be glued, the assembly thickness etc.).

4.

Mechanical performances in polyvinyl acetate assemblies dried under radiofrequency heating

4. Mechanical performances in polyvinyl acetate assemblies dried under radiofrequency heating

The most important effect of radiofrequency heating in glued assemblies is the temperature increase into the bondline due to the direct heating of water molecules constituting the dispersion under the oscillating electric field. The present chapter will elucidate the effects of this selective heating on the mechanical performances (in terms of the substrate/adhesive adherence, or *shear strength*, Figure 4.1) of joints glued with PVAc and tested in normal conditions (which means joints continuously kept at 23°C and 50% relative humidity for one week after setting).

Anodic current, A	Exposure time, sec.	Electric charge density, C/cm ³	Voltage, kV	Unit energy, J/cm ³
0.45	30	0.033	4	133
0.7	30	0.052	4	207
1	30	0.074	4	295
0.45	60	0.066	6	399
0.7	60	0.103	6	620
0.45	60	0.066	10	665
1	45	0.111	6	665
0.7	60	0.103	10	1034
1	60	0.148	10	1477

TABLE 4.1. Examples of possible combinations of anodic current and exposure time to get a specific unit energy (or the equivalent electric charge density). Values refer to a 10 mm assembly thickness (equal to the distance between the two capacitor plates) and to a laboratory-scale volume of joints.

The temperature level reached by joints during RF irradiation has been reported in Chapter 3. Considering the high values achieved during exposure, it is important that assemblies decrease their temperature before they can be removed from the press, in order to avoid distortions and early opening of joints. In fact, PVAc adhesives possess limited mechanical properties at high temperatures. Specific tests showed that 6 min are sufficient in 10 mm-thick flat assemblies. Longer times are needed in thicker assemblies or in different press configurations (for instance, in the case of not-flat assemblies, where the bondline is subjected to high stress immediately after the pressure release). In those cases, specific tests to establish the correct adhesive cooling time must be carried out.

Mechanical data reported in present chapter have been obtained after:

- 40 min from RF irradiation (this is the minimum time needed to let the side of a 10 mm-thick assembly reach the room temperature, and it represents a short “conditioning”, or waiting, time²);
- 7 days from irradiation (this value represents a long “conditioning” time).

This convention is necessary in order to make the various obtained data comparable.

As a consequence of temperature increase, RF exposure causes in joints a rapid decrease of moisture content in glue at the substrate/glue interphase (this parameter has been referred as MCI in the present text) (Figure 4.2). This process is quite independent on the considered PVAc product. Figure 4.2 shows how the drying trend is practically the same for two different PVAc dispersions: (a) Vinavil 2252 M and (b) Vinavil KM.



FIGURE 4.1. Example of the test arrangement used to evaluate mechanical performances of wood specimens glued with polyvinyl acetate dispersions.

²This time also depends on the assembly thickness. For instance, in the case of 40 mm-thick beech wood assemblies it is 120 min.

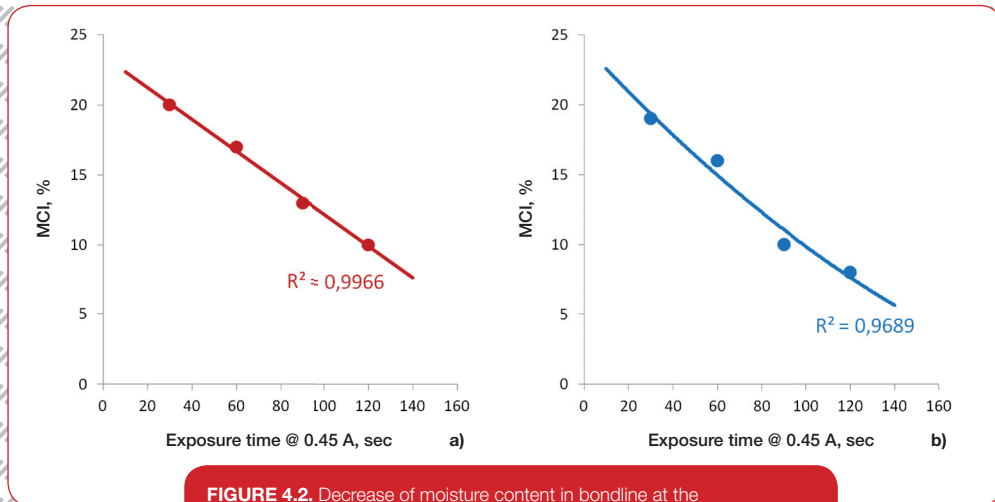


FIGURE 4.2. Decrease of moisture content in bondline at the substrate/glue interphase (MCI) vs. exposure time to RF at the anodic current of 0.45 A (kept constant): a) Vinavil 2252 M; b) Vinavil KM.

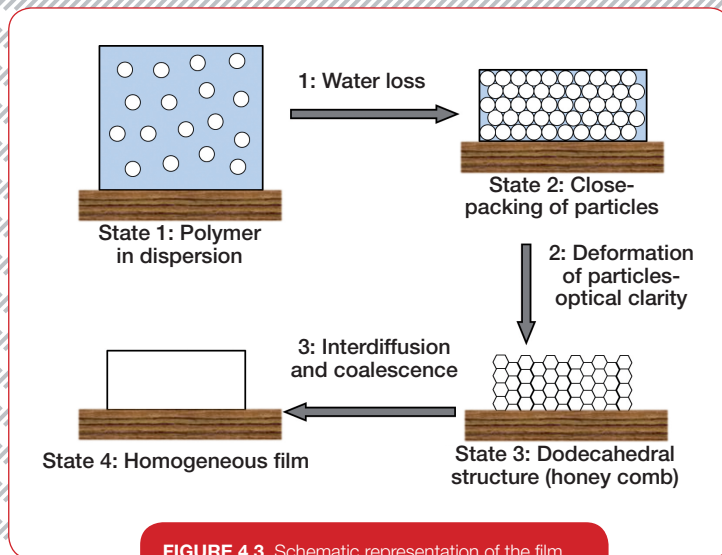


FIGURE 4.3. Schematic representation of the film formation process for a polyvinyl acetate dispersion.

Of course, this fast drying favours the water evaporation from dispersions, which causes the starting of the film formation process in PVAc. The film formation process (Figure 4.3) consists in transforming a stable dispersion of colloidal polymer particles into a continuous solid film (this is a complex process, which is affected by many factors mostly imputable to both chemistry and solid content of dispersions).

As a consequence of MCI decrease and the resulting film formation advancing, RF exposure causes in joints a rapid increase of shear strength, that is of the substrate/adhesive adherence (Figure 4.4). This increase is uniform (for a same product) along the considered exposure range at constant anodic current (in the specific case 0.45 A), that is from 30 to 120 sec. Nevertheless, as expected, the increase rate (i.e. the rapidity of variation of shear strength) depends on the chemistry of the polymer constituting the dispersion. Figure 4.4 shows that the raise of shear strength is much more appreciable for Vinavil 2252 M (Figure 4.4a) compared to Vinavil KM (Figure 4.4b).

The dramatic speed of strength increase due to RF heating can be appreciated even better when RF assemblies are compared with hot-pressed joints. In the case of 40 mm-thick beech joints, after 1 min, RF exposed specimens reach a shear strength of 15 N/mm² and a bondline temperature of 50°C (however, the strength value refers to specimens tested in normal conditions). Conversely, hot pressed (80°C) samples reach the same bondline temperature after approximately 15 min, but at that time the strength of the joints is 10 N/mm² (once again, this value is referred to specimens tested in normal conditions).

The increase of mechanical performances can be directly observed when the quantity of energy transferred to bondline through RF is changed. This change can be obtained by varying both the exposure time and the anodic current (in contrast, tension, V, was kept constant at 4 kV in data shown in Figure 4.5 and Figure 4.6). Results prove that the higher is the unit energy supplied to the assembly the lower is MCI and the higher is the shear strength value. Some examples of possible combinations of anodic current and exposure time to get specific unit energy (or the correspondent electric charge density) are shown in Table 4.1.

While MCI uniformly decreases with energy (Figure 4.5), shear strength first increases by increasing unit energy, reaches a maximum at 450-600 J/cm³

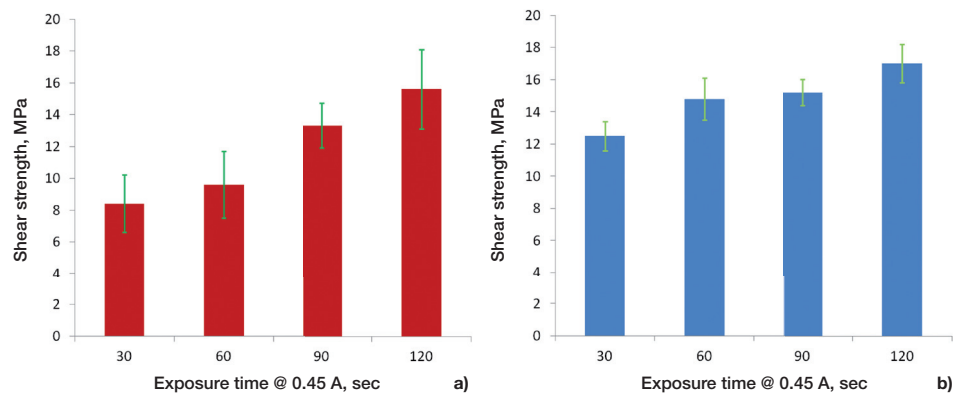


FIGURE 4.4. Increase of the substrate/adhesive adherence (shear strength) vs. exposure time to RF at the anodic current of 0.45 A (kept constant): a) Vinavil 2252 M; b) Vinavil KM.

and then decreases for higher energy levels³ (Figure 4.6). Once again, this behaviour depends on the chemistry of the specific product to be used. Figure 4.7 shows the comparison between two commercial PVAc dispersions, Vinavil 2252 M, belonging to Class D3 according to EN 204⁴, and Vinavil 2550 M, belonging to Class D2. These two products differ by their chemistry, and Figure 4.7 shows the different behaviour associated to such a factor. However, the difference is evident for the higher energies provided by the RF generator (higher than 300–400 J/cm³ in the specific case). It is also worth noticing that (regardless of the chemistry of the polymer constituting the glue) an increasing discoloration of the bondline is observed starting from 550 J/cm³ until 800 J/cm³, where the joint becomes appreciably brown-coloured⁵ (usually it is transparent for PVAc dispersions).

³ Considering that also the support is able to absorb energy (due to its moisture content), this value strongly depends on the specific conditions used in the practice (for instance, the material to be glued, the assembly thickness etc.).

⁴ EN 204:2001. Classification of thermoplastic wood adhesives for non-structural applications.

⁵ See Note 3.

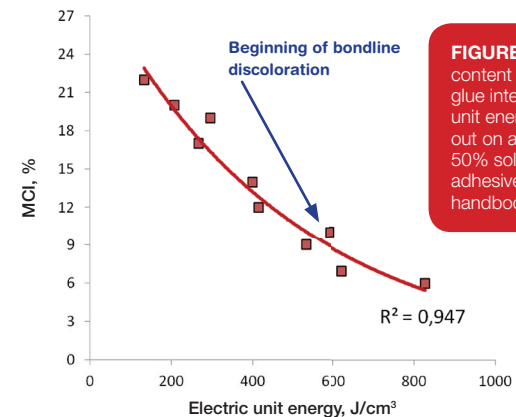


FIGURE 4.5. Decrease of moisture content in glue at the substrate/ glue interphase (MCI) vs. electric unit energy (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

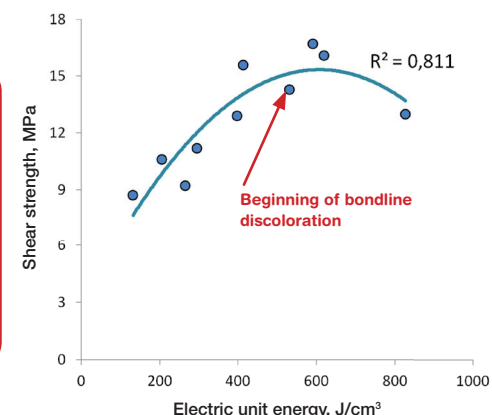


FIGURE 4.6. Increase of the substrate/ adhesive adherence (shear strength) vs. electric unit energy (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

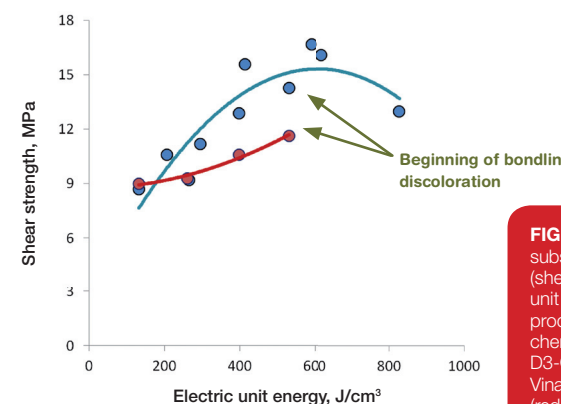


FIGURE 4.7. Increase of the substrate/adhesive adherence (shear strength) vs. electric unit energy for two commercial products having a different chemistry: Vinavil 2252 M, D3-Class (blue curve), and Vinavil 2550 M, D2-Class (red curve).

Data reported in Figure 4.2 to Figure 4.7 refer to short “conditioning” (or waiting) time, in the specific case, 40 min. After 7 days (long “conditioning” time), the results of assemblies exposed to lower levels of unit energy (electric charge $150\text{-}200\text{ J/cm}^3$)⁶ sharpen values comparable to the standard value (that is, the shear strength value of a joint glued and pressed at 23°C , and kept in constant, standard, condition for one week before being tested) (data not shown). Therefore, the obtained results show that in the case of low energy values supplied to the assemblies the conditioning time positively affects shear strength of joints.

In contrast, joints to which higher energies are supplied during pressing put in evidence higher shear strengths ($18\text{-}19\text{ MPa}$). Moreover, at the unit energy corresponding to electric charge of 800 J/cm^3 a decrease in mechanical performance can be observed⁷, which confirms the analogous decrease observed after 40 min conditioning time.

In both cases (short and long conditioning times), this behaviour is imputable to the polymer (glue) weakening. This occurrence also implies that too high energetic impulse must be avoided in glued assemblies dried under RF.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- RF exposure causes a rapid decrease of moisture content in glue at its interphase with substrates
- RF exposure causes a rapid increase of shear strength in joints
- The shear strength increase rate depends both on the chemistry of the polymer constituting the dispersion and on the geometry of the assembly
- Discoloration of the bondline is evidenced for excessive radiofrequency heating
- Too high energetic impulse must be avoided in glued assemblies dried under RF, in order to prevent polymer (glue) weakening
- Waiting time positively affects shear strength of joints in the case of low energy values supplied to the assemblies

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

HP: joints prepared by Hot-Pressing - **MCI:** Moisture Content in glue at the substrate/glue Interphase - **PVAc:** Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency - **Standard value:** shear strength of a joint glued and pressed at 23°C and kept in constant, standard, condition for one week before being tested

⁶ See Note 3.

⁷ See Note 3.

5.

Influence of the adhesive amount on the performances of PVAc glued assemblies heated with radiofrequency

5. Influence of the adhesive amount on the performances of PVAc glued assemblies heated with radiofrequency

It has been clarified in previous chapters that the high efficiency of radiofrequency heating is related to the direct heating of water molecules (due to mutual friction) under the oscillating electric field. However, both substrate and dispersion contain water (although in a very different amount between them), and therefore they are able to absorb energy from the electric field provided by the RF generator. Water is present as moisture in wood-based materials, and its amount can be quantified as the *moisture content*. Instead, in dispersions water is present in liquid form, and it constitutes the carrier of polymer particles.

The present chapter will consider the effect of the adhesive amount spread on substrates (constituted by wood-based materials) on the mechanical performances (in terms of shear strength) of joints glued with PVAc and tested in normal conditions (which means joints continuously kept at 23°C and 50% relative humidity).

As already described in Chapter 4, also in the present chapter mechanical data have been obtained after:

- 40 min from RF irradiation (this is the minimum time needed to let the side of a 10 mm-thick assembly reach the room temperature, and it represents a short “conditioning”, or waiting, time⁸);
- 7 days from irradiation (this value represents a long “conditioning” time).

This convention is necessary in order to make the various obtained data comparable.

As expected, for a same amount of glue the higher is the RF exposure time (and hence the energy supplied to the assembly), the higher is the shear strength of joints (Figure 5.1) and the lower is MCI (Figure 5.2). In fact, this condition is similar to that one described in Chapter 4.

Instead, when different amounts of glue (spread on the adherends) are compared for a same RF exposure time, it appears how the glue amount does

⁸ This time also depends on the assembly thickness. For instance, in the case of 40 mm-thick beech wood assemblies it is 120 min.

FIGURE 5.1. Increase of the substrate/adhesive adherence (shear strength) vs. electric unit energy for assemblies prepared by varying the amount of a same PVAc glue spread on the substrate (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

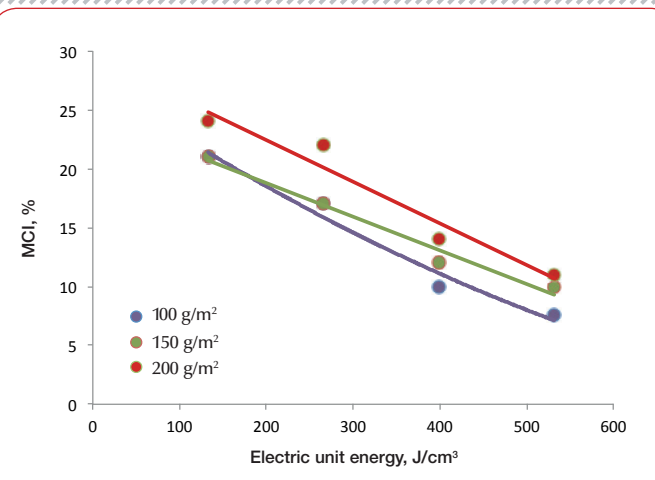
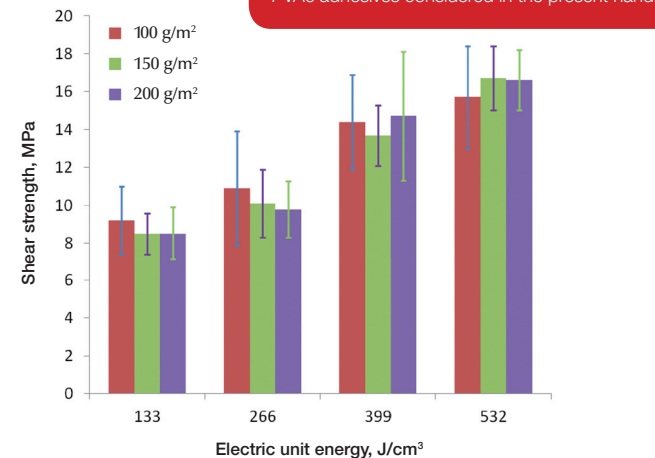


FIGURE 5.2. Decrease of moisture content in glue at the substrate/glue interphase (MCI) vs. electric unit energy for assemblies prepared by varying the amount of a same PVAc glue spread on the substrate (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

not play an appreciable role in determining the mechanical performances of samples, at least in the considered range (as shown in Figure 5.1).

This behaviour is related to the limited amount of water that can be found into the bondline as compared to moisture content in adherends made of wood-based materials.

In fact, in the case of a squared panel having area 1 m^2 , the water content of a PVAc dispersion having 50% solid content is 50 g, 75 g and 100 g for the glue spread at 100 g/m^2 , 150 g/m^2 and 200 g/m^2 , respectively.

On the other hand, assuming that the same panel:

- is 10 mm-thick;
- its density is 650 kg/m^3 ;
- its moisture content at the moment of gluing is 10%;

the panel will contain approx. 590 g of water. This means that the water content in dispersion is only 8-15% of the global amount of water heated under RF.

It is worth noticing that, while results reported above refer to short conditioning times (40 min), in the case of long waiting times (7 days) shear strength flattens to values which are equivalent for the various amounts of glues spread on the adherend surfaces. The same also applies in the case of the moisture content in bondline at the substrate/glue interphase (MCI).

This occurrence highlights once again how the parameter considered in the present chapter (that is, the adhesive amount spread on substrates constituted by wood-based materials) is not of practical interest for PVAc-glued assemblies dried under radiofrequency heating.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The glue amount spread on the adherends does not play an appreciable role in determining the mechanical performances of assemblies heated under radiofrequency
- This is related to the limited amount of water in bondline compared to moisture content in wood-based adherends

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

MCI: Moisture Content in glue at the substrate/glue Interphase - **PVAc:** Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency

6.

Effect of the adherend moisture content on the performances of PVAc glued assemblies dried under radiofrequency heating

6. Effect of the adherend moisture content on the performances of PVAc glued assemblies dried under radiofrequency heating

The previous chapters clarified how water content in assemblies plays a very important role in determining the performances of glued joints dried under radiofrequency heating. However, water can be present either as moisture in wood-based materials or as polymer carrier in adhesive dispersions. While Chapter 5 reported about the effect of water content in adhesives spread onto the adherend surfaces, the present chapter will evaluate the influence of moisture content in substrates made of wood-based materials. More in detail the mechanical performances (in terms of shear strength) of joints glued with PVAc and tested in normal conditions (which means joints continuously kept at 23°C and 50% relative humidity for one week after setting) are considered.

For these tests, substrates were kept in a climatic chamber set at different humidity conditions for a long time (up to constant weight). The adherends were glued and then exposed to RF at the end of this period.

If the energetic levels provided to assemblies are within the range of considered values (100-550 J/cm³)⁹, performances of joints appreciably diminish when the wood moisture content (WMC) is increased from 5 to 13%. This occurrence is imputable to the effect of energy depletion due to the increasing presence of moisture into adherends: in practice, part of the energy provided by the RF generator is spent to dry the substrate instead of the bondline. This is mainly clear in Figure 6.1, which shows how the moisture content in glue at the substrate/glue interphase (MCI) is higher (for the same energetic impulse supplied to the assembly) for the moistest joints.

The extent of performance decrease due to these water contents, from the driest to the most humid joints, is significant: it is of the order of 40% (referred to the value in normal conditions, that is at 9-10% moisture content) in the

⁹ Considering that also the support is able to absorb energy (due to its moisture content), this value strongly depends on the specific conditions used in the practice (for instance, the material to be glued, the assembly thickness etc.).

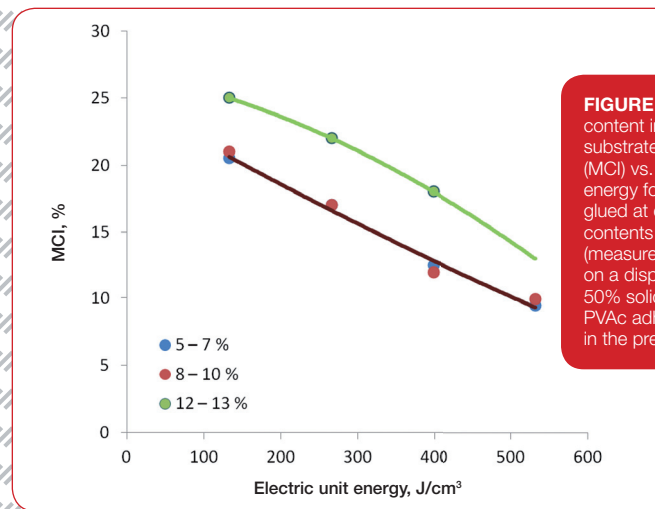


FIGURE 6.1. Moisture content in glue at the substrate/glue interphase (MCI) vs. electric unit energy for assemblies glued at different moisture contents of substrates (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

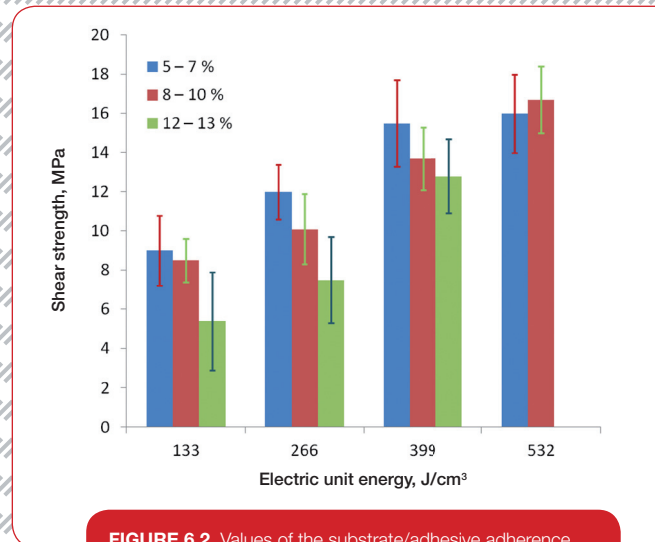


FIGURE 6.2. Values of the substrate/adhesive adherence (shear strength) vs. electric unit energy for assemblies glued at different moisture contents of substrates (measurements carried out on a dispersion with about 50% solid content, as all PVAc adhesives considered in the present handbook).

cases of the lowest supplied energies (electric charge densities of approx. 130 and 260 J/cm³) and of 20% after 400 J/cm³ (Figure 6.2)¹⁰.

It is important noticing that drying of too humid substrates must be avoided with the radiofrequency heating. In fact, the electrical conductivity of the supports is increased to such an extent that an electric arc can be developed, which makes the RF heating very dangerous (wood burning and even flames could develop). In this case, the power must be dramatically reduced, or the electrode arrangement properly modified.

For instance, for 10 mm-thick supports made of beech wood this electric arc develops already at moisture contents higher than 13%. Moreover, it develops also at 12% WMC when too elevated energies (532 J/cm³ in the considered example) are supplied to assemblies.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- Moist substrates absorb energy thus decreasing the aliquot taken up from the bondline
- Performance of joints appreciably decreases for a same energy supplied to humid assemblies
- Drying of too humid adherends must be avoided with the radiofrequency heating (electric arcs can be developed)

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

MCI: Moisture Content in glue at the substrate/glue Interphase - **PVAc:** Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency - **WMC:** Moisture Content in the substrate made of a Wood-based material

¹⁰See Note 9

7.

Influence of radiofrequency heating on the failure pattern on the surface of broken wood joints

7. Influence of radiofrequency heating on the failure pattern on the surface of broken wood joints

The present chapter reports about the influence of radiofrequency heating in determining the failure pattern on the surface of joints bonded with PVAc adhesives. The expression “failure pattern” is here specifically referred to the appearance of bonded wood surfaces that have been broken due to external stresses acting on the same plane of the glue line (they are usually referred as *shear stresses*). The failure pattern is mainly related to the ability of adhesives in tearing wood fibres under shear stress, and it is usually connected to both the adhesive penetration into the wood substrate (inducing, for instance, mechanical interlocking) and the cohesive glue strength at the time when forces are applied to assemblies.

In practical terms, the “failure pattern” refers to the quantity of wood fibres (as opposite to the visible glue layer underneath) that is broken under load in standard specimens. This parameter is often briefly referred as *wood failure percentage* (WFP).

This characteristic is visually evaluated by looking at broken surfaces after failure, and it must be assessed on standard specimens glued using the same wood species and broken in identical conditions, in order to carry out measurements that are both reproducible and comparable among various adhesives and laboratories. More in detail, in the case of polyvinyl acetate (PVAc) wood adhesives this parameter is usually measured according to standard ISO 6238¹¹, whereas other standards are applicable in different contexts (such as for plywood). Semiautomatic methodologies associated to surface colouring can be successfully used for quantitative evaluations of wood failure percentage, as recently proposed¹². As specified above, although this parameter is well-defined (and measurable) specifically for woody substrates, this adhesive’s characteristic is of sure interest also for all wood-based substrates, to which its importance can be directly extended.

¹¹ ISO 6238:2001. Adhesives. Wood-to-wood adhesive bonds. Determination of shear strength by compressive loading.

¹² Chiozza F., Toniolo F., Pizzo B. (2012) A semi-automatic method for the evaluation of wood failure percentage of polyvinyl acetate-based adhesives through image analysis. At: 8th World Adhesive & Sealant Conference (WAC2012), FEICA, September 18-21, 2012, Paris

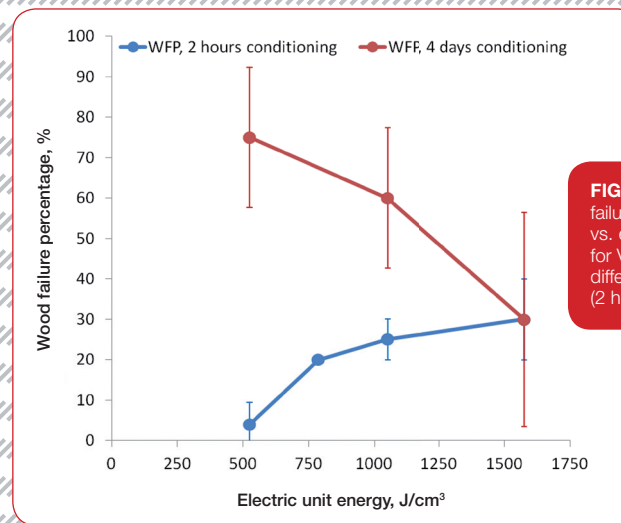


FIGURE 7.1. Wood failure percentage (WFP) vs. electric unit energy for Vinavil 2258 M at two different conditioning times (2 hours and 4 days).

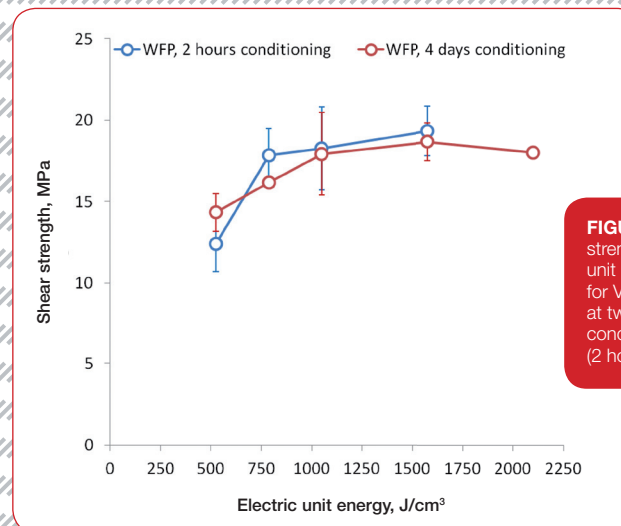


FIGURE 7.2. Shear strength vs. electric unit energy for Vinavil 2258 M at two different conditioning times (2 hours and 4 days).

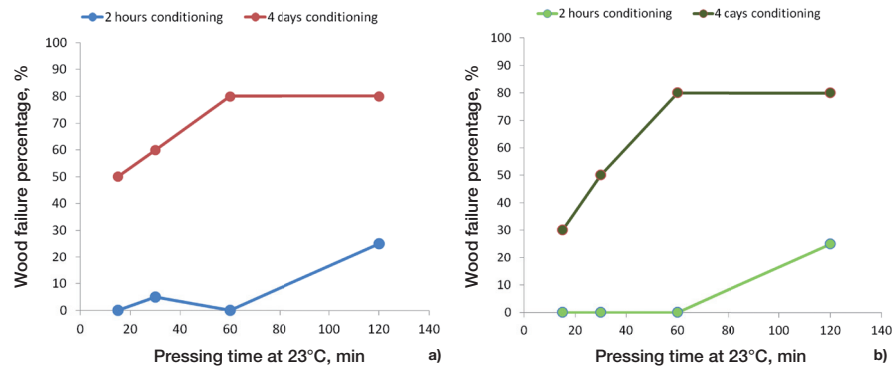


FIGURE 7.3. Wood failure percentage (WFP) vs. pressing time at 23°C at two different conditioning times (2 hours and 4 days) for Vinavil 2258 M (a) and Vinavil 2252 M (b).

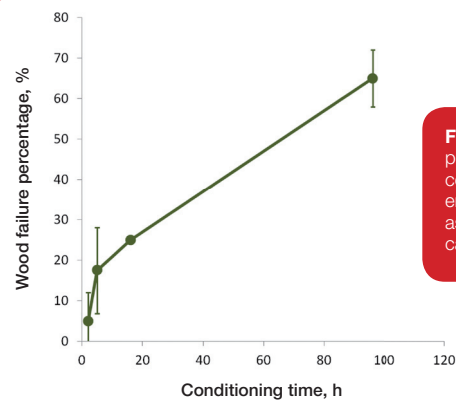


FIGURE 7.4. Wood failure percentage (WFP) vs. conditioning time at constant energetic impulse provided to assemblies (520 J/cm³). Tests carried out on Vinavil 2258 M.

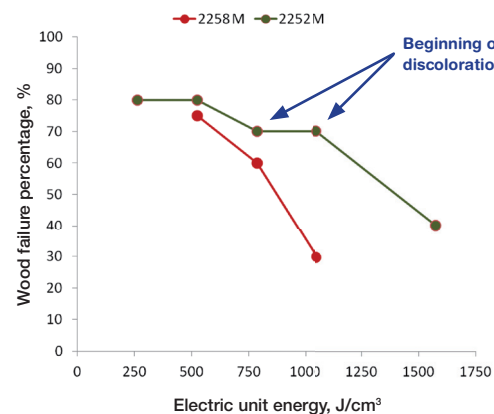


FIGURE 7.5. Wood failure percentage (WFP) vs. electric unit energy after 4 days conditioning time for Vinavil 2258 M and Vinavil 2252 M.

Results reported in the present chapter refer to tests carried out on two 20 mm-thick block specimens prepared using beech wood (global assembly thickness of 40 mm) and tested according to ISO 6238 (both shear strength and WFP can be evaluated in this way). The adhesives used were Vinavil 2258 M and Vinavil 2252 M. Moreover, in order to evaluate the effect of time on the results, assemblies were conditioned for two appreciably different time intervals (2 hours and 4 days) before being mechanically stressed. During this conditioning period, assemblies were kept at 23°C and 50% relative humidity.

The most noteworthy outcome of these tests is that the “conditioning time” is the most important parameter in determining wood failure in broken joints. Within this context, the “conditioning time” is the time lasted from the release of the pressure applied during pressing until the joints are put under mechanical stress. It can be noticed from data reported in Figure 7.1 that for short conditioning times (such as 2 hours) WFP appreciably increases by increasing the energy supplied to joints; however, WFP also increases by increasing the conditioning time (in present case from 2 hours to 4 days). On the other hand, interestingly, this latter aspect is not always connected to the strength of the same joints, which is instead comparable between the two considered conditioning times (Figure 7.2).

Therefore, in order to reach the maximum value of WFP, it is necessary that the conditioning time is sufficiently high¹³. This behaviour is related to the additional time necessary for the full development of mechanical characteristics of the adhesive when applied to the substrate. In fact, while appreciable cohesive strength is soon reached for the layers resting on the surfaces, thanks to the completion of the film formation process, additional time is required to get the complete physical-chemical stabilisation of the polymer-wood composite constituting the interphase.

It is worthwhile to observe that this same behaviour is also obtained in the case of adhesives set at 23°C, and therefore it is not related to the radiofrequency irradiation nor to the specific PVAc product used (Figure 7.3 a,b); it is rather a typical characteristic of PVAc-based wood adhesives.

Furthermore, this behaviour is not related to the amount of energy initially provided to assemblies. This occurrence was well-evidenced after specific

¹³ The effective time depends on the specific conditions (in terms of both thickness and assembly arrangement) adopted in the practice.

tests were carried out by varying the conditioning time while keeping constant the radiofrequency energy provided to assemblies (Figure 7.4).

Tests gave an additional interesting information related to the excessive exposure of a glued joint to radiofrequency. More in detail, a remarkable decrease of WFP values (up to 60% of their maximum, Figure 7.5) was observed in case of much exposed assemblies, together with the correspondent discoloration of the glueline (starting from 800-1000 J/cm³ in present tests¹⁴). More specifically, this occurrence was mostly evident with longer conditioning times (4 days in the specific case), as apparent from Figure 7.5. As already clarified in Chapter 4, this behaviour is imputable to both:

- the negative effect of excessive energy on the film formation process of the adhesive;
- the consequent mechanical alteration of the polymer at the interphase level.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The "conditioning time" is the most important parameter in determining wood failure in broken joints
- Instead, the conditioning time is not always connected to the strength of the joints
- This behaviour is not related to the radiofrequency irradiation and it is rather a typical characteristic of PVAc-based wood adhesives
- Remarkable decrease of WFP values in much exposed assemblies, together with the correspondent discoloration of the glueline, has been proved

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

PVAc: Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency - **WFP:** Wood Failure Percentage, that is the quantity of wood fibres (as opposite to the visible glue layer) that is broken under load in standard specimens

¹⁴ Considering that also the support is able to absorb energy (due to its moisture content), this value strongly depends on the specific conditions used in the practice (for instance, the material to be glued, the assembly thickness etc.).

8. Improvement of assemblies resistance to water due to radiofrequency heating

In the previous chapters it was shown how radiofrequency heating appreciably reduces time needed to dry assemblies glued with PVAc, and how water contents in both dispersions and substrates affects the mechanical performances of joints. It was also shown that excessive heating induces discoloration of bondlines and it can mechanically weaken the polymer constituting the glue (Chapter 4 and 7).

On the other hand, in high-performance PVAc dispersions (such as those belonging to Class D3 according to EN 204¹⁵), adhesives need to evidence an appreciable resistance to water, because those products (to be classified as D3) must be reliably used in both:

- interiors with frequent short-term exposure to running or condensed water and/or to heavy exposure to high humidity;
- exteriors not exposed to weather.

The present chapter will evaluate the effect of radiofrequency heating on the resistance-to-water characteristics of assemblies glued with Class D3 PVAc adhesives. In order to analyse consistent values, results shown in the present chapter refer to 10 mm-thick assemblies prepared by gluing beech wood, as also provided in Standard EN 204. After RF irradiation, specimens were kept for a certain period (see below) in standard conditions (23°C and 50% relative humidity) and then immersed in water for 4 days. Then, samples were tested when just removed from the bath, still wet.

Of course, the adopted conditioning phase of immersing samples in water for 4 consecutive days is not realistic. On the other hand, this same conditioning phase gives useful indications on the long-term performances and reliability of PVAc glues when used in possibly moist environments.

As written in other chapters, tested specimens have been soaked in water after:

- 40 min from RF irradiation (this is the minimum time needed to let the side of a 10 mm-thick assembly reach the room temperature, and it represents a short “conditioning”, or waiting, time¹⁶);

¹⁵ EN 204:2001. Classification of thermoplastic wood adhesives for non-structural applications.

¹⁶ This time also depends on the assembly thickness. For instance, in the case of 40 mm-thick beech wood assemblies it is 120 min.

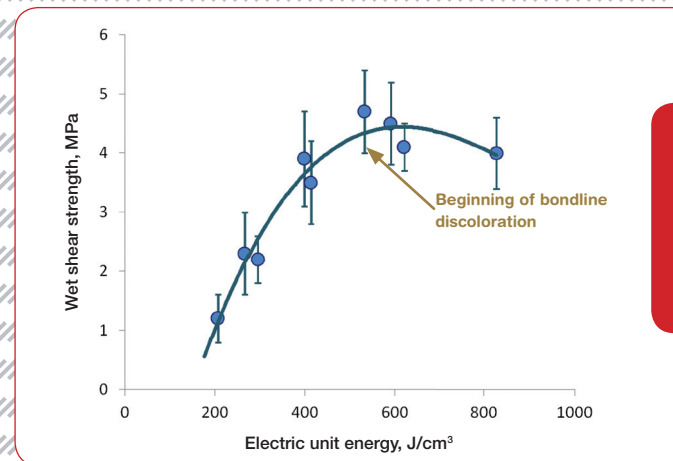


FIGURE 8.1. Increase of the substrate/adhesive adherence strength in wet conditions (wet shear strength) vs. electric unit energy for short conditioning times (40 min) (measurements carried out on Vinavil 2252 M).

- 7 days from irradiation (this value represents a long “conditioning” time).

This convention is necessary in order to make the various obtained data comparable.

Assemblies heated under radiofrequency evidence increasing substrate/adhesive adherence strength in wet conditions (*wet shear strength*) by increasing the energetic impulse initially supplied to the bondline (Figure 8.1). Moreover, for the lowest electric unit energies (up to 300 J/cm³)¹⁷ the measured wet shear strength is lower than 2.5-3.0 MPa. This latter represents the value for a commercial D3-class PVAc adhesive (such as Vinavil 2252 M) glued in standard conditions (that is, pressed at room temperature for two hours and left at 23°C and 50% relative humidity for one week before the 4 days conditioning phase), and it can be considered as a reference for this class of products. In contrast, when the unit energy corresponding to 400 J/cm³ or larger is supplied to the assembly¹⁸, the 3.0 MPa threshold value is always reached and also appreciably exceeded (Figure 8.1).

In the common practice, this means that the water-resistance characteristics of D3-class PVAc adhesives can be further improved by appropriately using radiofrequency heating. This occurrence is imputable to a progressive hydrophobisation of selected chemical components (usually hydrophilic) composing the formed film, and it constitutes a process driven by concentrated heat.

¹⁷ Considering that also the support is able to absorb energy (due to its moisture content), this value strongly depends on the specific conditions used in the practice (for instance, the material to be glued, the assembly thickness etc.).

¹⁸ See Note 17

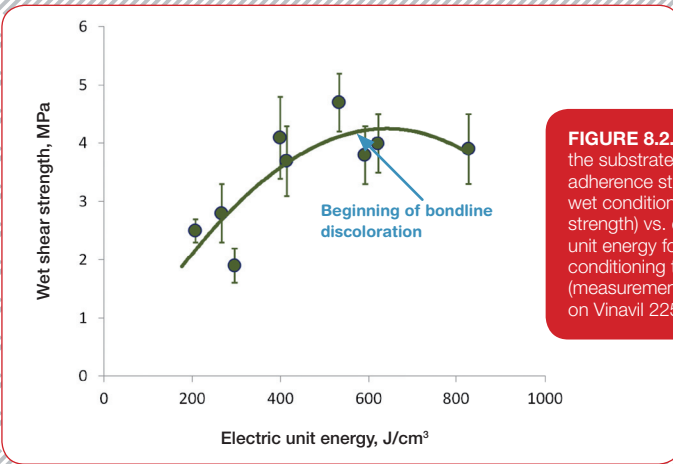


FIGURE 8.2. Increase of the substrate/adhesive adherence strength in wet conditions (wet shear strength) vs. electric unit energy for long conditioning times (7 days) (measurements carried out on Vinavil 2252 M).

On the other hand, it must be remembered here, once again, that overheating PVAc glued assemblies (that is, providing more than 550 J/cm³ for a 10 mm-thick joint, but this value must be carefully checked for the specific case to be possibly considered in the practice) induces increasing discoloration of the bondline and polymer weakening; therefore overheating should be virtually avoided, unless mentioned inconveniences can be tolerated.

As also observed in Chapters 4 and 5, a long conditioning time has a positive effect on the wet mechanical characteristics of joints. However, this positive effect is limited: in the case of the lowest unit energies (250 J/cm³ in the specific setting considered here) the performances in wet conditions reach in fact the reference value, whereas in the case of values of 300 J/cm³ or higher the increased performances observed for short conditioning times are also kept and are higher than the reference value (Figure 8.2).

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The substrate/adhesive adherence in wet conditions (wet shear strength) increases by increasing the energetic impulse initially supplied to the bondline
- For low unit energies, the performances in wet conditions are comparable to those of standard gluing
- Too large energies induce an improved resistance to water but provoke overheating of PVAc glues, with consequent discoloration and polymer weakening

LIST OF ABBREVIATIONS USED IN THE PRESENT CHAPTER:

PVAc: Polyvinyl Acetate Dispersion - **RF:** joints prepared by RadioFrequency

9.

Energy consumption

9. Energy consumption

Heating techniques allow appreciably accelerating the film formation process in polyvinyl acetate (PVAc) dispersions, thus significantly diminishing the time needed for glues to set. On the other hand, heating techniques use considerable energy to accomplish this task, even if to different amounts. In fact, radiofrequency heating is usually considered an efficient system: if efficiency is defined as the energy used in a process divided by the power supplied to the equipment, the efficiency of radiofrequency heating is usually 50-70%, whereas it is 10-30% in conventional methods based on heat conduction.

The costs spent in this heating process can be referred as operational costs, and in the present chapter they are specifically considered by comparing radiofrequency heating with hot-pressing (the most spread alternative methodology to speed up the glue drying process). More in detail, hot-pressing with plate temperatures set to either 80°C or 100°C was compared with radiofrequency heating where the generator tension was set to 4 kV.

For such comparison, assemblies were prepared by gluing together two 5 mm-thick beech wood boards. This kind of assembly was the same for all evaluations, in order to make measurements really comparable among them. Moreover, two different PVAc adhesives, Vinavil 2252 M and Vinavil 2550 M, were used, and different properties evaluated.

Furthermore, to compare equivalent data sets, the following procedure was adopted: a performance threshold has been selected and the evaluations have been repeated at various time intervals until that threshold was reached. Then, the energy consumed during the whole process (pre-heating and keeping the temperature during this time) has been calculated.

More in detail, the energy consumption was evaluated by:

- measuring the electric power absorbed by the device during the *pre-heating* phase and multiplying it for the measured time elapsed during the same phase;
- measuring the electric power absorbed by the device during the *temperature-maintaining* phase and multiplying it for the measured time elapsed during the same phase.

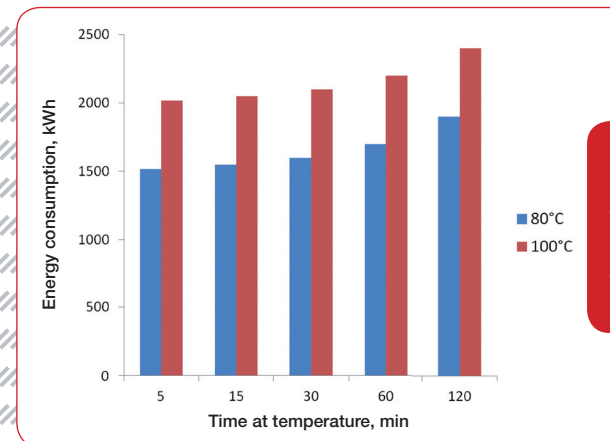


FIGURE 9.1. Energy consumption for assemblies prepared by gluing together two 5 mm-thick beech wood boards and hot-pressed at two different plate temperatures (80°C and 100°C) for different times.

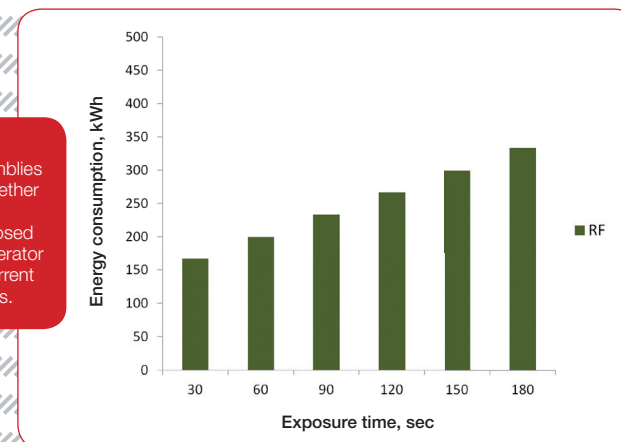


FIGURE 9.2. Energy consumption for assemblies prepared by gluing together two 5 mm-thick beech wood boards and exposed to radiofrequency (generator tension 4kV, anodic current 0.7 A) for different times.

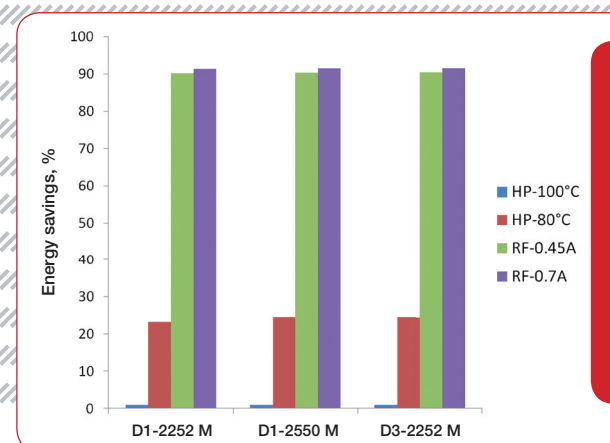


FIGURE 9.3. Energy savings (compared to the most energy-absorbing process) for the considered heating techniques (radiofrequency, RF, and hot-pressing, HP) and for the two polyvinyl acetate dispersions (Vinavil 2252 M and Vinavil 2550 M) taken into account. The value of 0 refers to the most energy-consuming process. For each adhesive, the evaluated characteristic was that one described in Chapter 4 and Chapter 8.

For the considered arrangement, the following electric powers were absorbed by devices:

- 6 kW for the pre-heating phase during hot-pressing;
- 0.2 kW to keep the reached temperature, always for hot-pressing;
- 2 kW during the starting operations for the radiofrequency heating;
- 4 kW during the radiation emission.

To give examples of the related absorbed energies, in hot-pressing the pre-heating phase implied an energy consumption of 1500 Wh for plates set at 80°C, and of 2000 Wh per plates set at 100°C. These values must be added to the energies needed to keep the temperature, which means, for instance, 17 Wh for 5 min pressing at both 80°C and 100°C, or 100 Wh for 30 min pressing. The resulting absorbed energies, in the specific conditions considered here, are shown in Figure 9.1. In contrast, the radiofrequency generator absorbed 133 Wh during the starting operations, whereas the energies needed during the radiation phase were 33 Wh in the case of 30 sec at 0.7 A, or 133 Wh for the combination 120 sec/0.7 A. The resulting energy consumptions are shown in Figure 9.2.

In order to make them more representative and generally usable (results shown in both Figure 9.1 and Figure 9.2 refer to the specific conditions considered in tests reported here) the same results can be shown as energy savings, that is, as the amount of energy saved when using radiofrequency compared to hot-pressing. More specifically, in Figure 9.3 the process consuming more energy was set to 0 (this meaning maximum consumption and hence 0 energy savings), whereas the other values were shown in percentage values (referred to the maximum absorption condition).

The results evidenced that a power saving up to approximately 90% was obtained with radiofrequency heating, whereas the most consuming technique was hot pressing, with up to 25% difference between the 80°C and the 100°C plates temperature.

However, in addition to operational costs other expenses must be considered to evaluate the effective convenience of using radiofrequency heating. These additional costs include:

- capital investment,
- space-related problems,
- maintenance.

Capital investment must consider both the equipment acquisition and the

costs related to devices mounted to take account safety and health issues. However, in modern machines the equipment cost usually includes these devices. Current prices to buy a high frequency generator are included in the range 700-2000€/kW¹⁹ for equipments most diffused in wood industry, where this variability is mostly related to the specific power of the generator (the unit price of more powerful generators being lower than for the less powerful ones).

Concerning the *maintenance* costs, they are mainly related to the diodes and triodes consumption (the service life of a triode is usually of 3-4000 working hours, after which their efficiency appreciably diminishes). On the other hand, no particular maintenance operations are further needed, excluding the cleaning of the triode cooling system from dust and wood debris, thus to avoid its early damage (this cleaning is usually carried out by means of compressed air).

Concerning the *space* needed for equipments, a rough evaluation of this subject could be based on the fact that, generally speaking, radiofrequency heating requires only 20 to 35% of the floor space of conventional hot-pressing heating units.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- Radiofrequency heating is an efficient heating techniques (mainly if compared with conventional methods based on heat conduction) but it is expensive to manage
- Operational costs are appreciably reduced compared to hot-pressing
- Other expenses (including, but not limiting to, capital investment, maintenance, space-related problems) must be particularly evaluated

¹⁹ Price referred to 2015

10.

**Brief outline on the
protection
issues related
to the use
of radiofrequency
heating**

10. Brief outline on the protection issues related to the use of radiofrequency heating

The present chapter gives a few hints on the issues, concerning the aspects related to protection, that arise when dielectric heaters are used in an industrial environment.

These issues are certainly oriented towards the operators protection, as specified (in Europe) in the European Directive 2006/42/EC on machinery and of the related harmonised standards. However, in addition to operators, also the other equipments present in industries need to be protected against possible electromagnetic emissions from the radiofrequency apparatus, as specified (in Europe) in the Electromagnetic Compatibility Directive 2004/108/EC and of the related harmonised standards. However, the present chapter will only consider the issues related to the first aspect.

As already explained in Chapter 2, dielectric heating produces intense electric field which is mostly concentrated in the area of the applicator (for instance between the two plates connected to the radiofrequency generator), where the material to be glued is positioned (Figure 2.5). In contrast, the magnetic field is limited to the zones very close to the strips connecting the generator and the applicator, that is, in the areas interested by the high frequency currents.

In these conditions, the agent able to cause possible safety problems is just the electric field, which is mostly intense in the region very close to the applicator and rapidly decreases at a distance from it. A scheme of possible decrease rates is shown in Figure 10.1: the electric field, whose intensity is very high within the applicator (several tens of kV/m), also interests the geometrical space close to the plates edges, although the value of E_{eff} decreases by increasing the distance from them. Of course, if a machine is well-shielded, the electric field intensities should be confined to the immediate vicinity of the same machine.

However, modern radiofrequency heaters already possess devices able to appreciably limit the electric field at a same distance from the machines. The examples shown in Figure 10.1 refer to two different applicators used to glue wood: as apparent, the decrease rate in B is much more effective than in A. In the specific case, this is due to a more efficient construction system and

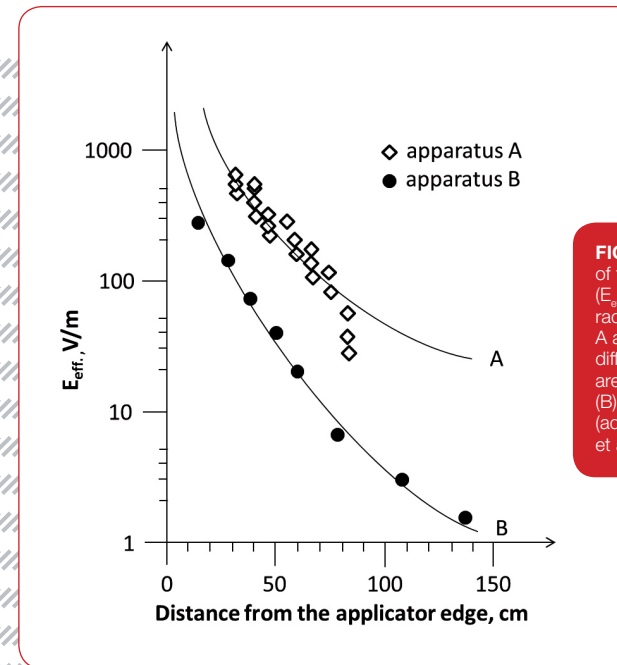
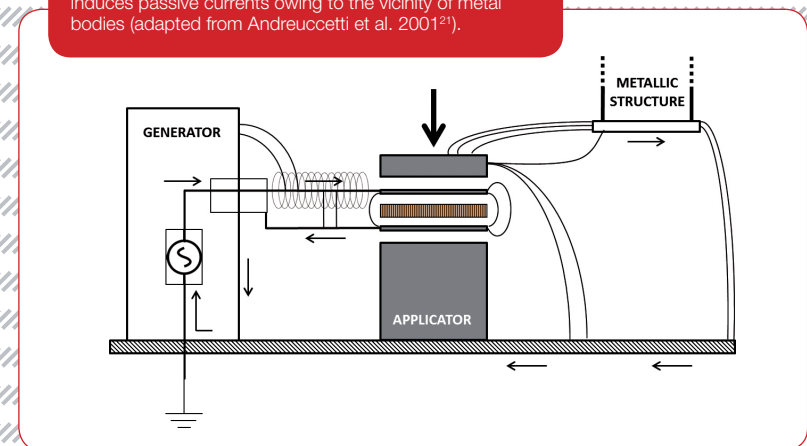


FIGURE 10.1. Values of the electric field (E_{eff}) at a distance from radiofrequency applicators. A and B refer to two different machines which are poorly (A) and efficiently (B) electrically shielded (adapted from Andreuccetti et al. 2001²⁰).

FIGURE 10.2. Schematic example of incorrect installation of a radiofrequency generator and applicator, which induces passive currents owing to the vicinity of metal bodies (adapted from Andreuccetti et al. 2001²¹).



²⁰ Andreuccetti, D., Bini, M., Checcucci, A., Ignesti, A., Millanta, L., Olmi, R. and Rubino, N. Protezione dai Campi Elettromagnetici Non Ionizzanti; IROE-CNR: Firenze, 2001

²¹ ibidem

installation (screening, grounding system, etc.). Therefore, the condition of B is appreciably safer for an operator working at that machine.

An example of incorrect positioning (or even installation) is the generation of passive currents owing to the vicinity of metal bodies close to the generator (see the schematic example in Figure 10.2), which could considerably modify the electric field distribution around the machine, and can guide currents to remarkable distances from the apparatus.

It is worthwhile to observe that the areas of danger also strongly depend on the correct installation of the dielectric heater, or on possible modifications carried out after its correct installation. These modifications include the variation of the applicators geometry, the variation of the distances between the plates, a lacking (or not correct) maintenance (for instance, wear of electric contacts), incorrect repairs etc.

All of these variables must be carefully controlled after the proper installation of the apparatus, in order to guarantee a safe use of radiofrequency generators over time.

MAIN POINTS TREATED IN THE PRESENT CHAPTER

- The electric field is mostly intense very close to the applicator and rapidly decreases at a distance from it
- However, the electric field intensities are confined to the immediate vicinity in well-shielded machine
- Great attention must be paid to the generation of passive currents owing to the presence of metal bodies close to the generator
- Dielectric heaters for industrial use must comply with the requirements specified in a series of standards for equipment protection

11.

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12.

Technical Data Sheets



VINAVIL KM

02WD007 - 03/13

Vinavil KM is a polyvinyl acetate aqueous dispersion, with 50% solids content, particularly suitable to prepare wood adhesives.

	Unit	Value	Method
1. SUPPLY SPECIFICATIONS			
Solid content	%	50±1	MVPP 01
Brookfield viscosi	(1) mP	43.000±5.000	UNI EN ISO 2555
pH		4.5±0.5	ISO 976
2. TYPICAL VALUES			
Minimum film-forming temperature	°C	6	UNI 8490-14
Prevailing particle size range	µm	0.3+3.0	MVANS 20
Dispersing system		Polyvinyl alcohol	
Density at 23°C	kg/dm ³	1.1	MVPP 18
Mechanical stability		Excellent	MVAT 013
Rheological behaviour		Pseudoplastic	
Freeze resistant stability	cycles	>5	UNI8490-13

(1) 20 rpm, spindle 7, 23°C

APPLICATIONS

Vinavil KM is suitable for the manufacture of wood adhesives. It may be applied as is supplied or formulated for bonding wood, either with or without plastic laminates, in hot and cold conditions. Thanks to its quick setting time Vinavil KM can be used with high speed gluing machines in building field. Vinavil KM can be used in building sector to make parquet adhesives.

SPECIFIC PROPERTIES

Vinavil KM is a modified polyvinyl acetate homopolymer with polyvinyl alcohol as emulsifying system. Its particle size distribution and macromolecular structure give Vinavil KM fast setting time and high cohesive power; these properties make it suitable for the manufacture of wood adhesives.

PACKAGING

Vinavil KM is available in bulk and in 125 kg drums.

STORAGE

Vinavil KM is stable for at least 6 months when stored between +5°C and +40°C.

Data, information and suggestions are provided for guidance purpose only. VINAVIL S.p.A. accepts no responsibility for the results obtained therefrom, nor for their utilization in infringement of possible patent rights. The analytical methods are available on request.



VINAVIL 2550 M

02WD004 - 03/13

VINAVIL 2550 M is a 51% modified polyvinylacetate water dispersion which complies the durability class D2 according to EN 204.

	Unit	Value	Method
1. SUPPLY SPECIFICATIONS			
Solid content	%	51±1	MVPP 01
Brookfield viscosit	(1) mPa.	12.000±3.000	UNI EN ISO 2555
pH		7.0±0.5	ISO 976
2. TYPICAL VALUES			
Minimum film-forming temperature	°C	+3	UNI 8490-14
Prevailing particle size range	µm	0.6+3.0	MVANS 20
Density at 23°C	kg/dm ³	1.1	MVPP 18
Freeze resistant stability	cycles	>5	UNI8490-13

(1) RVT 20 rpm, spindle 5, 23°C

APPLICATIONS

VINAVIL 2550 M may be applied as supplied or as a component of a formulation for bonding wood, either with or without plastic laminates. It is successfully used when water resistance to EN 204 D2 classification is required. Then it is particularly suitable for interiors with occasional short-term exposure to running or condensed water and/or to occasional high humidity conditioning (e.g.: kitchen fixtures). Final joints obtained by using VINAVIL 2550 M show high bond strength as well as breaking of the substrate itself or, anyway, high percentage of wood tear when tested under shear stress in compression. VINAVIL 2550 M viscosity allows to use it as a final adhesive, in particular in Do It Yourself applications.

PACKAGING

VINAVIL 2550 M is available in bulk, 1000 l mini bulks and 125 kg net PE drums.

STORAGE

VINAVIL 2550 M is stable during 6 months if stored at a temperature range between +5°C and +40°C.

Data, information and suggestions are provided for guidance purpose only. VINAVIL S.p.A. accepts no responsibility for the results obtained therefrom, nor for their utilization in infringement of possible patent rights. The analytical methods are available on request.

VINAVIL 2252 M

02WD005 - 04/13

VINAVIL 2252 M is a 52% polyvinylacetate aqueous dispersion used for making mono-component wood adhesives with high water resistance, D3 class.

The special features of VINAVIL 2252 M include the following :

- a) excellent water resistance as D3 class according to EN 204
- b) excellent bond strength on hard and soft woods, with high percentage of wood tear
- c) high bond strength and heat resistance according to WATT 91
- d) excellent creep resistance
- e) good setting time

	Unit	Value	Method
1. SUPPLY SPECIFICATIONS			
Solid content	%	52±1	MVPF 01
Brookfield viscosit	(1) mPa.	15.000±3.000	UNI EN ISO 2555
pH		3.0±0.2	ISO 976
2. TYPICAL VALUES			
Minimum film-forming temperature	°C	+3	UNI 8490-14
Density at 23°C	kg/dm ³	1.1	MVPF 18
Average particles size	µm	0,4+3,0	MVANS 20
Freeze resistant stability	cycles	>5	UNI8490-13

(1) RVT 20 rpm spindle 5, 23°C

APPLICATIONS

VINAVIL 2252 M is successfully used as a mono-component adhesive when water resistance, to EN 204 D3 classification is required.

Tests for the evaluation of this properties are carried out on specimens made as follows:

Application of adhesive: both sides at the rate of approx. 150 gr/m²

Pressing condition : 0.5+1.0 N/mm²

Pressing time : 1-2 hours.

The joints obtained by using VINAVIL 2252 M show an excellent resistance to static loads.

Moreover the good penetration of the dispersion into substrates and the excellent cohesive strength of the adhesive enable the making of bonded joints that, under shear stress in compression, show a breaking of the wood itself or high percentage of wood fiber tear.

VINAVIL 2252 M shows good setting time and a good heat resistance.

It is important to point out that when joints are made under direct heat or high frequency drying conditions, changes in the colour of the glue line may be observed, especially all when using light coloured woods.

The maintenance of the water resistance (class EN 204 D3) occurs only for modifications that does not lead to an alteration of the pH values of VINAVIL 2252 M. It is possible for example, to add fillers, at the maximum amount of 10% whitout modify the D3 class.

Fillers must not be alkaline: i.g. calcium sulphate bihydrate and not calcium carbonate.

By adding di-isocyanate VINAVIL 2252 M meets the requirements of durability class D4 according to EN 204.

The resultant adhesive has a pot life variable between 8+10 hours and 2-3 days.

This depends on the type of additive used.

PACKAGING

VINAVIL 2252 M is available in bulk, 1000 l minibulk and in 125 kg net PE drums.

STORAGE

VINAVIL 2252 M is stable during 6 months, if stored at a temperature range between +5°C and +40°C.

VINAVIL 2258 M

02WD0005 - 10/14

VINAVIL 2258 M is a 50% polyvinylacetate aqueous dispersion used for making in combination with inorganic salts two-component wood adhesives with high water resistance, D4 class.

The special features of VINAVIL 2258 M include the following :

- a) excellent water resistance as D4 class according to EN 204
- b) high bond strength and heat resistance according to WATT 91
- c) excellent creep resistance
- d) good setting time
- e) pot life of at least 5 days with unchanged adhesive properties

	Unit	Value	Method
1. SUPPLY SPECIFICATIONS			
Solid content	%	50±2	MVPF 01
Brookfield viscosit	(1) mPa.	18.000±4.000	UNI EN ISO 2555
pH		5.0±0.5	ISO 976
2. TYPICAL VALUES			
Minimum film-forming temperature	°C	+4	UNI 8490-14
Density at 23°C	kg/dm ³	1.1	MVPF 18
Average particles size	µm	0,4+3,0	MVANS 20
Freeze resistant stability	cycles	>5	UNI8490-13

(1) RVT 20 rpm spindle 6, 23°C

APPLICATIONS

VINAVIL 2258 M is successfully used as a two-component adhesive when water resistance, D4 class according to EN 204 is required.

The D4 properties are reached by using the following formulation

materials	weights
VINAVIL 2258 M	100.0
AlCl ₃ ·6H ₂ O (50% ww aqueous solution)	5.0

The adhesive is ready to use after mixing and shows a pot life of at least five days. It can be used for longer storage times but it is useful to know that viscosity increase after 15 days is about 200%.

Tests for the evaluation of this properties are carried out on specimens made as follows:

Application of adhesive: both sides at the rate of approx. 150 gr/m²

Pressing condition : 0.5+1.0 N/mm²

Pressing time : 1-2 hours.

PACKAGING

VINAVIL 2258 M is available in bulk, 1000 l minibulk and in 125 kg net PE drums.

STORAGE

VINAVIL 2258 M is stable during 6 months, if stored at a temperature range between +5°C and +40°C.

Data, information and suggestions are provided for guidance purpose only. VINAVIL S.p.A. accepts no responsibility for the results obtained therefrom, nor for their utilization in infringement of possible patent rights. The analytical methods are available on request.

FABIO CHIOZZA

Born in 1968 in Savona (Italy), Fabio Chiozza is a researcher at Vinavil SpA, the Italian company leader in polymers science and service to the chemical industry. He joined Vinavil 20 years ago in R&D Technical Assistance Department located in Villadossola (VB) Italy. Since 2002 he has been Manager of the Adhesive Department and since 2008 also of the Textile one. He received the degree in Chemistry at the University of Genoa with a specialization in Physical Chemistry of Biopolymers.

His main occupation is focused on thermoplastic polymers used in adhesives, textiles, food and building. His research includes studies on chemical and physical characteristics of adhesion of surfaces, rheology, biopolymers, biodegradable and compostable process, thermoplastic wood adhesives, paper and packaging adhesives, risk assessment/product and process conformity (GMP) according to the different legislations about materials in contact with food, binders for textile industry, textile printing, normative draft. The R&D activity allowed him to be co-inventor in patents concerning wood adhesives, labelling adhesives and textile binders. He is convener at CEN of Working Group 12 in TC 193/SC1 that deals with "Adhesives for non-load-bearing timber structures"; he coordinates in Unichim the national technical group for the standardization activities about wood adhesives; he is presiding the adhesive division for wood and furniture in Federchimica /AVISIA. He is UNI delegate in CEN TC193/SC1 "Adhesives for wood and derived timber products", he attends to the tasks of WG 3 "Adhesives for paper and board, packaging and disposable sanitary products" in CEN/TC193 and in UNI/Unichim mirror group.

Dr. Chiozza attended several international scientific conferences as speaker/author of different works that have been also published in scientific journals and professional magazines.

BENEDETTO PIZZO

Born in 1969, Benedetto Pizzo is a researcher at CNR-IVALSA, the Trees and Timber Institute of the National Research Council of Italy. Since 2002 he has been in charge of the Laboratory of Chemistry of Wood and Wood Products. He received his M.Sc. with honours in Chemical Engineering and his Ph.D. in Technology of new materials in 1999. His research interests concern the study of the interactions involving wood, in particular, between wood and other materials to which it is often coupled (with main emphasis to adhesives), and between wood and the environment in which it is preserved. His activity develops through further specific lines: wood bonding and coating; effects of wood extractives on relevant technological wood properties (natural durability, shrinkage/swelling, wettability, gluability, etc.); wood consolidation.

He has been advisor of several students for their B.Sc., M.Sc. and Ph.D. thesis in various degree Courses, and has been the Italian delegate at the Management Committee of COST Action E34 "Bonding of Timber". He is WG delegate at COST Actions FP1006 "Bringing new functions to wood through surface modification" and FP1101 "Assessment, Reinforcement and Monitoring of Timber Structures". He is member of the Italian Committee for Normalisation on Cultural Heritage of UNI. He is also member of the Italian Association of Archaeometry and of the Society of Applied Spectroscopy. Dr. Pizzo published over 140 papers among scientific JCR journals, professional magazines, monographs and international or national proceedings of conferences.

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