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Report on the evaluation of cushion material processing by the dry forming method

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Abstract

The objective of this research was to evaluate processing of cushion material by dry forming methods. Firstly, the raw material was disintegrated in high solid content in such a way that fibre defects were not formed. The tribo charging phenomena was used to attach hot melt adhesives on dry disintegrated cellulose surfaces in order to form glued fibre network.

Critical properties of the hot melt adhesives are needed to optimize the gluing in cushion material processing, where controlled charging of fibres and hot melt adhesives oppositely and attaching them together is needed. Results showed that the most important powder properties were size distribution, bulk density and tribo charging properties. The electrostatic adhesion was the most efficient when single fibres were used instead of paper flakes.

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1. Introduction

Processing of the cushion material using electrostatic methods includes the research steps depicted in Fig. 1. Firstly, the raw material is disintegrated in high solid content in such a way that fibre defects are not formed. The next stage is to use the electrostatic forces to attach glue to disintegrated fibres. The final issue is to produce cushion material from fibres coated with gluing hot melt adhesives.

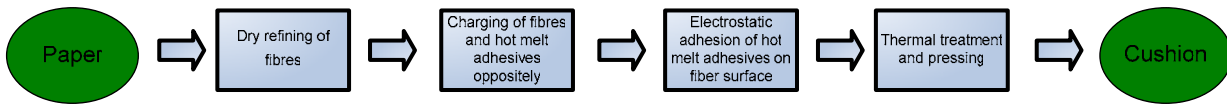


Figure. 1. Cushion material processing by the dry forming method.

2. Theory

2.1 Particle charging

2.1.1 Fundamental consideration

The prime requirement of all processes that rely on the electrostatic particle handling is to apply an electrical charge, usually unipolar, to the individual particles. In order to complete the process, the charged particles have to be manipulated in such a way that they adhere to a substrate.

2.1.2 Corona charging

The corona charging is perhaps the most widely used method of particle charging (Hughes 1997). In its simplest embodiment, the charging electrode may be a sharp pointed needle-like electrode, or a fine gauge wire. The electrode is connected directly, or via a high resistance load, to a high voltage generator. As a direct result of the electrode geometry depicted in Fig. 2, the local electric field at the pointed electrode will be greatly enhanced. For a given applied potential, the smaller the radius of curvature of the needle point, then the greater will be the local enhancement of electric field.

If the combination of needle geometry and potential is sufficient to create a local electric field of about 3MV/m (Hughes 1997), the electrical breakdown of the air itself in the vicinity of the point will occur. This corona discharge is ultimately responsible for particle charging in electrostatic systems. Assuming that the point electrode was subjected to a high voltage of negative polarity, then the local discharge, or ionisation of the air, results in charge separation and a creation of unipolarly charged molecules, or ions. Almost instantly after transition from metal to air, the high mobility electrons are rapidly trapped by neutral air molecules, creating low mobility negative ions. Likewise, if the needle electrode had been connected to a positive polarity high voltage, then the low mobility positive ions would be generated.

These slower moving ions, which drift away from the charging electrode under the action of the electric field, are ultimately responsible for particle charging. If airborne particulates are subjected to this stream of ions, interaction will occur by which of ionic attachment onto the surface of individual particles. The mechanism of ionic attachment onto individual particles is not clearly understood.

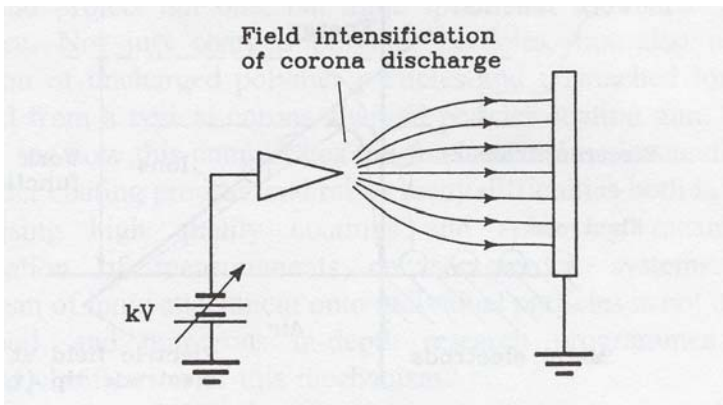


Figure 2. Field intensification at a sharp point (Hughes 1997).

2.1.3 Tribo charging

The word tribo comes from the Greek for “rubbing”, *tribos*. In the case of two different solid materials brought into intimate contact, the usual result is an imbalance in charge between the two molecular layers that are in contact. Depending on the crystallographic and chemical structure of the two materials, re-organisation of charge will occur across the interface in an attempt to restore electrical balance. This migration of charge will usually be by electronic transfer, and the degree and direction of migration will be dictated primarily by what is known as the Tribo-electric Series (Bailey 1998, Hughes 1997). Many of the most common materials used in engineering applications have been evaluated in terms of their position in the tribo series, which facilitates a degree of predictability in terms of charge exchange behaviour. For materials which have not been evaluated, however, predicting the direction of electronic transfer when in contact with a different material will require some assumption. In the table below (Table 1), rubbing any material in the list with any material below it will cause the upper material to become positively charged. For example rubbing celluloid on nylon will produce a negative charge on the celluloid and a positive charge on the nylon. The farther apart the materials are in the list, the greater the charge will be.

All materials display this charge exchange phenomenon (Hughes 1997). Charge exchange will occur across all solid/solid, solid/liquid and liquid/liquid interfaces. For many materials, the occurrence of charge re-organisation at the interface will not be obvious. This is due primarily to the fact that most materials are electrically conducting. Only when the materials are electrically insulating does the charge exchange result in the long-term creation of unipolar charge either on surface of solids, or within the bulk of liquids.

There is still considerable uncertainty as to the precise physical mechanism of the tribo charging phenomena (Hughes 1997). It is relevant that at least two mechanisms may be responsible for charge exchange across a solid interface. In the case of non-frictional contact between two different materials, an electronic transfer mechanism related to the electronic energy levels for the materials is probably the most widely accepted model. In the event of a sliding or frictional contact, however, it has been established that some degree of material transfer may actually occur between materials. A direct result of this will be a change in the net charge on each surface, leading to an effective charge exchange across the interface. Combination of these two mechanisms will be probably responsible for some degree of tribo charging.

Table 1. Triboelectric Series (available from http://www.rfcafe.com/references/electrical/triboelectric_series.htm).

Positive (+)
Air
Human Hands
Asbestos
Rabbit's Fur
Glass
Human Hair
Mica
Nylon
Wool
Lead
Cat's Fur
Silk
Aluminum
Paper
Cotton
Steel
Wood
Lucite
Sealing wax
Amber
Polystyrene
Polyethylene
Rubber balloon
Sulphur
Hard rubber
Nickel, Copper
Brass, Silver
Gold, Platinum
Sulfur
Acetate, Rayon
Polyester
Celluloid
Polyurethane
Polyethylene
Polypropylene
Vinyl
Silicon
Teflon
Saran Wrap
Negative (-)

2.2 Electrostatic effects

2.2.1 Electrostatic attraction

In particle charging applications, the net charge associated with the particle will be as a direct result of that particle either carrying a surplus of electrons, or having lost electrons and therefore displaying an equal and opposite polarity representing the departing electrons. Particle charging may then therefore only concern either electron attachment or electron loss.

Coulomb was the first to postulate the interactions between charge and the effects of polarity. Coulomb's Law simply states (Hughes 1997):

- a) Charges of the same polarity are repelled from each other, while charges of opposite polarity attract each other (see Fig. 3).
- b) The force between two charged particles is:

$$F = k \frac{q_1 q_2}{r^2} \quad (1)$$

Here, F is the force between the particles, q_1 and q_2 are the charges of particles 1 and 2. The separation distance between the particles is r, and k is a constant, 8.99×10^9 (Nm^2/C^2).

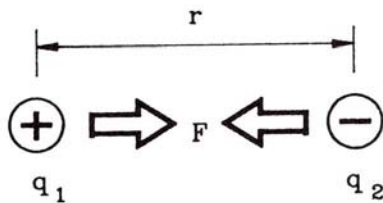


Figure 3. The electrostatic interaction between two charged particles (Hughes 1997).

2.2.2 Electrostatic adhesion

In all electrostatic applications particle charging is only part of the overall sequence of events. Equally important is the ability of particles to adhere to a substrate. Electrostatic adhesion again relies primarily on the implementation of Coulomb's Law in relation to electrically insulating particles which carry charge.

As long as the charge on the particle is not neutralized, the force of attraction will be retained, and the particle adhesion to the substrate will be remained. For some highly resistive polymer particles, electrostatic adhesion can be quasi-permanent, with good adhesion properties being retained for periods of months, or sometimes even years.

3. Materials

Tested powders were two different tall oil based hot melt adhesives. Tree powder coatings (epoxy, polyester and epoxy/polyester based), one pigment and six household flours were used as reference powders. The basic material from which the cushion material will be made up were paper fibres and flakes of softwood dry refined with hammer mill.

4. Methods

4.1 Corona charging

Corona charging equipment was constructed (see Fig. 4). The equipment contained two tungsten wires, from which the other wire was connected to a positive polarity high voltage generating positive ions. Another wire was connected to a negative high voltage generating thus negative ions. When fibres/flakes were led in the vicinity of the positive ions generating electrode wire, they were charged positively, powders were negative charged in the vicinity of the negative ions generating electrode wire.

Experiments of charging of fibres/flakes and powdered hot melt adhesives were carried out. The oppositely charging of the materials succeeded and it was revealed with electrostatic plate separator. Once the particles were charged in corona system, they were allowed to fall into the horizontal electric field between the two electrode plates connected to a high voltage. As the particles fell through the separator, they were deflected very strongly towards the positive or negative electrode plate depending on their charge.

However, attaching powdered hot melt adhesives and fibres/flakes together did not succeed for now and charging method based on tribo phenomenon seemed to be better.

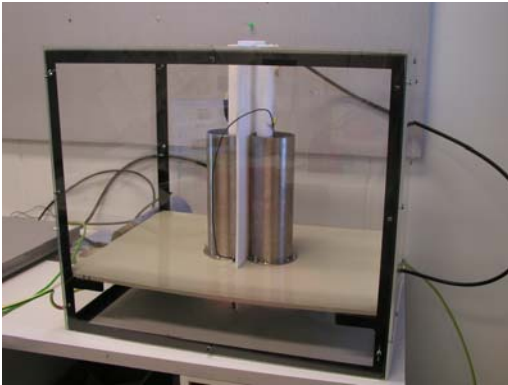


Figure 4. Corona charging equipment.

4.2 Tribo charging

A batch of paper flakes or fibres and tested powder were settled inside the charging chamber. The materials were mixed for minute and the powder which were not attach to the flakes or fibres were sieved gently for about 30 s. Adhesion was determined by dividing the retained powder on fibres after sieving by the amount of powder before sieving.

The tribo charging values of powders were determined using a Faraday cup attached to an electrometer (Model 6514 Keithley System Electrometer). Batch of powder was settled inside the charging chamber, shaken for a minute and then poured into the inner cup. The cup was weighed before and after a test in order to get the real mass value in the Faraday cup. Tribocharging value was obtained by dividing the charge generated by the powder mass. The tribocharging value generated for each powder was relative to polypropylene, which was the material of the powder charging unit. Charging tests were carried out in relative humidity of $25 \pm 5\%$ and temperature of $20 \pm 1\text{ }^{\circ}\text{C}$ inside the climate chamber. Samples were pre-conditioned.

Powder particle size was determined utilizing the Beckham Coulter laserdiffractometer with the dry powder system. The mean value ($v, 0.5$) is reported. Bulk density was measured of the weight of the powder per unit volume (g/ml). Microscopy was used to reveal adhesion of the powder on fibre.

Powder properties were correlated with adhesion. All data were converted to the following units: particle size (μm), bulk density (g/ml), adhesion (%) and charge to mass (nC/g).

5. Results

5.1 Effect of powder properties on attaching of powders on cellulose surfaces using electrostatic methods

5.1.1 Effect of particle size

Figs. 5 and 6 show the effect of powder particle size on adhesion efficiency on flake surface. Results pointed out that smaller particle were more effective improving the adhesion efficiency. In other words, smaller particle size led to better retention of glue.

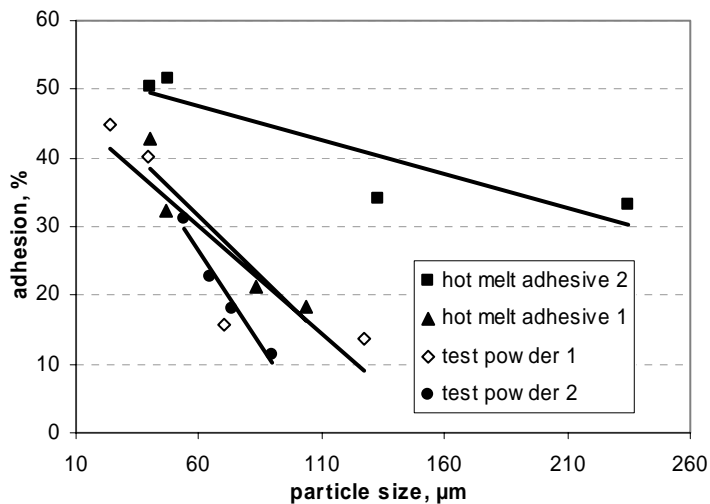


Figure 5. The effect of powder particle size on adhesion efficiency on softwood flakes. The initial powder content was 50%.

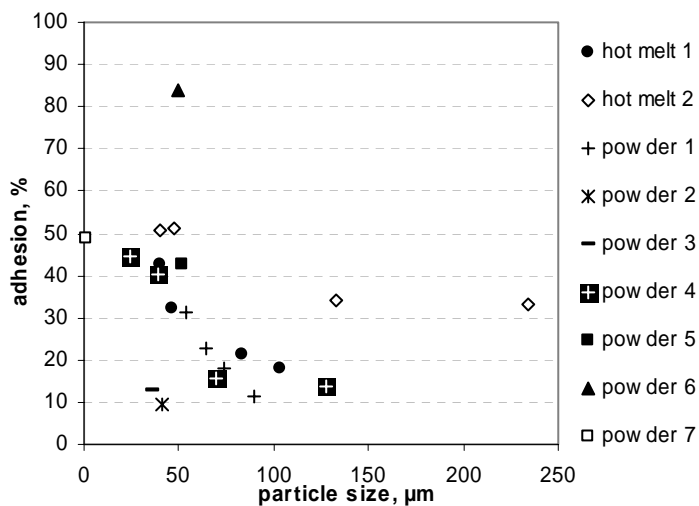


Figure 6. The effect of powder particle size on adhesion efficiency on softwood flakes with all tested powders. The initial powder content was 50%.

5.1.2 Effect of powder bulk density

Figs. 7 and 8 show the effect of powder particle bulk density on adhesion efficiency on flake surface. According to the results, particles having low bulk density seemed to adhere better on

softwood flake surface compared to high bulk density ones. Low density clearly improved the retention of glue.

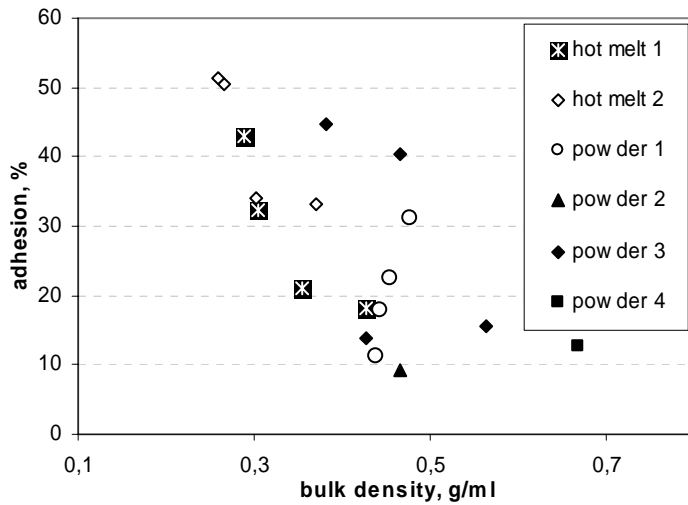


Figure 7. The effect of powder bulk density on adhesion efficiency on softwood flakes. The initial powder content was 50%.

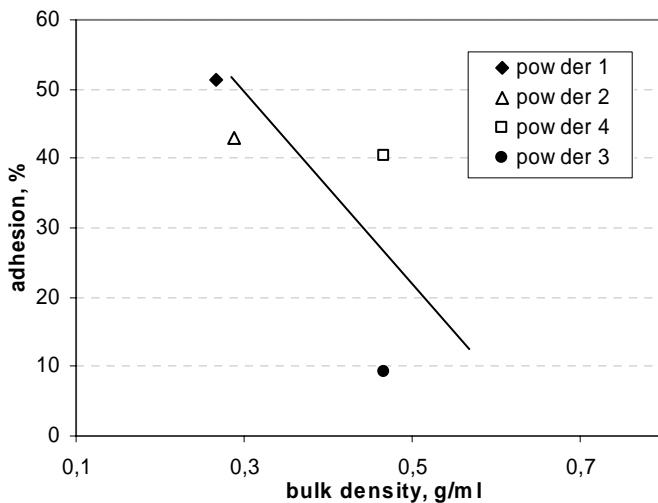


Figure 8. The effect of powder bulk density on adhesion efficiency on softwood flakes. The initial powder content was 50%. Particle size of all powders was 40 μm .

5.1.3 Effect of tribo charge value

In Figs. 9 and 10 the charging and discharging properties are presented for two tall oil based hot melt adhesives. According to the results, tribo charging effect was stronger for small sized particles. In addition, tribo values seemed to fall close to zero in fifteen minutes.

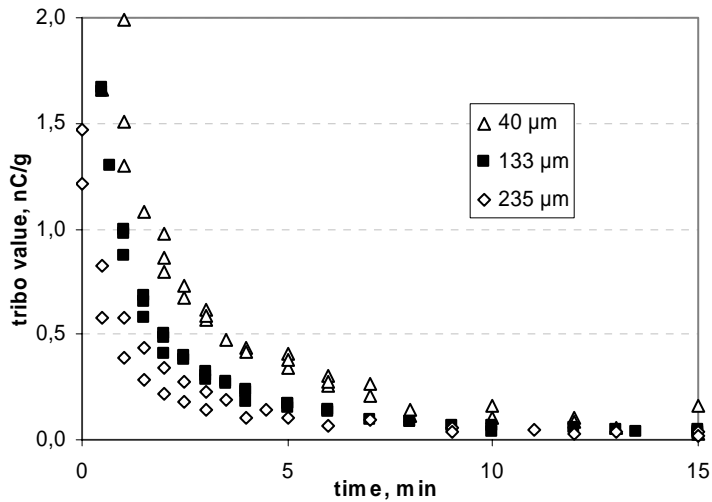


Figure 9. Charging and discharging properties of the hot melt 2 (relative humidity 31.6%, temperature 23.3 °C).

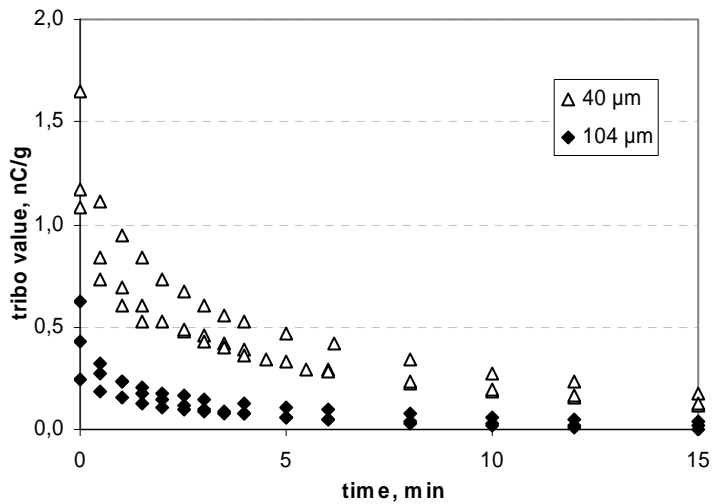


Figure 10. Charging and discharging properties of the hot melt 1 (relative humidity 31.6%, temperature 23.3 °C).

Effect of tribo charge value on electrostatic adhesion has been presented in Fig. 11. It was observed that the higher the tribo value for powders, the higher the electrostatic adhesion on flake.

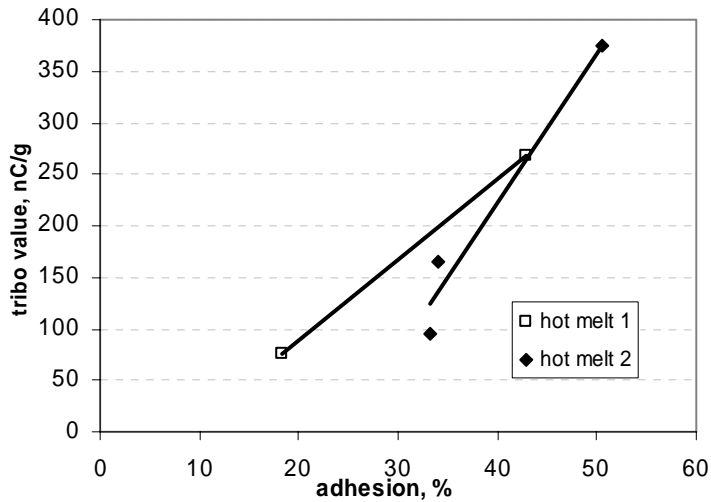


Figure 11. Tribo value as a function of adhesion efficiency on paper flakes for the two tall oil based hot melt adhesives.

Effect of temperature and relative humidity on tribo charging value

Besides the physical properties of powders, also environmental factors affect on charging process. In Figs. 12 and 13, the effect of temperature on charging properties is presented. It was observed, that low temperature facilitated the tribo charging value for both of the hot melt adhesives. At temperatures high enough, particles not seemed to charge at all (see Fig. 12). In Figs. 14 and 15 instead, the effect of relative humidity has been described. Relative humidity seemed to affect strongly on tribo charging value. Tribo charging effect was stronger in low relative humidity.

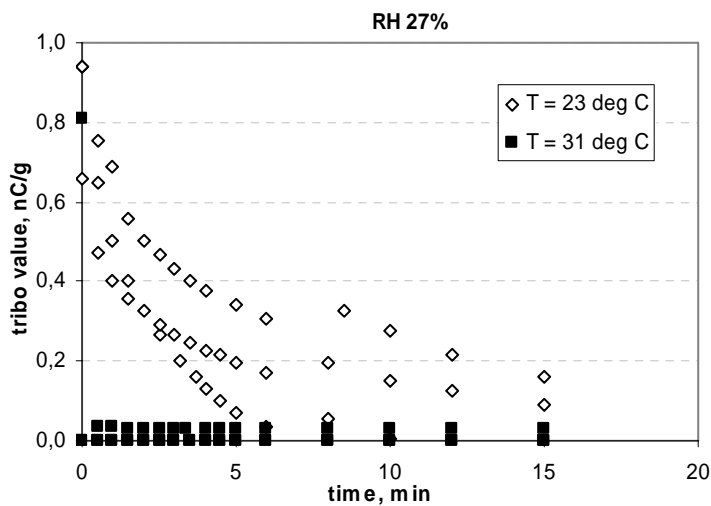


Figure 12. Tribo charging value as a function of discharging time. Used material was tall oil based hot melt adhesive (hot melt 1).

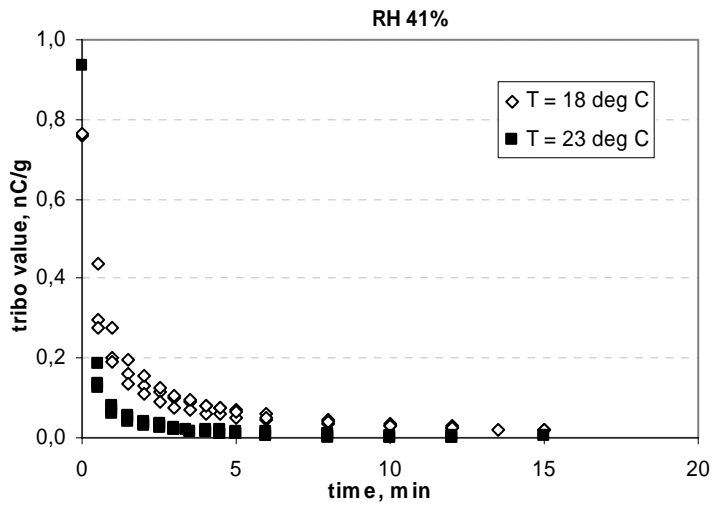


Figure 13. Tribo charging value as a function of discharging time. Used material was tall oil based hot melt adhesive (hot melt 2).

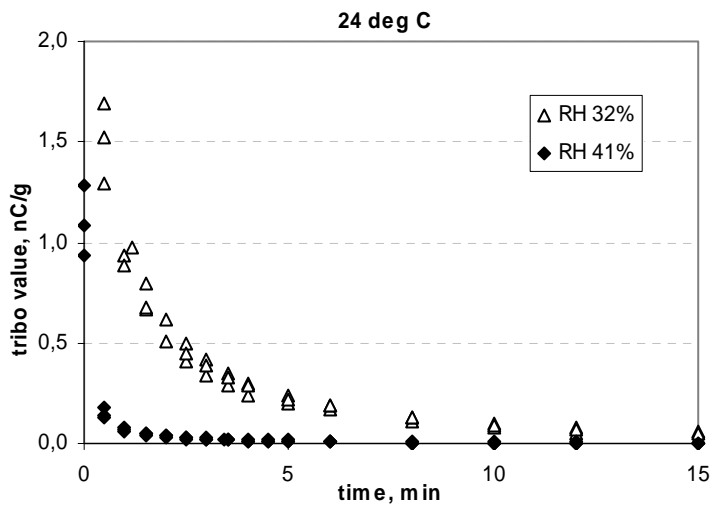


Figure 14. Tribo charging value as a function of discharging time. Used material was tall oil based hot melt adhesive (hot melt 2).

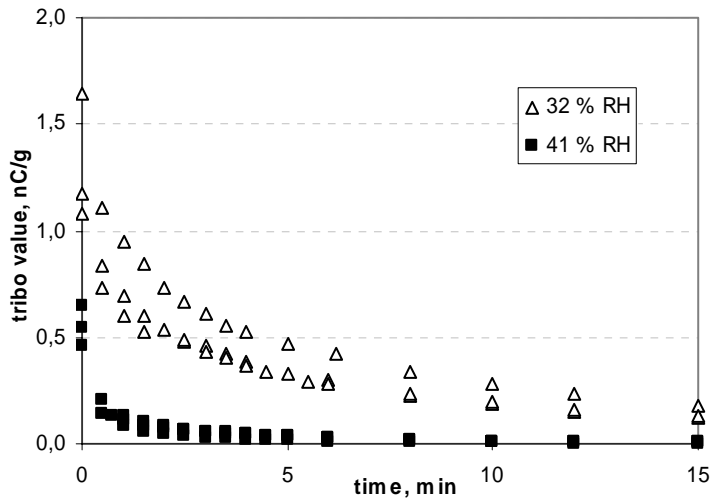


Figure 15. Tribo charging value as a function of discharging time. Used material was tall oil based hot melt adhesive (hot melt 1).

5.2 Effect of cellulose properties on attaching of powders on cellulose surfaces using electrostatic methods

5.2.1 Effect of specific area

Effect of specific area of the cellulose is presented in Fig. 16. Experiments were carried out with different size of softwood flakes and fibres. Results showed higher area in fibres (compared to flakes) offered better basis for the attachment.

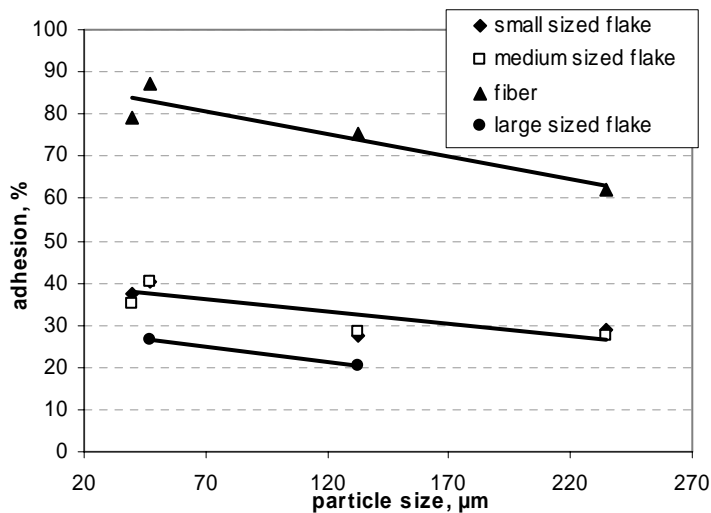
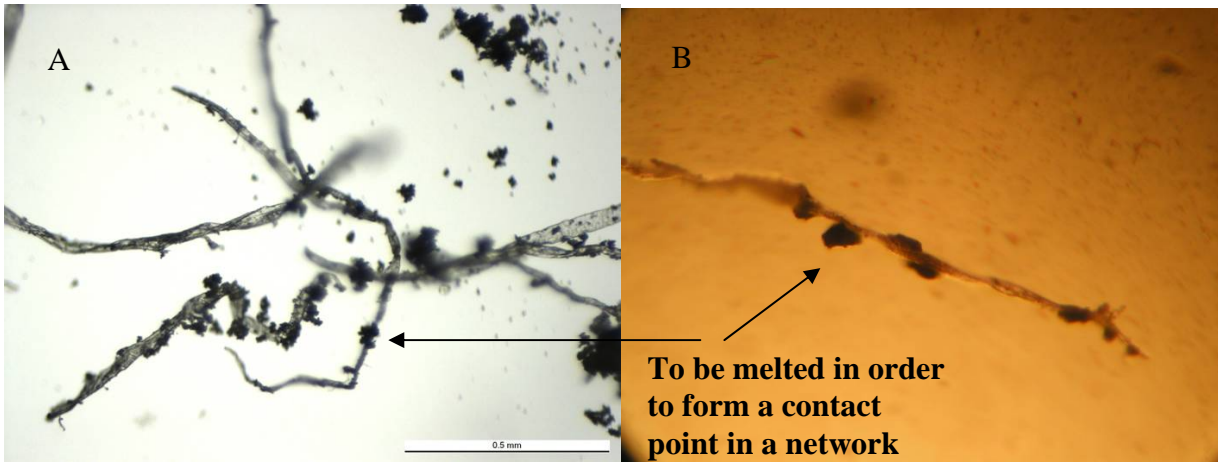


Figure 16. Effect of specific area of the cellulose on electrostatic adhesion.

Electrostatic adhesion of hot melt adhesive and test powder on fibre surface has been presented in Figs. 17 and 18.



Figures 17 and 18. Microscope pictures of softwood fibres coated with A) hot melt adhesive (40 μm) and B) epoxy based powder coating (50 μm).

6. Discussion

With decreasing particle size of the powder the adhesion efficiency increased on the flake and fibre surface (Figs. 5 and 6). According to the literature (Rhodes 1998), small sized particles have larger surface area compared to large ones. Furthermore, the larger the surface area of the particle the more charge it can theoretically pick up (Biehl and Barringer 2004). The larger the charge a powder particle can attain, the greater the attraction it has for the substrate, and vice versa, resulting in greater adhesion efficiency (Mazumder et al. 1997).

Besides the particle size (Figs. 5 and 6), also particle bulk density affected adhesion efficiency (see Figs. 7 and 8). According to Bailey (1998), Coulombic attractive forces exist between the charged materials. These Coulombic forces dominate as the charged particles move closer. Biehl and Barringer (2004) have researched with food powders, that the gravitational forces acting on large particles may over-come the electrostatic forces, causing them to land while charging. In addition, they observed that less dense particles showed a greater improvement with electrostatic adhesion efficiency. They assumed this to be due to the electrostatic forces dominating over gravitational forces in powders with low particle densities according to the Coulombic law. Therefore, the absolute improvement in adhesion may have been greater for less dense powders because the attractive forces were stronger for them.

The tribo charging values were measured as a function of time for all powders. Results of these are presented in Figs. 5 and 6. According to Sunawi and Barringer (2005), small sized powders have higher absolute tribocharging values. In addition, the larger charge a powder particle can attain, the greater attraction it has for the substrate, resulting in greater adhesion efficiencies (Mazumder et al. 1997). Powders that are efficiency charged achieve a uniform deposition efficiency and good adhesion (Cross 1981). All the powders were tribo charged positively. This was probably due to the position of the material of the charging unit (polypropylene) low down in tribo-electric series (see Table 1).

Greason (2000) has studied effects of relative humidity and temperature on charging in tribocharging system. He yielded two observations: 1) at a given temperature, an increase in the relative humidity caused a decrease in the net charge generated due to triboelectrification and 2) at a given relative humidity, an increase in the temperature caused a decrease in the charge generated due to triboelectrification. Results are in accord with results presented in Figs. 12, 13, 14 and 15.

Results presented in Fig 16 show that there is clear difference in adhesion efficiencies between fibres and flakes. The higher adhesion on fibre compared to flake was probably due to the higher surface area, and charge and thus more efficient adhesion. Also, the repetitive mixing of the fibres or flakes and powder may allow smaller particles to get into fibre or flake crevices and thereby increase adhesion efficiency.

7. Summary and conclusion

Critical properties of the hot melt adhesives are needed to optimize the gluing in cushion material processing, where controlled charging of fibres and hot melt adhesives oppositely and attaching them together is needed. Results showed that the most important powder properties were size distribution, bulk density and tribo charging. The electrostatic adhesion was the most efficient when single fibres were used instead of paper flakes.

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