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THE EFFECT OF MOISTURE IN CERTAIN WASTES AND THEIR RECOVERY, PROCESSING AND RECYCLING

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KUVAILULEHTI

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Tekijä(t) Hanna Silvennoinen	**Koulutusohjelma ja suuntautuminen** **Materiaalitekniikka**

Nimeke

Kosteuden vaikutus eräiden jätteiden hyötykäyttöön, prosessointiin sekä kierrätykseen

Tiivistelmä

Tämän opinnäytetyön tarkoitus on selvittää fyysisiä tekijöitä, jotka vaikuttavat eräiden heterogeenisten kierrätysmateriaalien kuivausprosessiin. Tavoitteena on myös selvittää muutamia esteettisiä muutoksia, jotka tapahtuvat materiaalien kuivuessa. Tutkimus jakautuu kahdeksi osaksi, teoreettiseen tarkasteluun sekä kokeelliseen osuuteen.

Teoreettisessa osuudessa näkökulmana on keskittyä kosteuden muutokseen, fysikaalisiin ilmiöihin absorptiossa ja haihtumisessa sekä kosteuden vaikutukseen eräiden materiaalien hyödynnyksessä. Tämä työ keskittyy kahteen materiaaliin, REF:n ja SLF:n, sekä niiden prosesseihin, materiaaliketjuihin sekä uusiin uudistuksiin niiden prosesseissa. Syy näiden kahden materiaali valitsemiseen on, että näiden kahden materiaalin kosteuspitoisuus on ensisijaisen tärkeää kun tarkastellaan niiden kierrätettävyyttä sekä hyödynnettävyyttä.

Kokeellisessa osuudessa näitä kahta materiaalia tutkittiin useaan kertaan niiden kuivuessa kahden viikon ajan huoneenlämmössä. Niitä tutkittiin, arvioitiin sekä valokuvattiin neljän tekijän perusteella koko kuivatusprosessin ajan. Tämän tutkimuksen tavoitteena on mahdollisesti löytää joitain perussääntöjä, jotka voisivat helpottaa materiaalin kosteuspitoisuuden arviointia ilman kuivatusta.

Tulosten joukosta voitiin havaita joitain trendejä tiettyjen kosteuspitoisuuksien välillä. Saatiin myös joitain yllättäviäkin tuloksia, joiden luultiin olevan tärkeitä tekijöitä kosteuden absorpoinnissa oikeastaan olematta sitä. Yksi näistä yllätyksistä oli se, että vaahtomuovin osuudella ei ollut niin suurta vaikutusta kosteuspitoisuuteen kun aikaisemmin oltiin luultu.

Asiasanat (avainsanat)

Kosteus, kierrätys, hyötykäyttö, kierrätyspolttoaine, SLF

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DESCRIPTION

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The effect of moisture in certain wastes and their recovery, processing and recycling

Abstract

The scope of this thesis is to find out the physical factors effecting heterogeneous recycling materials during drying process. Also the aim is to find out some aesthetical changes during drying. The study divides into two parts, theoretical inspection and experimental study.

In the theoretical part the perspective is concentrated on variation of moisture, the physical phenomenon in absorption and evaporation and the effect of moisture in recovery of some specific materials. This thesis focuses on two different materials, REF and SLF and their process, material chain and innovative improvements in processing. The reason why these two materials were picked out is that in these two materials moisture content is essential when talking about recycling and recovery.

In the experimental study these two materials were observed multiple times for two week while drying them in room temperature. There were four different factors that were observed, evaluated and photographed during the drying process. The aim of this observation is to possibly find out some basic rules which could help to identify the materials' state of moisture content without drying.

Among the results, there could be found some trends between different moisture contents. Also there were some surprising results, which were thought being an important factor in moisture absorption that actually weren't. One of these surprises was that the amount of foamed plastics didn't have that big of an effect on the moisture content that earlier were thought.

Subject headings, (keywords)

Moisture, recycling, recovery, recovered fuel, SLF

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SISÄLTÖ

1 INTRODUCTION

This study concentrates on the effect of moisture on recovery, processing and recycling of certain wastes. These materials are recovered fuel, REF and shredder light fraction, SLF. REF is considered as product, because it is treated before it enters the end-user, usually a power plant. SLF on the other hand is considered as waste, that comes as a side fraction from recycling chain of metal scrap.

According to European Union Directive 2000/53/EC by the year 2015 95 % of the material from end-of-life cars has to be recovered or recycled. In order to meet the target EU has stated, something has to be done also to the non-ferrous materials. These materials cover about 25 % of car's weight and the percentage is rising all the time due to composite innovation in automotive industry. SLF cannot be recovered as a solid fuel due to the fact that it is extremely heterogeneous and it can contain some characteristics of hazardous waste, such as oil and other liquids from cars. This fraction has to be processed in order to recycle the materials in it or recover it to heat and energy. (Heiskanen, Kaila, 2013)

REF is a product that is processed from dry industrial waste materials. It is source separated, so it does not presumably include any organic impurities such as food. It is processed in order to meet the REF classification requirements stated in standard SFS-EN 15359 and it has relatively high calorific value compared to many other solid fuels. The calorific value comes mainly from high content of plastics. (Vesanto, Hiltunen, 2007)

Material and energy recovery are introduced in EU legislation in directive 2008/98/EC (European Commission, 2012). The basic principle of the directive is waste hierarchy, also called waste pyramid. The pyramid is cut in five parts, from bottom to top, prevention, preparing for re-use, recycling, recovery and disposal. These five concepts represent the order of waste handling.

Figure 1 Waste hierarchy (European Commission, website)

The first part of the pyramid, prevention, stands that production of waste should be avoided. The second part, preparing for re-use, stands that the product should be re-used as it is meant to be used. For example old clothes belong to flea market, not to rubbish bin. The third part, recycling, means that the produced waste, if it's not re-usable, should be recycled as material. For example PET-bottles are melted after use, and produced as new bottles. The fourth part, recovery, means that the energy inside the produced waste should be recovered for example in incineration and afterwards produced to heat or electricity. The last part, disposal, means that the produced waste should be disposed of in a way that it is no harm to the environment, human health, animals or anyone handling the waste. (European Commission, website)

This thesis is divided into two parts, theoretical examination and experimental part. In the theoretical part the target is to clarify the mechanisms of absorption and evapora-tion processes of heterogenic materials. Also the target is to study what sort of prob-lems or benefits moisture brings when it comes to processing and recycling these stud-ied materials. In the experimental part the target was to observe the materials during drying process in room temperature and find out the possible changes in physical and aesthetical characteristics during the process. These factors and possible tricks to evaluate moisture content without drying the materials are extremely useful for staff members throughout the processes.

The studied materials can also be explained with waste hierarchy. REF is mostly source separated, so the sorting has been already made between sections which are recyclable as material and which have to be recovered as energy. This material is also a fraction from separating process in recycling yard's own fields. So REF can be placed in recovery-section in waste hierarchy and can be said that all the clean recyclable material has been separated already from the material.

SLF on the other hand is a different case compared to REF, because it was disposed in Finland to landfills up until 1.1.2010 due to its extremely heterogeneous structure. (Zevenhoven, Saeed. 2003) SLF is nowadays stored in intermediate storages. The maximum storage time is three years according to Finnish waste legislation. After these three years, the waste is considered taxable. (Finland's environmental administration, website) After three years, the material needs to be processed and recycled. (Kutila, 2013)

2 STENA RECYCLING OY AND ITS PROCESSES

Stena Recycling Oy (later referred as Stena) is a recycling company originated from Sweden. It was established in 1939 by Sten Allan Olsson who started the business with trading scrap and raw rubber. The company is still owned by the Olsson family and nowadays the Stena Metall group, which Stena Recycling Oy belongs to, works in many business areas, not only recycling, for example offshore drilling and ferry lines. Stena operates in Sweden, Norway and Finland and also in Poland and Denmark and has business partners all over the world. (Stena Metall Group, homepage)

Recovered fuel (REF) consists in this case dry residue from different industries such as packaging and paper industries. Therefore REF should not be confused with municipal solid waste, (MSW). There are two important differences between these two materials and one of them is moisture. Moisture content of MSW comes mainly from food waste and therefore the moisture content is higher than in industrial waste. In worst cases, the amount of food waste in MSW can be up to 50-80 %. (Tchobanoglous, 2002) The other important difference is that REF is a product as itself. MSW on the other hand is a material which is waste, which can become a product only after productizing. (Kutila, 2013)

REF is classified in five different categories, from REF I to REF V. These classes are defined in standard SFS-EN 15359, which explains the properties of different categories. The variables of different categories are net calorific value, chlorine and mercury contents. The material can be a mix of different categories, for example it can have mercury value according to REF I but have chlorine value according to REF III. The values are shown in Table 1. Net calorific value or lower calorific value is the amount of heat energy when water is in gaseous phase. So the heat of vaporization for water is decreased from the higher calorific value. (Halliday, Resnick, 1993)

TABLE 1 REF Classification (SFS-EN 15359)

Classification	Net calorific value MJ/kg	Chlorine %	Mercury mg/MJ	
	Mean	Mean	Median	80th percentile
1	≥ 25	$\leq 0,2$	$\leq 0,02$	$\leq 0,04$
2	≥ 20	$\leq 0,6$	$\leq 0,03$	$\leq 0,06$
3	≥ 15	$\leq 1,0$	$\leq 0,08$	$\leq 0,16$
4	≥ 10	$\leq 1,5$	$\leq 0,15$	$\leq 0,30$
5	≥ 3	≤ 3	$\leq 0,50$	$\leq 1,00$

In some cases REF can be delivered as a fuel straight from the source to end-user, but mostly the materials are processed before delivery. Usually the process includes one or two crushers and magnetic separator. For separating non-ferrous metals from the material the plant might also have an eddy current separator. (Tchobanoglous, 2002)

To ensure quality good of the fuel and to minimize the need of processing, it is important to have good source separation. Usually the recycler has informed customers not to put certain products and materials among the material to keep the quality of the final products good. These materials are mostly food, metals, hazardous wastes and PVC-plastic. All of these materials have straight effect on the materials processability and composition. (Tchobanoglous, 2002)

The other studied material is called SLF, Shredder Light Fraction. SLF is produced mostly in industrial recycling of metal scrap, like automotive scrap. The process usually happens in three steps. In the first step ELVs, end-of-life vehicles, are received in the recycler's yard, which must be legal representative. There the car is dried from fluids and the wheels are removed. After this step the car is delivered to a shredder, where most of the iron based and non-ferrous metals are extracted. The material left from this process is called Auto Shredder Residue, ASR. (Srogi, 2007) According to K. Srogi (2007) ASR includes materials shown in Table 2.

TABLE 2 Materials that usually can be found in ASR (Srogi, 2007)

Material	Weight percent [%]
Plastic	19-31
Rubber	20
Textile and fibre materials	10-42
Wood	2-5
Metal	8
Oil	5

ASR can be divided in two fractions, SLF and Shredder Heavy Fraction, SHF, which is shown in the picture 1 as fraction number 2. This fraction is produced after ferrous materials are separated from the material with magnets. SHF usually contains high density plastics, and some nonmagnetic metals. With separating these non-magnetic metals the materials can be used as fuel in several industries and metals can be used in zinc-coating shops. The difference between these two materials, SLF and SHF is that SLF is separated from the matrix material by sucking above the shredded core with air and SHF is the material that is left after treating the material with magnets and air separation. (Srogi, 2007)

SLF is considered as hazardous waste mostly due to its heterogeneous composition and heavy metal content. (Heiskanen, Kaila, 2013) In some cases and countries it can be considered also as municipal solid waste, depending on its chemical characteristics. (Ciacci, Morselli, 2010) The studied material, SLF is extremely heterogeneous, so it is quite hard to sample and demonstrating the ingredients are almost impossible due to the fact that every sample is different and might not be representative. (Kutila, 2009)

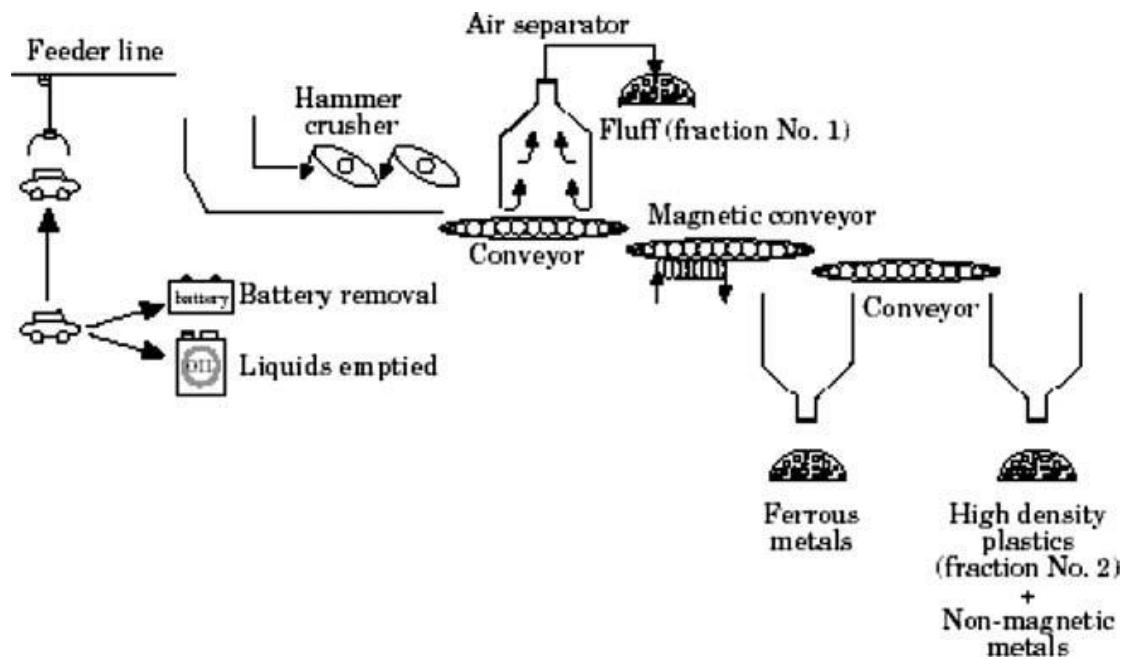SLF represents about 50 % of the whole stream of both SLF and SHF. (Heiskanen, Kaila 2013)

Figure 2Automotive wreck elimination process (Srogi, 2007)

In figure 2 there is shown an elimination process of automotive wreck. According to this figure SLF is shown after air separation, in the picture called as fluff, fraction number 1. SHF on the other hand is in the last line of the elimination process, called high density plastics, fraction number 2. Together these two fractions can weigh up to 25 % of the vehicle's weight. (Srogi, 2007)

In Table 3 there is shown three different samples that have been sorted out. First the amount of material is squared so that there is less than 1000 grams to separate. Then the material is separated in to two different categories, over and under 10 mm pieces. After that the material is sorted out by material types. This table shows the fact that the material is extremely heterogenic and the composition can vary each moment depending on the separation process. (Kutila, 2009)

TABLE 3 Sorting results of three different SLF-samples (Kutila, 2009)

	Sample 1 (%)	Sample 2 (%)	Sample 3 (%)
>10 mm	49,3	53,7	23,9

< 10 mm	50,7	45,0	75,5
Metals	2,1	4,1	4,6
Soft Plastic	5,5	6,1	9,1
Pad and foamed plastic	18,3	25,0	0,7
Hard plastic	13,1	11,5	14,3
Rubber	2,5	3,0	1,3
Fabrics	1,0	2,0	0,4
Paper and Cardboard	6,7	1,9	2,0
Wood	16,4	8,3	5,9
Cable	1,4	0,5	2,1
Stone	0,4	0,7	0,3
< 5 mm and unsorted	32,6	36,8	59,3
Total	100	100	100

3 MOISTURE

Moisture is the amount of water absorbed into the material as vapor or liquid. It can be expressed in two separate ways, as a percentage of the wet weight of the sample or as a percentage of the dry weight of the sample. The wet weight method is used more often and the formula for expressing it is

$$M = \frac{(w-d)}{w} \times 100\% \qquad , \text{where} \qquad (1)$$

M= moisture content, %

w=sample weight as delivered

d=sample weight after drying

(Tchobanoglous, 1993)

3.1 Determination

When determining moisture content in solid fuels, the method is usually based on the ISO 589 standard. The standard stands that the samples are in air conditioned aging oven at 105℃ until the weight is stable. Usually this method takes about 16 hours,

when the samples are laid down as a carpet that is max 3 cm thick. Drying of the samples over 24 hours is not recommended. This technique is called loss of drying (LOD). (Alakangas, 2000)

A method used for coal DIN 51 718 what is also called as kiln drying method. According to this method, the sample is at temperature of 105℃ as long as the weight loss is 0,05 % in 30 minutes. (Standardisierung biogener Festbrennstoffe, 2002) This method is also used for other solid fuels. Both of the moisture contents are calculated with formula (1).

3.2 Variation of moisture

Because the studied materials are collected, processed, handled and stored outdoors, the weather can play a big role in variation of moisture. (Tchobanoglous, 2002) Finland is geographically placed in a so called intermediate climate, which has characteristics from both, maritime and continental climate. The weather is highly connected with wind directions and how high and low pressures are situated. The annual amount of rain varies from 500 to 650 mm. The driest area is Lapland and the wettest areas are in the southern and central parts of inland. The amounts of rain are highest during summer, and the driest season is spring. The number of rainy days is much higher during the winter and autumn than in the summer. (Meteorological office, 2012)
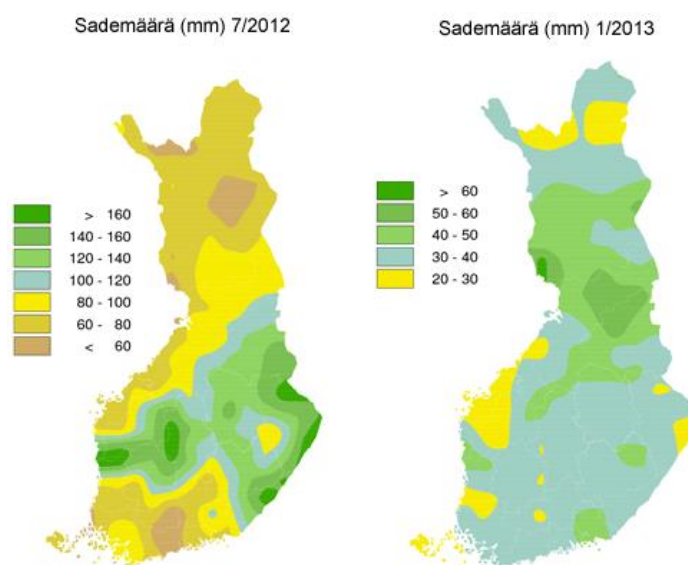

Figure 3 the amounts of rain in July 2012 and January 2013 (Meteorological office)

As can be seen from the figure 3, the difference between the amounts of rain can vary significantly within 6 months. For example in Pori or in the west cost the difference, according to the Meteorological office of Finland, illustrated in the figure 3, can be over 100 mm. Also near Russian border the difference can rise up to 80-90 mm. This information is only valid for this particular half and year.

Not only temperature and the amount of rain are the factors for describing the weather but also relative humidity and dew point have a big role in weather.

Different wastes have different characteristics when it comes to moisture content and specific weight. As it can be seen from table 4, the typical moisture contents vary from nearly 100 % to 0 % depending on the materials. Typically municipal wastes include more moisture than commercial that can be also stated from the picture. Usually this is because food waste is mixed in the municipal wastes, therefore the moisture content can rise up to 40 % while commercial waste rises to 30%. (Tchobanoglous, 1993)

This 10 % difference is minimal compared to the differences between organic wastes where the typical moisture content can rise up to 94 % (manure). These single fractions including wood and food have definitely the highest moisture content. These materials include water as themselves, because they are living organisms and they photosynthesize, where water is essential to produce glucose and oxygen. (Tchobanoglous, 1993)

TABLE 4 Typical specific weight and moisture content data (Tchobanoglous, 1993)

TABLE 4-1
Typical specific weight and moisture content data for residential, commercial, industrial, and agricultural wastes

Type of waste	Specific weight, lb/yd³		Moisture content, % by weight	
	Range	Typical	Range	Typical
Residential (uncompacted)				
Food wastes (mixed)	220–810	490	50–80	70
Paper	70–220	150	4–10	6
Cardboard	70–135	85	4–8	5
Plastics	70–220	110	1–4	2
Textiles	70–170	110	6–15	10
Rubber	170–340	220	1–4	2
Leather	170–440	270	8–12	10
Yard wastes	100–380	170	30–80	60
Wood	220–540	400	15–40	20
Glass	270–810	330	1–4	2
Tin cans	85–270	150	2–4	3
Aluminum	110–405	270	2–4	2
Other metals	220–1940	540	2–4	3
Dirt, ashes, etc.	540–1685	810	6–12	8
Ashes	1095–1400	1255	6–12	6
Rubbish	150–305	220	5–20	15
Residential yard wastes				
Leaves (loose and dry)	50–250	100	20–40	30
Green grass (loose and moist)	350–500	400	40–80	60
Green grass (wet and compacted)	1000–1400	1000	50–90	80
Yard waste (shredded)	450–600	500	20–70	50
Yard waste (composted)	450–650	550	40–60	50
Municipal				
In compactor truck	300–760	500	15–40	20
In landfill				
Normally compacted	610–840	760	15–40	25
Well compacted	995–1250	1010	15–40	25
Commercial				
Food wastes (wet)	800–1600	910	50–80	70
Appliances	250–340	305	0–2	1

(continued)

Commercial (cont.)				
Wooden crates	185–270	185	10–30	20
Tree trimmings	170–305	250	20–80	5
Rubbish (combustible)	85–305	200	10–30	15
Rubbish (noncombustible)	305–610	505	5–15	10
Rubbish (mixed)	235–305	270	10–25	15
Construction and demolition				
Mixed demolition (noncombustible)	1685–2695	2395	2–10	4
Mixed demolition (combustible)	505–675	605	4–15	8
Mixed construction (combustible)	305–605	440	4–15	8
Broken concrete	2020–3035	2595	0–5	—
Industrial				
Chemical sludges (wet)	1350–1855	1685	75–99	80
Fly ash	1180–1515	1350	2–10	4
Leather scraps	170–420	270	6–15	10
Metal scrap (heavy)	2530–3370	3000	0–5	—
Metal scrap (light)	840–1515	1245	0–5	—
Metal scrap (mixed)	1180–2530	1515	0–5	—
Oils, tars, asphalts	1350–1685	1600	0–5	2
Sawdust	170–590	490	10–40	20
Textile wastes	170–370	305	6–15	10
Wood (mixed)	675–1140	840	30–60	25
Agricultural				
Agricultural (mixed)	675–1265	945	40–80	50
Dead animals	340–840	605	—	—
Fruit wastes (mixed)	420–1265	605	60–90	75
Manure (wet)	1515–1770	1685	75–96	94
Vegetable wastes (mixed)	340–1180	605	60–90	75

Adapted in part from Refs. 6 and 8.
Note: lb/yd³ × 0.5933 = kg/m³

3.3 Water absorbability of different heterogenic materials

Water absorption in this particular case means the amount of water absorbed into a certain material as free water or vapor. The term absorption is also used when describing for example acoustics and electromagnetic radiation. The standardized method for

determining liquid water absorption is in standard ISO 62. This standard is especially for plastics but it can also be applied to other materials. The test is carried out in specified conditions and the dried material is exposed to water for certain amount of time. The result is shown as a percent increase in weight. (ISO 62:2008)

Other type of water absorption is humidity absorption, where the absorbent water is in gaseous phase. This type of absorption occurs more in nature, because of humidity in air. Determining the amount of water absorbed into material the standard ASTM D570 is used. This standard is also meant for plastics, but it is applicable to other materials as well. It is technically the same test as ISO 62. Water can be absorbed in to material in numerous ways, chemically, with adhesive forces, in materials capillaries, with osmotic pressure and as a free vapor. (Hautala, Peltonen 2002)

Different materials absorb water differently. For example a sponge can soak up many times more water than a rock or a piece of metal. Within plastics the values of absorption can vary significantly. Figure 4 shows the differences more clearly.
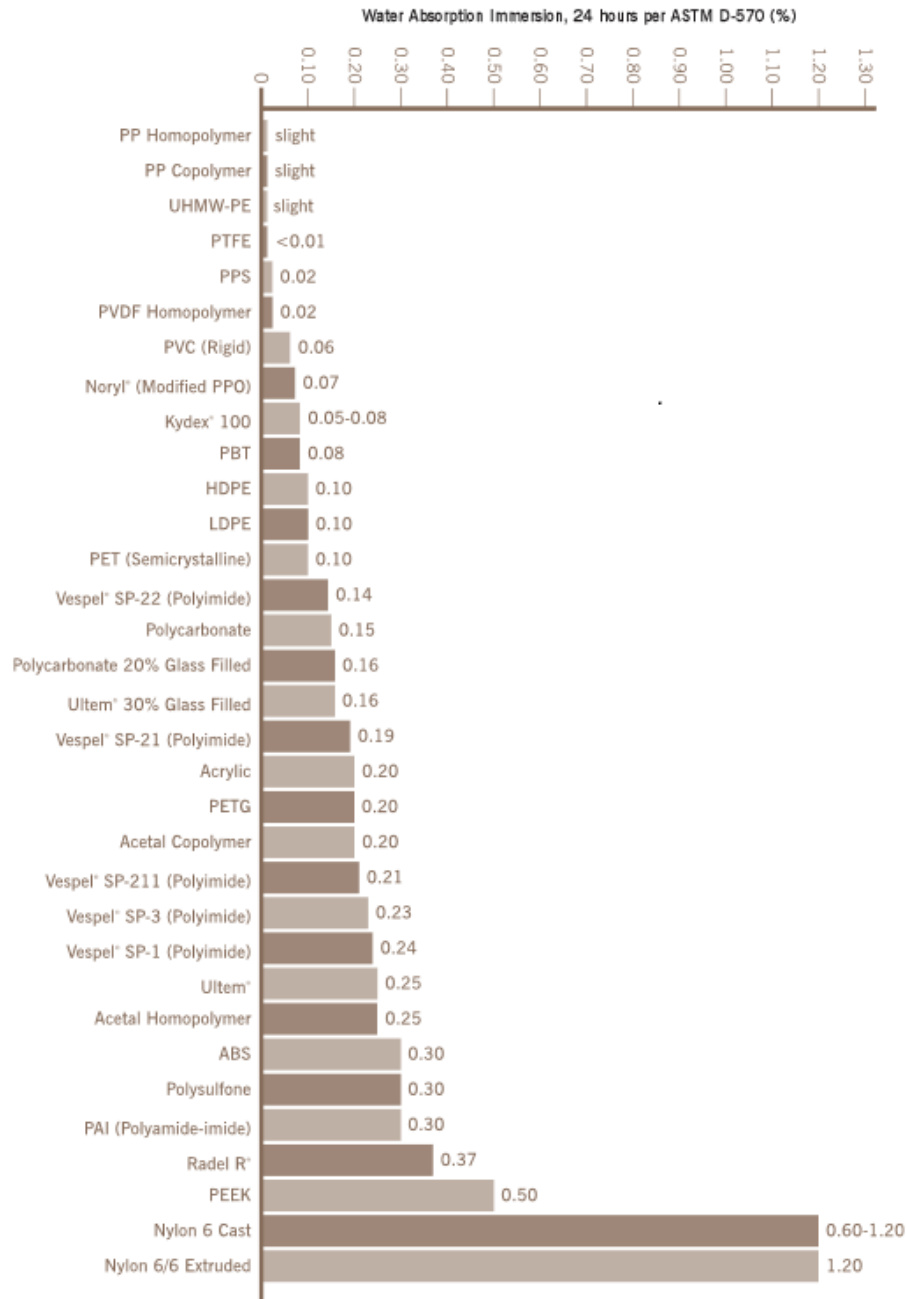
Water Absorption Immersion, 24 hours per ASTM D-570 (%)

Material	Value
PP Homopolymer	slight
PP Copolymer	slight
UHMW-PE	slight
PTFE	<0.01
PPS	0.02
PVDF Homopolymer	0.02
PVC (Rigid)	0.06
Noryl® (Modified PPO)	0.07
Kydex® 100	0.05-0.08
PBT	0.08
HDPE	0.10
LDPE	0.10
PET (Semicrystalline)	0.10
Vespel® SP-22 (Polyimide)	0.14
Polycarbonate	0.15
Polycarbonate 20% Glass Filled	0.16
Ultem® 30% Glass Filled	0.16
Vespel® SP-21 (Polyimide)	0.19
Acrylic	0.20
PETG	0.20
Acetal Copolymer	0.20
Vespel® SP-211 (Polyimide)	0.21
Vespel® SP-3 (Polyimide)	0.23
Vespel® SP-1 (Polyimide)	0.24
Ultem®	0.25
Acetal Homopolymer	0.25
ABS	0.30
Polysulfone	0.30
PAI (Polyamide-imide)	0.30
Radel R®	0.37
PEEK	0.50
Nylon 6 Cast	0.60-1.20
Nylon 6/6 Extruded	1.20

Figure 4 Water absorption of different plastics (Curbell plastics)

As can be seen from the figure 4, nylon also known as polyamide, absorbs most of all the different plastics. The maximum value that nylon reaches is 1,2 % moisture increase in total mass after 24 hour immersion. This value is more than 10 times higher compared to other commonly used plastics, such as HDPE or PET with maximum moisture increase 0,1 %. The two values for casted and extruded nylon have the highest values of the figure, although the difference between these two can be up to 50 %.

This difference is caused by physical characteristics in production. Extrusion and casting differ in many ways, but the most significant difference is the used pressure. Also the amount of hydrocarbons affects the absorption value. These two different types of nylon shown in the figure 4, Nylon 6 and Nylon 6/6 have very short hydrocarbons. The number after prefix PA means the number of hydrocarbons before amide-group. If there are two numbers mentioned, it means that it consists of two types of monomers. (Valuatlas, website) The values in the table are from the test ASTM D-570, which was explained earlier.

In heterogenic materials the difference between absorption rates can of different phases play both, big or small role depending on the phases weight percentage. In this case wood is one of the materials that is from the nature and has characteristics that very rare materials have, such as hygroscopicity which means that the material has the ability to soak up humidity from the air to its molecules. Hydroscopic materials include cellulose, such as paper, cardboard and sugar. Wood also has capillaries, which are supposed to transfer water from the ground all the way up to the top of tree and its branches; this is so called capillary action. This phenomenon happens when cohesive forces inside water are greater than adhesive forces between the surface of capillary and water, in other words water's surface tension is greater than the forces that come from outside. Not only wood have capillaries, but also other porous materials, such as paper. Cohesive forces are the forces inside a material, in this case water. Adhesive forces are the forces between two different materials, in this case water and the capillaries. Water has big surface tension because of the strong polar hydrogen bonds in the surface within the water molecules. (Hautala, Peltonen, 2002) The main attraction in this case is in the water that can be absorbed from outside such as rain, surrounding water and relative humidity.

Density and water diffusivity of different woods are the factors that the amount of water capable to absorb is dependent on. Diffusivity is molecular movement between two different concentrations towards the balance. The water diffusivity coefficient (D) in solid materials determines the rate how water moves from the surface to the inner parts of the material. These two factors are a result of wood being a porous material and its chemical components are pretty reactive. (Khazaei, 2008) This law, which determines the diffusivity coefficient, is called Fick's first law and the formula is

$$q_n = -DA\frac{\Delta c}{\Delta x} \qquad\qquad \text{, where} \qquad\qquad (2)$$

q_n= material flow (kg/s)

D = Diffusivity coefficient (m^2/s) specific for each material

A = Cross-sectional area (m^2)

Δc = Difference of concentration (kg/m^3)

Δx = Length (m)

In gases the diffusivity coefficient is about 10^{-5} m^2/s, in liquids 10^{-8}…10^{-9} m^2/s and in solid materials about 10^{-11}…10^{-12} m^2/s. When talking about porous materials, the diffusivity coefficient is around air's value, because diffusing happens mostly through air holes. (Hautala, Peltonen, 2002) Diffusivity is usually determined by observing a component A in a very little concentrated mixture B. So always when presenting diffusivity coefficient, it has to be told that what are the two components effecting with each other. In a way it can be compared to friction coefficient. (Aalto University, Course of Chemistry equipment technique part 4)

In heterogeneous materials and especially these REF and SLF, the amount of so called fines is significant; as can be seen also from Table 3 on the page seven. The weight percent of this fraction can be up to 60 % and it is the heaviest fraction of the whole matrix. (DeGaspari, 1999)

These fines are mostly dust and the fraction size is mostly smaller than 5 mm. The absorption of this material can be explained with materials that are related to sand. If we take one glass full of sand and we add water to the glass, the amount of water can be even 50 % of the volume of sand. This is because the water gets in between the sand grains and fills up the wholes. In this case, the absorption rate of sand is insignificant compared to other materials. But when these grains are materials that can absorb water, it's a whole different story. (Hautala, 1998)

The surface area of porous materials is large, especially when it contains these small fractions. The more surface the material has, the more water can be absorbed. If this phenomenon is shown with an example of two different materials, porous and rough

the difference of surface area is seen more clearly. In the rough material, the mass is 1 kg and the pieces are balls with radius of 3 cm with density of HDPE ($0,941$ g/cm^3) The material with small pieces has the same mass, but balls with radius of 0.5 cm and same density. The surface area can be calculated with simple geometric equations. The results of the comparison are shown in Table 5.

TABLE 5 Surface areas in porous and rough materials

	Rough material	Porous material
Mass of sample	1 kg	1 kg
Density	$0,941$ g/cm^3 (HDPE)	$0,941$ g/cm^3 (HDPE)
Volume for one ball	113,04	0,523
Mass for one ball (g)	106,37	0,492
Balls in kilogram (pcs.)	9,4	2302,5
Area for one ball (cm^2)	113,04	3,14
Area for all balls (cm^2)	1062,6	7229,9

According to table 5, we can state that the difference of surface area between rough materials and porous materials is significant. In this specific case the bigger object had nearly 15 % of the surface area of the smaller fraction. When this surface is able to absorb a certain amount of water, the difference in moisture content can rise high.

When this dusty material is exposed to water, the molecules start to layer up to the surface. When there is enough water, the layers grow big enough that they affect each other and pull the dust closer to each other with the power of cohesive forces. This is so called bonding effect, where the dust particles "attract" each other and therefore form big lumps. (Hautala, 1998)

3.4 Water evaporation of different heterogenic materials

Evaporation means that the state of some liquid changes to gaseous phase. Usually this happens for example when boiling water. The energy that is moved to liquid water is high enough to cut the strong hydrogen bonds between water molecules' and the material starts to evaporate. When pressure remains stable the temperature in the material doesn't change during boiling or melting. The energy is going to change the

state. (Lehto, Luoma, 1995) Although it has to be made clear, that evaporation differentiates from boiling dramatically. When talking about boiling there is always high temperatures involved whereas evaporation happens at lower temperatures and all the time.

Molecules of one substance, in this case water are on a constant change. Although water might be in liquid phase, in open space the molecular movement is so fast that its kinetic forces overcome the cohesive forces and departs from liquid and enters the air as gas. This movement between phases which does not include rising temperature is called evaporation. With this phenomenon comes along with a term of heat of vaporization which defines a quantity of heat that liquid must absorb for 1 g to be converted to gaseous phase. Water has a high heat of vaporization compared to other materials which have approximately same molecular masses. For example at 25°C for evaporating 1 g of water 580 cal is needed but for heating ammonium or butane only half of the energy is needed. The reason why water has high heat of vaporization is that the hydrogen bonds between water molecules are much stronger than for example between hydrocarbons. Heat of vaporization can be calculated when normal boiling point is known. (Reece, Urry 2011) When the same phenomenon happens from solid to liquid phase, the energy needed for transformation is called heat of fusion. (Halliday, Resnick, 1993)

When observing some soaking wet porous materials the drying process is classified in three steps. These three steps have been named according to the drying speed and rate. (Lorne, Davis 2011) Figure 5 shows theoretically the drying as a function of time. First when the sample is in the so called critical moisture phase, where the water from the capillaries moves away as fast as the surface evaporates until the hydraulic continuity is broken. At this point the drying is highly connected with factors from surroundings and is linear with time. The border line between soaking wet and somewhat dry moves towards the center as the drying in this period takes place. This period is called constant rate period, CRP. (Lorne, Davis 2011) In the figure, this phenomenon happens during the first hour. After the first step in between whiles 1-2 hours the capillaries are empty and the only mechanism of drying is diffusion from inside of the sample. Here the water can move around as vapor because the pores are not any longer filled with water. This part is called the first falling rate period, FRP1 and the speed

of drying declines on average as a square root of time. (Lorne, Davis 2011) The third part, in the figure from 2 to 3 hours is when the entire sample reaches the critical amount of moisture and the speed of drying reduces close to zero. (Hautala, Peltonen 2002) This step is second falling rate period FRP2 and during this time the rate of drying is even slower than a square root of time. (Lorne, Davis. 2011)
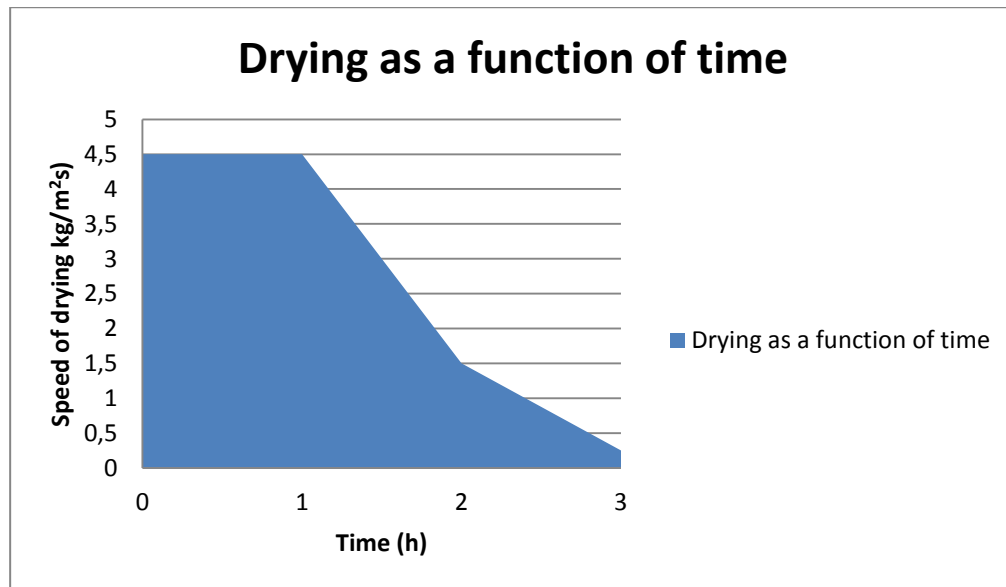

Figure 5 Drying as a function of time (Hautala, Peltonen 2002)

The first two steps occur well at the room temperature and humidity, because the capillary water evaporates when the relative humidity is under 98 %. The last amount of water left in the material is chemically combined, non-evaporable water which is combined with adhesive forces in the surface and is only a couple of molecules thick. This type of moisture is called residual moisture. Only hydrophilic surfaces can include non-evaporable water. (Hautala, Peltonen 2002) The limit of molecule layers is about 10 molecules. When the layer is thicker, the water starts to act like free water, no longer like ice. (Hautala, 1998)

As mentioned earlier in this chapter, temperature and circumstances play a big role in drying. Relative humidity, later referred as RH is one of the basic factors when describing circumstances. RH is calculated with formula 3 and 4. (Hautala, Peltonen 2002)

$$RH = \frac{p}{p_w} \times 100\% \qquad , \text{where} \qquad (3)$$

p = partial pressure of water vapor (kPa)

p_w = saturated vapor pressure of water (kPa)

When temperature is stable p_w tells how much there can be water vapor in the air. This value changes at the same time with temperature. When temperature rises 1 %, the saturated vapor pressure rises 10 %. Air is saturated with water vapor when p=p_w. The formula can also be shown with values of humidity, like shown in formula 4, (Hautala, Peltonen 2002)

$$RH = \frac{\rho}{\rho_w} \times 100 \text{ \%} \tag{4}$$

where ρ [kg/m^3] stands for absolute humidity of air and ρ_w [kg/m3] for maximum humidity at certain temperature. When temperature raises both values rise at the same time. This fact supports the general idea of drying happening faster in warmer atmosphere. In table 6 there are some values of saturated vapor pressure and maximum humidity at different temperatures. (Hautala, Peltonen 2002)

TABLE 6 Saturated vapor pressure and maximum humidity at different temperatures (Hautala, Peltonen 2002)

t(°C)	-10	0	10	20	50	80	100	120	200
p_w(kPa)	0,29	0,61	1,23	2,34	12,3	47,3	1,1	200	1500
ρ_w(g/m^3)	2,36	4,85	9,41	17,3	82,5	290	588	1100	6900

It is noticeable how fast the values are rising, even at rather low temperatures. When the temperature increases from 0 °C to 10 °C the maximum humidity content almost doubles and the temperature increase from 10 °C to 20 °C achieves humidity content which is four times as big as at 0°C. This means that at room temperature of 20°C the amount of water that is capable of vaporizing in the air is four times bigger than at the temperature of 0°C.

When humid air is cooled down in closed space and the absolute humidity doesn't change, the maximum humidity raises, according to formulas 3 and 4. Therefore at

some point the air gets saturated and the water starts to condense. This point is called condensation temperature or dew point. (Halliday, Resnick, 1993)

When drying materials outside, it would be good if the temperature would be high and there would be a little wind. This is because when temperature is rising, also maximum humidity ρ_w and saturated vapor pressure p_w are rising as can also be seen from the table 5. When these two values are rising, it means that more water can be present in the air at that temperature. When the concentration difference is greater, more water from the material is needed to equalize the concentration. The wind brings dry air to the surface, where the water is evaporating away therefore making the reaction faster. (Hautala, Peltonen, 2002)

When talking about wood and its moisture content, it has to be noted that the moisture depends on the relative humidity and the temperature of surroundings. The point, where wood can't neither loose nor gain moisture from the surroundings in steady state is called Equilibrium Moisture Content EMC. Figure 6 shows the relationship more clearly. (Hautala. 1998)
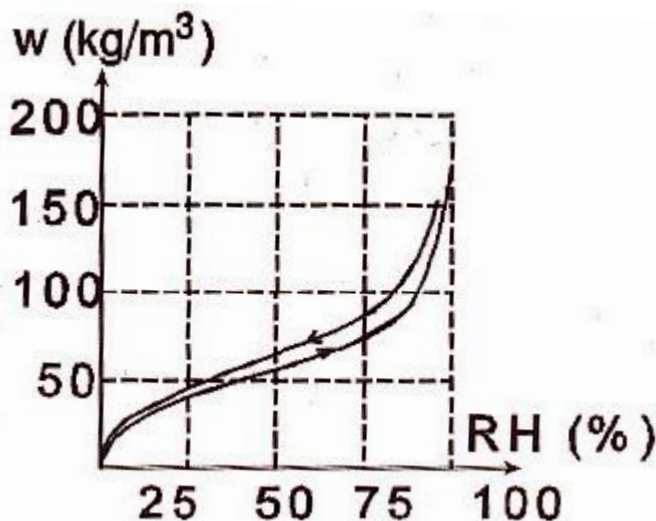
Figure 6 Equilibrium Moisture Content for pine (Hautala, 1998)

Figure 6 shows the relationship between relative humidity of environment and the amount of water in woods unit volume. The fast increase in the water content, when

RH≈70 % occurs because the water inside the capillaries reduces the vapor pressure and therefore the concentration is bigger. (Hautala, 1998)

The Figure 7 illustrates statistical information for several days about relative humidity in Jyväskylä, Finland in May 2007. The reason for the public statistics is that then the relative humidity of air was unusually high in the central parts of Finland, in Jyväskylä. Besides, that the values were high, the normal variation and a relationship between temperature and relative humidity can be seen clearly from the figure 7. (Meteorological office, monthly statistics)
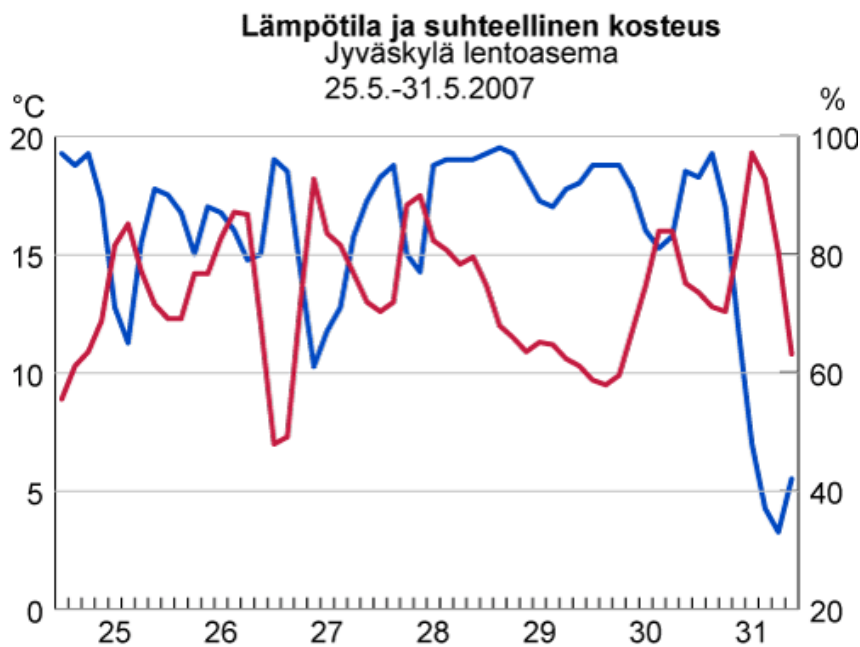
Figure 7 Relative humidity and temperature in Jyväskylä. Blue curve refers to relative humidity and the red curve to temperature. (Meteorological office, website)

The red curve in the figure represents temperature and its values are on the left and the blue curve is for relative humidity with values on the right. As it is quite clearly shown in the figure, the relationship between these two values is strong. When the temperature is rising, the relative humidity is decreasing because the absolute water vapor content of the air does not change.

Other statistical information about relative humidity is shown for last two days of observation. This information is published for each weather observatories in Finland. In

figure 8 is shown relative humidity from 26th to 28th April in Helsinki, Kaisaniemi. In figure 9 the temperature is shown at the same times as the relative humidity.

Figure 8 Relative humidity in function of time (h) (Meteorological office, website)
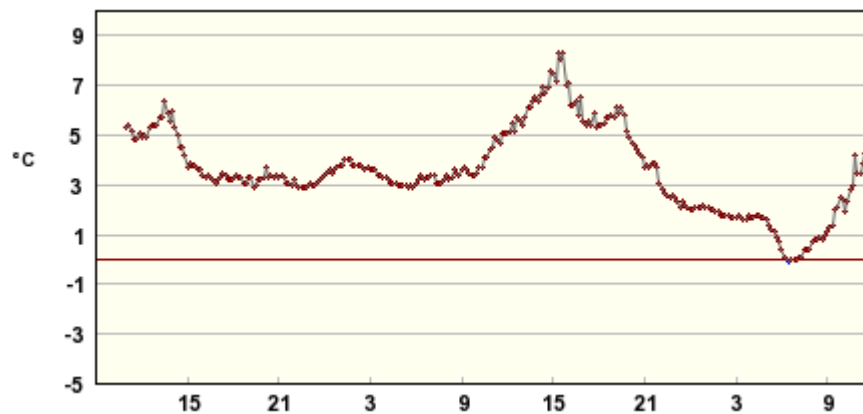

Figure 9 Temperature in function of time (h) (Meteorological office, website)

The relationship between temperature and relative humidity can be seen from the figures. When the temperature decreases, for example between 3 am and 9 am in end of the figure, at the same time the relative humidity rises significantly in the figure 8. Also when the temperature increases in the half way of the figure 9, at 15 pm, the humidity decreases rapidly in the figure 9.

3.5 The effect of moisture in different processes

Before reusing or recovering the recycled materials, processing is usually a necessary operation to do. Two main processes are most usual and widely used size reduction

and separation methods. (Tchobanoglous, 1993) From these two, separation methods are most often used to make SLF and crushing is used to REF's size reduction.

3.5.1 Size reduction methods

As mentioned in the earlier chapter, crushing is commonly used method for size reduction. There are also other methods which are divided to two different categories, high-speed impact equipment and high-torque shear equipment. High-speed impact equipment is a unit that operates at high speed. These sorts of equipment are for example hammer mills, flail mills and rotary grinders. Hammer mill that is also shown in figure 2 on page 6 is used when rough size reduction is needed and it needs to be done via cutting. With hammer mill it is also possible to produce material with specific maximum particle size but with the approval of wide range of particle sizes. Hammer mills tend to be noisy and generate lots of dust while working. (Tchobanoglous, 2002) Hammer mills are usually used for crushing ELVs, construction and demolition wastes and paper wastes. (Christensen, 2010)

High-torque shear equipment is the stations where the size reduction operates at lower speed, but with much higher torque. When using these devices, also hydraulic power is used. Shearing and shredding are most widely used high-torque shear equipment. (Tchobanoglous, 2002) These shredders and shears have counter rotating blades that shear material as it is input into the center of two or one counter rotating shafts. The size is reduced and small enough particles are dropped down between the shafts. These shredders are not only good for bag breaking, but also have the benefit for creating less dust and are safe to use when explosives are potential in the material. (Tchobanoglous, 1993) Figure 10 represents a shredder, which has only one counter attached and the screen surrounding it separates the particles by size. (Christensen, 2010)
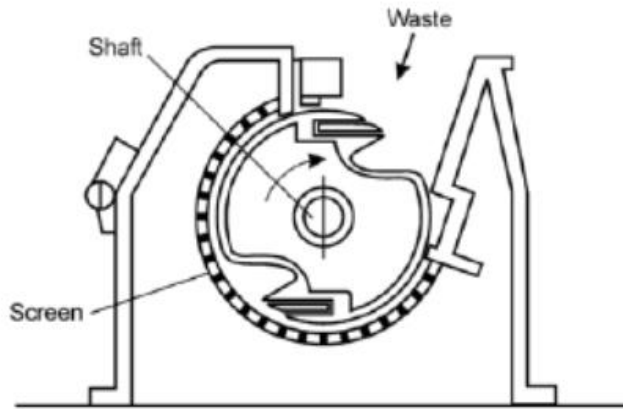
Figure 10 Shredder with one rotating counter (Christensen, 2010)

3.5.2 Separation methods

There are five different factors to differentiate recycling materials which are size, magnetism, density, electrical conductivity and color. (Tchobanoglous, 2003) In this thesis the purpose is to focus on size, density and magnetism.

When separating material by size, there are three most commonly used methods, vibrating screening, rotary drum screening and disc screening. Vibrating screen works like filter on the move, material is put on top of the filters and by vibrating the material moves over and the oversized particles are filtered out. Rotary drum screening is also filtering, but the material moves in a tube that rotates and filters the oversized particles out by having the filter in the walls of the tube. Disc screening has a table full of discs where on top the material is fed. The oversized particles move away as the discs rotate and the wished sized particles fall through. (Tchobanoglous, 2003)
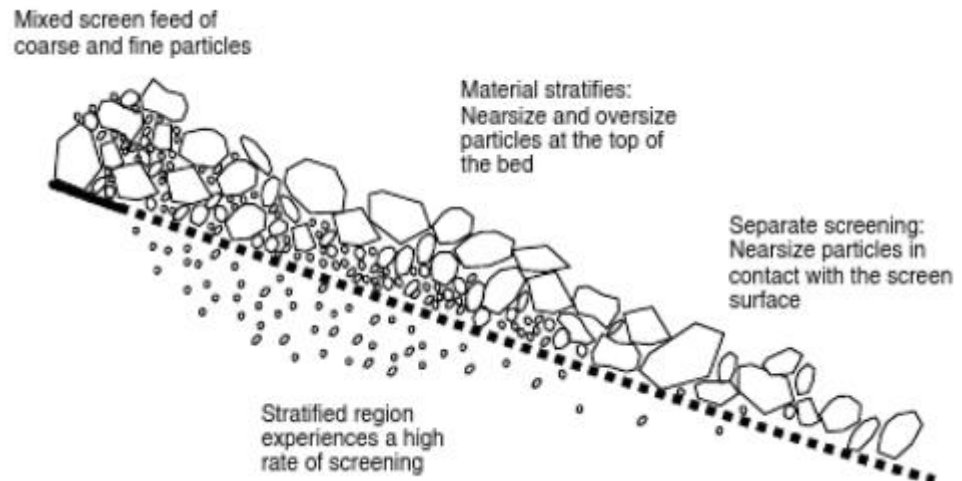
Figure 11 Principle of screening process (Wills, 2006)

With these screening processes, moisture is one of the key characteristics affecting the process among particle-size distribution, particle shape, bulk density, flowability, friability and static charge. Surface moisture can have a significant negative effect on the performance, because high levels of moisture bind particles together and therefore they can be screened out as too large objects. Also surface moisture can increase the state of clumping by having the same effect than binding. (DeCenso, 2000) These negative affects show especially when screening out small particle sizes of, around 0,5 cm max. According to Yepsen (2008) when recycling demolition waste, horizontal screens do not work for wet and sticky materials. He stated that when the material is too wet, the screens can get clogged. (Yepsen, Rhodes 2008) As a thumb rule, particles smaller than 5 mm, the screening must be performed to completely dry materials. (Wills, 2006)

There are few ways to prevent this binding and clumping when working with damp materials, for example heating the screens. The heat breaks the surface tension of water between the screen wire and particles. Also placing so called ball-deck underneath the screen bringing additional vibration could help dealing with these materials. (Wills, 2006)

Another separation type is when separating ferrous material from other wastes. This type of separation is called magnetic separation. This application is shown in figure 2 on page 6 right after air separation station. When separating material according to

their magnetic properties, it happens above the conveyor belt. In the separation station there can be only one belt or two belts. When working with one belt, the magnet is placed at the end of the belt to separate the ferrous material. The other option is that the magnet is in the moving conveyor belt on top of the moving shredded waste stream underneath. (Tchobanoglous, 1993)

One of the ways to separate certain materials from other materials is to sort them by density. The most commonly used method is air separation, where so called light fraction separates from heavy fraction. This application is shown in also in figure 2 on page 6. Air separation is mostly used when organic material is separated from inorganic material, such as metals. When materials with different weight are fed to moving air stream rather high speed, the light materials will float with the air while the heavier materials will fall down opposed current. (Tchobanoglous, 1993)

3.6 The effect of moisture in material and energy recovery

Moisture can ruin many materials in a way that they are impossible to recycle. For example if paper and cardboard are tried to source separate in clean, dry place. The material might be recyclable if transported straight from first customer to second customer, but the quality can most likely get worse if it is transported first to recycler's yard and from there to customer. In the yard the material lays outdoors and if there is rain, the material will get wet. Especially paper and other fiber products are sensitive to moisture, because it cuts fibers and makes the material dirty. In this case the material will be qualified as energy waste. This so called downshifting can happen quite often for numerable reasons. One of the biggest reasons is that these materials can lay for long periods of time outdoors and the material gets wet, and also due to small yards where mixing with other surrounding materials can happen. (Tchobanoglous, 2002)

4 STUDIED MATERIALS

4.1 Shredder Light Residue, SLF

European Union defines in Directive 2000/53/EC that by the year 2015 85 % of ELVs should be re-usable and/or recyclable and 95 % re-usable and/or recoverable by weight per vehicle. The directive also states that the treatment and disposal of these ELVs should be developed. (Eurlex, website) In order to meet that target, something has to be done also to non-ferrous parts in the car, which accounts for about 25 % of vehicles weight. (Degaspari, 1999) In the 50s car didn't have any hardly any plastic in them, now there can be even 120 kilograms of plastic per vehicle, so the problem is rising and the trend tends to go up due to new innovations of composite materials and such. (Taylor, 2010).

Literature review revealed some studies on SLF processing. One of these was innovated in Argonne National Laboratory and was first licensed in Eiper, Belgium with a player called NV Salyp. (DeGaspari, 1999)

This sorting operation sorts SLF from ELV's to three streams: polyurethane foam, thermoplastics and inorganic fines. The separation happens with two-stage trommel. First the fines are sorted out in the beginning of the trommel which has mesh screen of 0,5 cm. These fines can consist anything from metals to dirt and fibers and therefore it is the heaviest fraction of the material. In the next stage the flat plastic pieces are removed using staggered arrangement of longitudinal slots. After these plastic parts have been removed, the parts go through a magnet, which sorts out all the metallic parts. The last stage of the trommel is designed to separate solid pieces of flexible polyurethane foam. The foam passes a magnet to separate all the ferrous parts. (DeGaspari, 1999)

In this separation line, foam is the one that is more likely to be re-entered to markets as material. Foam can consist only 5 percent of SLF's weight but it can take up to 30 % of the volume and the material can consist even 50 % of the weight moisture, dirt and other residues. The process for foam continues from the trommel to shredder which reduces the particle size to 5-15 cm. These smaller pieces continue to washing

of two sections. In the first section, the materials settle to float while all heavy residues like metals sink to the bottom. The next part is the actual washing with different aqueous solutions of surfactants and detergents. When the material is clean from the entire residue it continues to rinsing and onwards to dryer via two soft rubber squeeze rolls. These rolls squeeze all the water from inside and a vacuum that is placed right on the foam prevents the material for reabsorbing the water back inside the pores. After these rolls, the material goes on to conveyor dryer which blows the material with heated air for 15 minutes. (DeGaspari, 1999)

As stated in the chapter 3.5.2, the moisture has a significant effect on screening process, especially when talking about fines. The bonding and clumping has serious negative impact to sorting because all the fines might be stuck in some other materials or they might have created big lumps, so they can't be screened out so easily. This problem might go away by simply drying the material before entering the trommel. As stated in the same chapter, the thumb rule should be that material with greater than 5 mm particle size the material should be entirely dry. (Wills, 2006)

This sorting system is not the only innovation in the world, although it is one of the few which is described so deeply and published to the big audience. Other sources describe some other innovated methods more narrow explanations. For example one way is described as sink float technology, which separates recyclable streams of PP/PE, ABS and mixes plastic and rubber from ASR. Another way is to gasifying ASR and recycling all the remaining parts, metal and glass. (Taylor, 2010)

According to Kuwanayama (2011) dry-type of separation methods, for example using air classification have been applied to ASR treatment, but not yet wet-type. In Kuwanayama's publication, the main issue is to determine how reattachment ratio, entrapment ratio and disentanglement ratio effect on ASR's entanglement properties. Kuwanayama stated that particles smaller than 16 mm were not easily reattached to other particles during the screening process. In the publication the process was to sample out three particle sizes, < 16 mm, 16-5,6 mm and >5-6mm. Then the material was hand unraveled and screened again. After multiple screening, the material was dried for 24 hours and then put to a floating container with rotor. On the top of the rotor there is a net, with 1 mm openings to prevent bigger parts hitting the rotor. The

publication discovered that most of the fiber-like materials appear only in the biggest fraction size. As a conclusion of the test, the proposed treatment flowchart for ASR using wet treatment is shown in the figure 12.
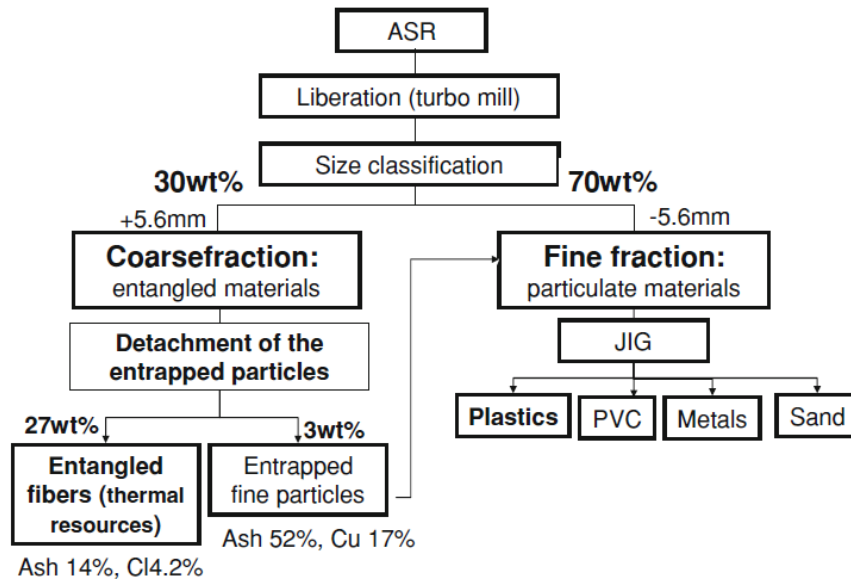

Figure 12 Flowchart for separating ASR by using wet treatment (Kuwayama, 2011)

In the figure 12 ASR is crushed for liberation of ingredients and the separated according to particle size. The bigger fraction, coarse fraction is immersed and handled with detachment methods to separate fines and fiber-like materials. These fines can be treated by jigging with the fine fraction. (Kuwanayama, 2011)

4.2 Recovered fuel, REF

REF is made to be used as a fuel in incineration and other power plants among other fuels like sludge and wood. Each power plant has its own environmental permit, which regulates everything from emissions into the air to recycling and waste management. According to these permits power plants are divided to two different categories, incineration plants and co-incineration plants. Incineration plants are the ones that use municipal and industrial waste as a fuel. In these power plants the fuel is not treated before incineration. In co-incineration plants waste is defined as a fuel among the others. Here the fuels are pretreated (crushed, sorted etc.) before energy utilization. It is quite rare that municipal waste is used in these plants; the waste fuel comes from

industrial sources where the waste is most likely presorted. It is estimated that these power plants use about 300-400 tons annually in waste co-incineration. Tens of power plants have the permit to burn this industrial waste but only about ten of them are using it regularly. Often the price and availability of REF compared to those of other optional fuels are the factors that determine if the plant uses REF or not. (Pöyry, 2012)

When talking about the effect of moisture in these fuels, it is important to mention that the moisture contents can be tens of weight percent of the material. When adding water to material, the value for net calorific value decreases, because energy is first needed to dry the material down, vaporize the water. For example some of the most used plastics, PP, PE and PA burn almost as clearly as oil and they have net calorific values of 79,80 MJ/kg(PP), 78,38 MJ/kg (PP) and 67,33 MJ/kg(PA). (Abdel-Bary, 2003) According to table 1 in page 4 (REF classification) these materials bring significant caloric value to REF, when they itself have even four times higher caloric values.

The effect to the fuel tons is that these co-incineration plants have a certain amount of fuel tons that they have a permit to burn per year. But these power plants buy material according to their energy content. (Lahti Energia, website) So the amount of water is calculated to the weight of the materials while the water is actually decreasing the energy content. (Halliday, Resnick, 1993)

Usually when burning REF with fluidized bed boiler, the moisture content is not an issue. This is due to the fact that this equipment can recover energy from extremely high moisture fuels, like sludge. When wood/coal mixture were burned in fluidized-bed combustion and the main focus was if the moisture content would have any effect on the burning. (Helmer, 1998) The results of the test were that wood moisture content does not have any effect on SO_2 emissions and emission of oxides and nitrogen were reduced when using moist wood chips compared to air-dried wood ships. Helmer(1998) also stated that combustion efficiency increases when decreasing wood particle size and increasing the ration wood/fuel towards wood. When using moist wood as a fuel, it always has lower emissions of NO due to the fact that the temperatures generated are lower compared to using dry wood and more NO emissions is generated the higher the temperature rises. The energy is needed to evaporate the water out, so that's why the temperature is lower. (Helmer, 1998)

Another test was co-firing paper mill's sludge and coal in circulating fluidized bed boiler. Also in this test the emissions of SO_x and NO_x decreased when increasing the amount of sludge in the fuel. Due to the fact that sludge has extremely high moisture content, the temperatures decreased in the boiler so the formation of CO increased during firing. All the ash was able to be burned in cement manufacturing process and the emissions met the local requirements. (Tsai, 2002) When using fluidized bed boilers as a combustion method, the limit to moisture content of fuel is as high as 62 %. With this moisture content and lower, there is usually no need to use fossil fuels on side. (Pifer, 2005)

5 EXPERIMENTAL STUDY

The experiments were made to both of the studied materials, SLF and REF. The main target was to find out how the drying process effects physically the materials. As already mentioned in earlier chapters, there are some theoretical effects while the material is drying. These effects do not necessarily show as clearly as hoped. Therefore the interest is on the physical factors during drying. If these factors are radical, observing those will help employers to estimate the moisture content of these materials without sending samples to laboratory. This is not only time saver but also has financial effects.

The experiment was based on earlier experience from the field and also on standards mentioned in chapter 3.1. The experiment was made in the material laboratory at Mikkeli University of Applied Sciences. The experiments were made to both of the studied materials, although not at the same time. The scope of the experiment was to find out what exactly happens during drying and is there some way to estimate the moisture content without drying the material for two weeks.

Focus was on four different factors observed during the drying. The first factor was the visual appearance, observing if the material looks wet or dry or if there is for example some water on bottom of the material. The second factor was "the balling"-test. In this test a part of the material was balled in hand for a few seconds. After opening the fist, observing if the material would stay ball-shaped or would it spread in the

hand. The third factor was so called paper towel test. A handful of the material was placed on paper towel for 30 seconds and observing at which point the wet dots would disappear and at which point the dust would be the only material left on the paper. The fourth factor was the dusting factor, observing at which point the dust would start to appear to the bottom while lifting the material with hands.

Before starting the actual experiment, the samples were collected. The experiments of SLF were made with three different samples with two corresponding samples, so six separate samples all together. The first sample was collected on 8th of February at 10am and the second sample was gathered on the same day, at 11am o'clock with an extra announcement that it is collected from the bottom and therefore might not be as representative as others. The third sample was gathered during the same day, at 1pm. To the second experiment for SLF the arrangements and samples were taken the same way. All the samples were taken on 22nd March. The first sample was taken on 11 am, the second at 12am and the third 1pm. All three samples have three corresponding samples collected from falling stream of SLF +9mm. All of the samples were gathered into airproof buckets, so the moisture wouldn't evaporate out while transporting them to Mikkeli.

Figure 13 Experimental arrangements, samples placed on the floor to dry on top of plastic bag

The first experiment was started with SLF on the 19th of February 2013. Before placing the samples to dry, they were weighted in the buckets. The samples were laid on the laboratory floor, under fume cupboard. The reason for placing the samples under flowing air was that the odor of the samples was quite powerful at the beginning and there were other people working around during the days. After weighting the samples they were spread on refuse sacks as about 30 mm thick layer. To get the starting weight, the buckets were weighted individually after making sure that there was no moisture or parts of material inside. The second experiment for SLF was started on 3rd of April with the same procedures as in the first experiment.

The third test was made with REF. The test was made also with three samples with two corresponding samples. The samples were taken during the week 11. The experiment was started on 18th of March. This experiment differentiates a little bit from the tests made to SLF. The timing of examinations was changed in a way that the drying

during hours 18 to 30 was observed with extra frequency. The first three samples were laid at 9 o'clock and the other three were laid on the same day at 15. Although the samples were laid at different times, they were examined at the same times and frequencies.

To gather all the possible info, the samples were photographed and observed for two days three times per day and after that every second day. This frequency was based on earlier experience and a physical fact explained in chapter 3.4 that the material dries the fastest during the first two days. The photo bank includes photos of all the four observed factors, shown as clearly as possible.

After these two days of intensive observation, the frequency to observing was every second day, when all the assumed dramatic changes had already happened. Also the odor from SLF's disappeared during the first two days. The observation was stopped after two weeks of drying. When the material was dry, it was sorted to different fraction categories. Because the two materials have different sections in it, the SLF material was sorted to nine different sections and REF to six different sections shown below in Table 7.

TABLE 7 Sorting sections of SLF and REF

SLF	REF
Metals	Foamed plastic
Pad and foamed plastic	Foil plastic
Foil plastic	Hard plastic
Hard plastic	Textile and fiber
Rubber	Wood
Fabric and fiber	Paper and cardboard
Paper and cardboard	
Wood	
<5 mm and unsorted	

As can be seen from the Table 7, REF is a material that is not allowed to include metal parts for the sake of high melting point, so they are totally left unsorted. If metal ap-

peared during sorting, it is mentioned later on. Also rubber is left out for the sake of the fact that during sorting, there appeared none rubber.

When the sorting was done, five samples were sent to laboratory to get the values of residual moisture RM. When analyzing the moisture content of the samples before RM, it had to be assumed that the value was 0 %. So due to this fact, all the values are calculated with using 0% as residual moisture content in the end of the experiment.

6 RESULTS

Because the experiments were almost fully esthetical, the some of the results are not straight quantitative answers. The information was gathered to tables which evaluated these four different factors in different states of moisture content. Tables were made in forms of matrix for each separate sample.

All the samples have corresponding samples and the pairs for SLF are 1 & 3, 2 & 4, 5 & 6 and 1½ & 1 2/2 etc. For REF the pairs are 1 & 3, 2 & 4 and 5 & 6. Moisture contents of each sample have been shown in tables 8 and 9. Values have been calculated with formula 1.

TABLE 8 Moisture contents of SLF samples [%]

1	2	3	4	5	6	1½	1 2/2	2½	2 2/2	3½	3 2/2
29,7	28,7	29,7	27,9	29,0	28,4	42,5	40,7	47,0	41,7	34,0	35,1

TABLE 9 Moisture contents of REF samples [%]

1	2	3	4	5	6
43,9	46,5	55,4	43,9	41,3	45,6

Before the evaluation, the information about drying was gathered shown as moisture content as a function of time. All the same materials were gathered to same function, so there is shown in figures 14 and 15 moisture content as a function of time for SLF and REF.
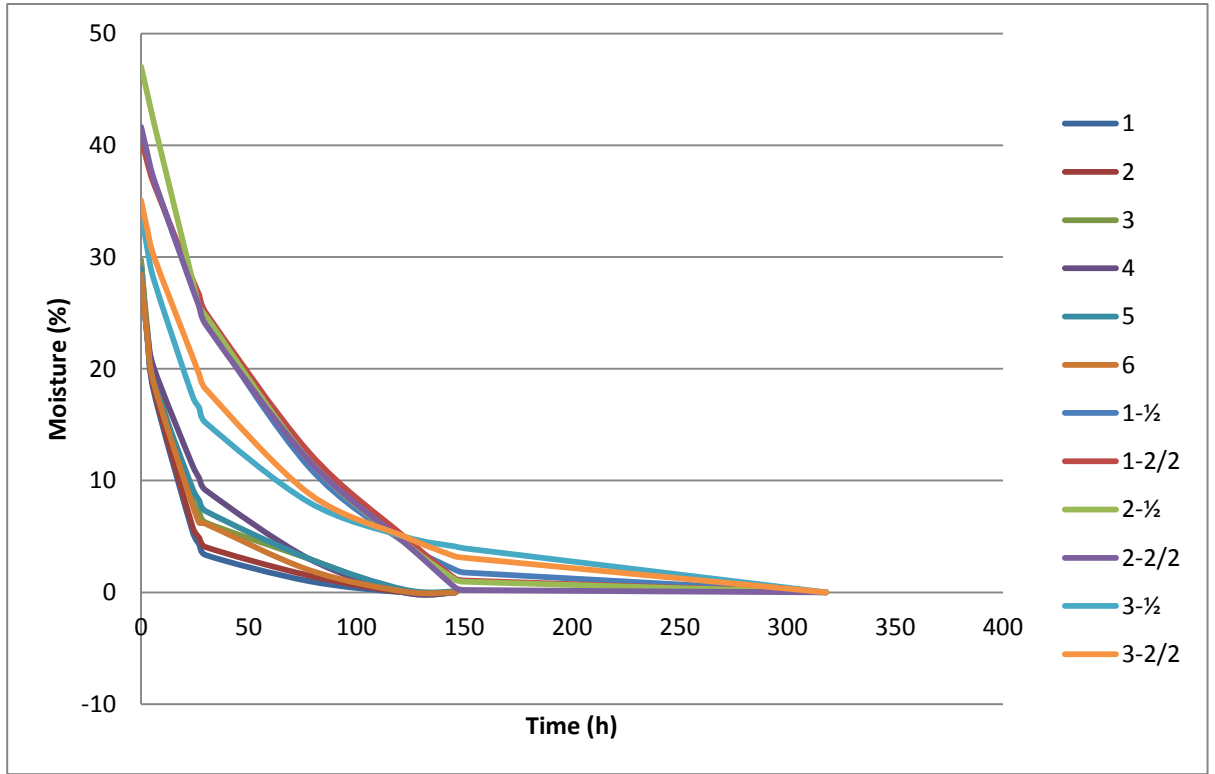
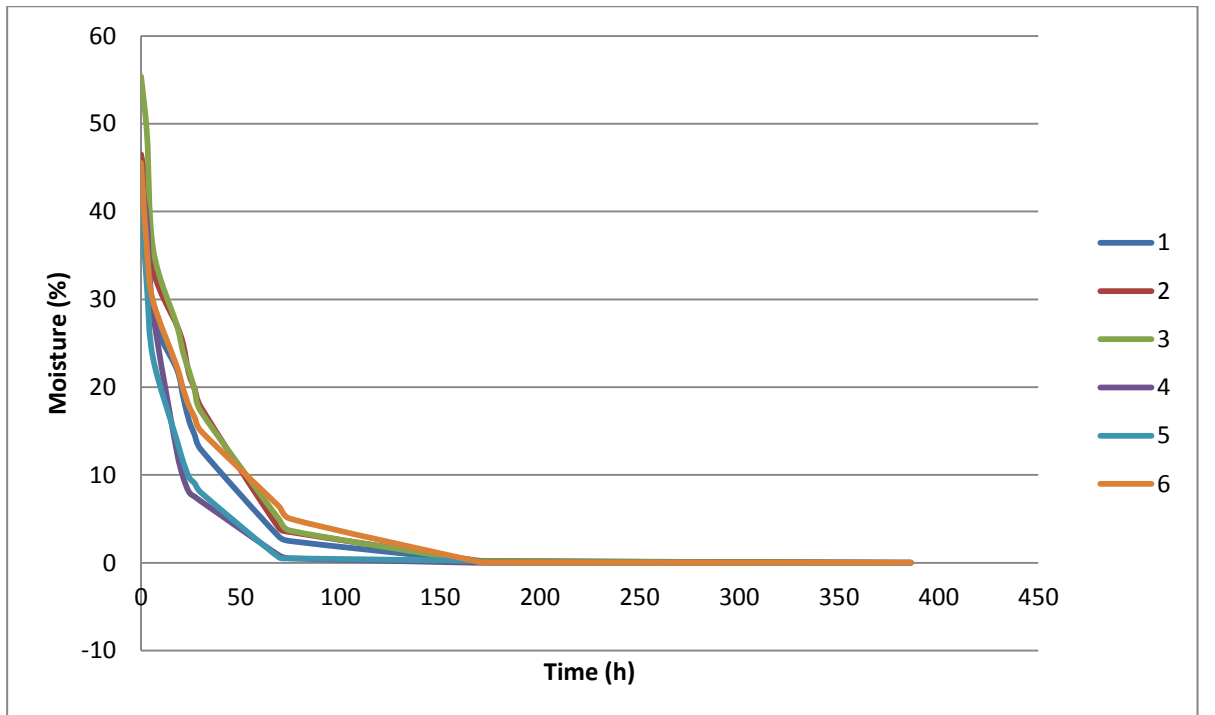**Figure 14 SLF's moisture content [%] as a function of time [h]**

Figure 15 REF's moisture content [%] as a function of time [h]

During the drying some atmospheric values were gathered occasionally. The atmosphere didn't change radically during the measurements. The biggest difference was in temperature a maximum of 1°C. The average for the temperature is 22,1 °C and for relative humidity 8 %. The reason for the relative humidity's small value might come from the extractor fan on the top of the samples.

After the samples were dried, the next task was to sort out the materials of the samples. Because the sorting is pretty time consuming process, it was decided that only half of the materials were sorted. Below in the table 10, 11 and 12 represent the sorting results of SLF and REF samples.

TABLE 10 Sorting results for first samples of SLF

Fraction	1½	2½	3½
0-10 mm	24,02 %	36,98 %	14,30 %
Foamed plastic	7,88 %	1,17 %	17,86 %
Foil plastic	2,18 %	7,28 %	3,91 %
Hard plastic	29,42 %	9,53 %	28,12 %
Rubber	8,12 %	3,14 %	7,89 %
Wood	5,61 %	7,61 %	2,26 %
Textile and fiber	1,77 %	1,84 %	1,34 %
Paper	0,57 %	0,67 %	0,85 %
Metal	6,74 %	8,29 %	10,16 %
Unidentified	13,73 %	23,48 %	13,30 %

TABLE 11 Sorting results for second samples of SLF

Fraction	3	4	6
0-10 mm	8,92 %	31,45 %	19,99 %
Foamed plastic	13,20 %	13,83 %	21,74 %
Foil plastic	7,73 %	4,01 %	2,71 %
Hard plastic	25,05 %	15,59 %	19,41 %
Rubber	2,09 %	1,66 %	1,33 %
Wood	15,65 %	13,37 %	0,66 %
Textile and fiber	3,99 %	1,76 %	20,05 %

Paper	9,09 %	4,98 %	2,54 %
Metal	2,44 %	1,21 %	2,04 %
Unidentified	11,85 %	12,13 %	9,54 %

TABLE 12 Sorting results for samples of REF

Fraction	1	4	6
0-10 mm	19,97 %	7,96 %	15,10 %
Foamed plastic	2,9 %	1,85 %	0,66 %
Foil plastic	11,34 %	13,30 %	7,19 %
Hard plastic	23,26 %	20,91 %	24,29 %
Textile and fiber	3,68 %	9,32 %	2,89 %
Wood	20,39 %	11,70 %	8,41 %
Paper	18,45 %	34,97 %	41,46 %

For evaluating the aesthetic phenomenon during drying the matrixes with each five observed issues were made. Because these matrixes were made to each sample with all observed factors, the amount of information is quite big. To show the results as clearly as possible, it was decided that all these matrixes were put together, sort of on top of each other to show the main movements of each observed factor. These matrixes were put on bar chart. As a result, the charts represent all the four criteria and a range of 1-x-0 to evaluate the criteria. It was also necessary to add a range for those samples that were not able to be evaluated in that particular moisture scale. This value is marked as N as no result. Different criteria and ranges are explained in the table 13.

TABLE 13 Criteria and ranges used to evaluate the drying process

	Balling test	Bottom's state of wetness	Dusting	Paper towel test
1	Ball forms	Water on the bottom	Material has no fines	Paper is wet
x	Ball somehow forms	Moisture on the bottom	Fines start to form	A bit of moisture on top
0	Ball doesn't form	Bottom is dry	Bottom has plenty of fines	Paper is dry, only fines left

The evaluation data for each test is shown for each material in figures 16 to 23.
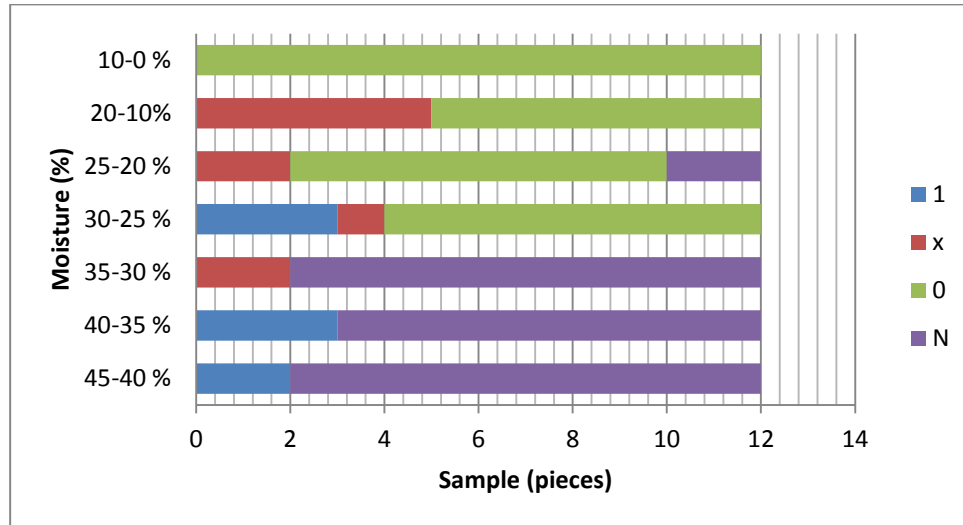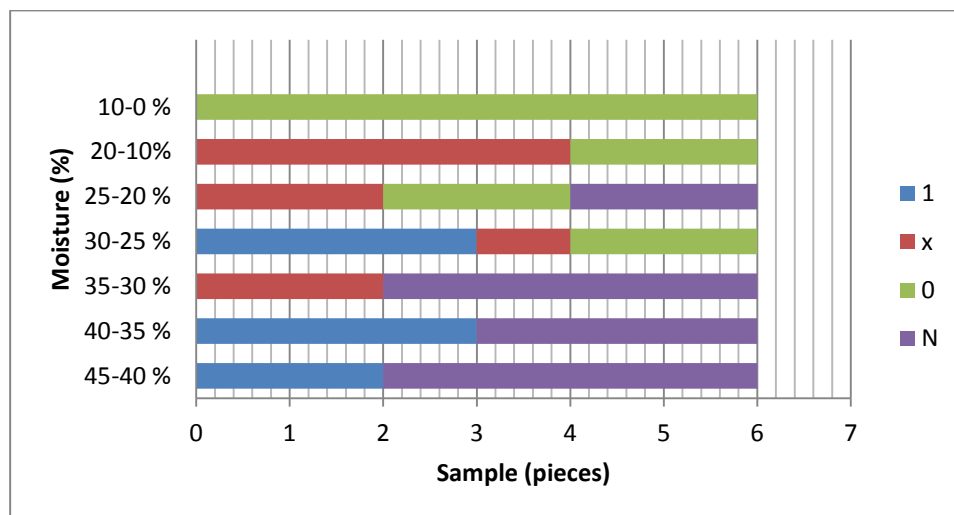

Figure 16 SLF's balling test
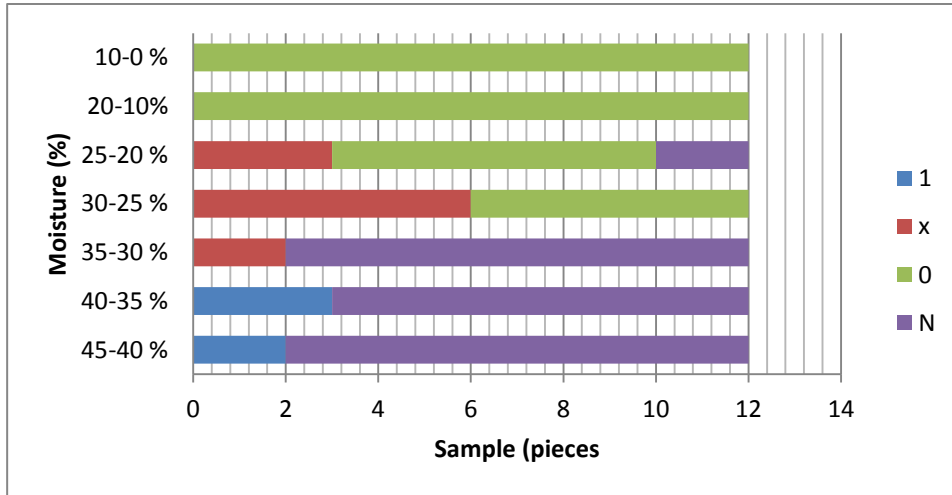

Figure 17 REF's balling test
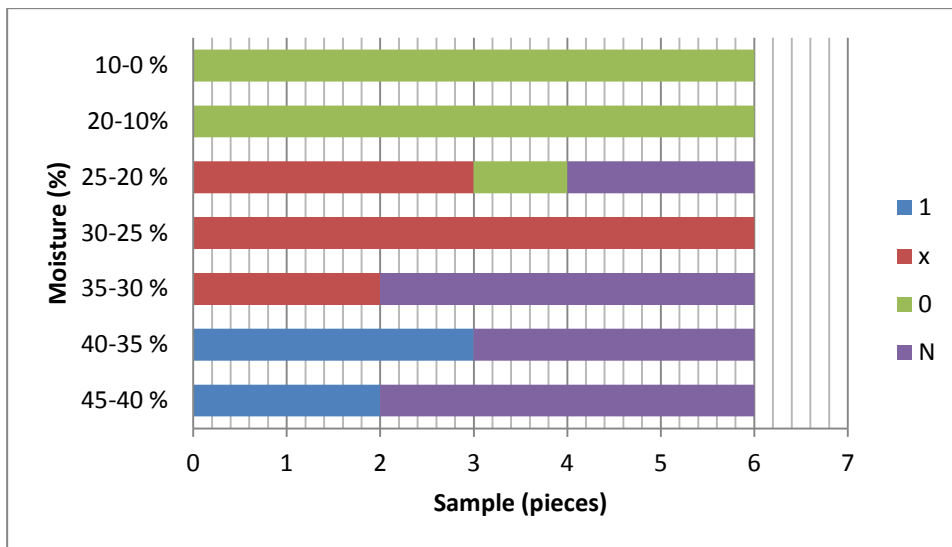
Figure 18 SLF's bottom's state of wetness

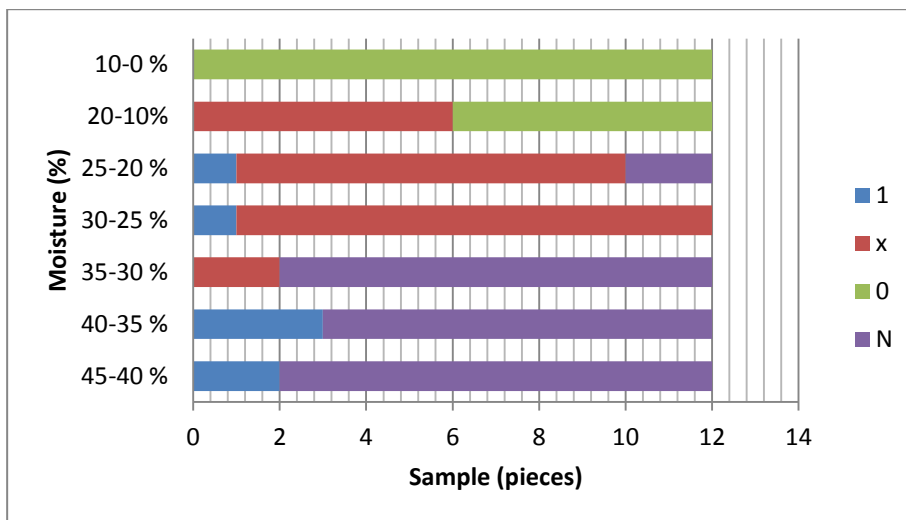**Figure 19 REF's bottom's state of wetness**

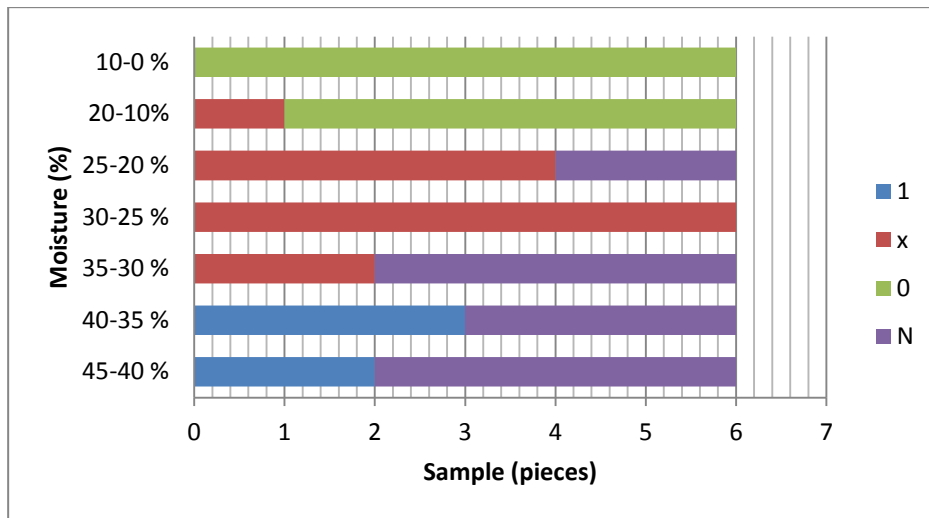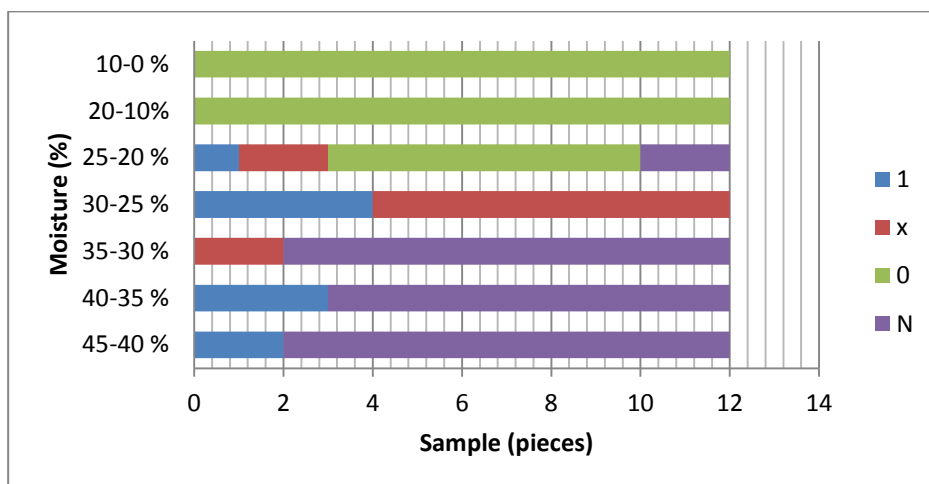**Figure 20 SLF's dusting**

Figure 21 REF's dusting

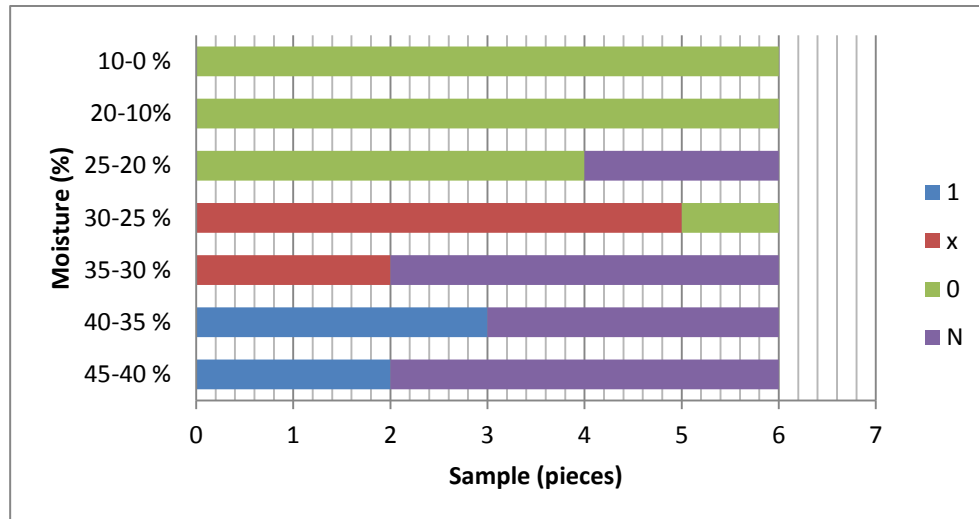
Figure 22 SLF's paper towel test

Figure 23 REF's paper towel test

7 DISCUSSION

This section is divided into two parts, where both of the observed materials are handled separately.

7.1 Shredder Light Fraction, SLF

The experiment was made to help the people working with the materials estimate the moisture content without having to dry it. When it comes to the aesthetical factors of SLF, there could be found some similarities in some groups of moisture content and some changes showed even dramatically when the samples dried to a certain dry-level. When the paper towel tests were made, the changes between moisture contents 30-25 % and 20-25 % were enormous. When the samples dried down from 25 % of moisture, there were only little signs of moisture left on the paper as it can also be seen from the figure 22. In bar 30-25 % only values x (A little moisture on top) and 1(Paper got wet) occurs but from there downwards 0 (Paper is dry, only fines left) is the most popular value and 1 only occurs on only one sample. So with these samples and tests it could be stated that when the moisture content decreases below 30-25 %, only the fines are left on the paper.

Also the test for measuring bottom's state of wetness showed some approximate actions happening while drying. When the moisture content decreased below 30 %, the

most common value was again 0 (Bottom is dry), as in the earlier experiment. Only some signs of moist and pure water occurred, but they disappeared when the moisture decreased to the level of 25-20 %. By evaluating the bottom's wetness it could be stated that if all the water is gone, the moisture content is below 30 %. The fines start to appear when the moisture is 30 % and below, so these two facts clearly have bond together. This is because the bonding of the fines and their location more likely on top of other materials stated in chapter 3.2.

The same phenomenon than in the two earlier tests happens in the balling test. When the moisture content decreases below 30 %, the most popular value is 0 (Ball doesn't form) and some balling occurs all the way to below 20 %. With the dusting experiment it's a different thing. The material starts to dust remarkably only below 20 % of moisture, if even then. The value x (fines start to form) is the most popular up until the material has moisture content of 20 %. Below this the fines appear more dramatically.

When it comes to estimating the moisture content of heterogenic material, it is quite critical to know what the material includes and what sort of materials are the ones that are active when absorbing moisture. As can be seen from the SLF's sorting tables 10-11 the amount of fines varies from around 10 % up to nearly 40 %. These samples with the extreme variation are 2 ½ with 36,98 % of fines and sample 3 with 8,92 % of fines. Due to the issues stated in chapter 3.3 (Water absorbability of different heterogenic materials) such as the effect of specific surface area, it might be presumable to think that the moisture content with the ones of high amount of fines would be the highest. The moisture content of the samples were 47,0 % (2½) and 29,7 % (3). The moisture percent for sample 3 is not the lowest of all samples, but it is counted as low compared to other samples with average of all the samples being 34,5 %. The moisture content for sample 2 ½ is the highest of all 12 SLF samples. So by these statements it could be possible to say that the amount of fines has a relationship for moisture content. Although as said in earlier chapters, the material is so heterogenic and hard to sample that with this samples it could be a pure coincidence.

As stated in chapter 4.1, foamed plastic can soak up in even 50 w-percent of dirt and moisture, so the amount of it could be considered as one of the factors effecting on the moisture. Although according to the SLF's sorting results, sample 6 had the most of

foamed plastic and had a moisture content of 28,4 %, which is five percentage points below average. The sample with most moisture content, 2 ½, had the least of foamed plastic. So with these observations it can be somewhat said that foamed plastic does not necessary have such a big impact in moisture content.

A lot of information about absorbability and evaporation handles wood and its characteristics. The amount of food in the samples 1 ½, 2 ½ and 3 ½ varies a little bit but still stays under 10 % at all samples. Even if the amount were small, the moisture content follows the amount of wood when comparing the samples to each other. Sample 2 ½ has the most wood in it, 7,61 % and also has the highest moisture content. The moisture content decreases about 10 % when the amount of wood in the sample 1 ½ decreases 25 %. In the sample 3 ½ the amount of wood is only one third of sample 1 ½ and the moisture content has decreased 25 % to moisture content of 35 %. So the relationship between wood and moisture content in these three samples is pretty obvious. The issue isn't the same with the samples 3, 4 and 6. Sample 3 has the most wood in it and has the highest moisture content. Sample 4 has only a little bit smaller amount of wood and the moisture content is only two percentage points lower than in the sample 3. In sample 6 the wood content was clearly the lower, only 0,66 weight-percent and the moisture content was still higher than sample 4's.

Other materials that could be considered as high absorbable are textile materials. The amount stays pretty constant in four samples, around 1-2 %. In sample 3 the amount is 3,99 % and surprisingly in sample 6 the amount rises up to 20,05 %. The moisture content does not follow the expectations, that with these textile variations, sample 6 would be the wettest material. Instead it actually is the second driest.

When approaching the issue from the point of view that which materials doesn't absorp water, the results are quite surprising. The materials that in this case clearly absorp less water than any else are metals and hard plastic. In three first sorted samples the amount of hard plastic follows the values of moisture content. The sample 2 ½ has moisture content of 47 % and it has 9,53 % of hard plastics and 8,29% of metal. The driest sample of those three is 3 ½ and it has 28,12 % of hard plastic and 10,16% of metal. In the other round of samples, the wettest sample is 3 and it has 25,05 % of

hard plastics and 2,44% of metal while the driest material has 19,41% of hard plastic and 2,04% of metal.

These SLF samples were gathered at different times. The first samples were taken in the beginning of February and the second samples at the end of March. While the weather has such a big impact to the material as stated in the chapter 3.2, it should be considered to be one factor that might effect to the moisture content. The samples were taken in Pori, Finland. According to Finnish meteorological office, the amount of rain during February 2013 was 20-30 mm and during March 10-20 mm. (Meteorological office, website). Change isn't that great, compared to the changes between the moisture contents of the twelve samples.

While the drying was on, it was able to be captured the moisture content as a function of time as shown in figures 14 and 15. For SLF the most of the material loss happened during the first 50 hours. During that time, all of the samples moisture content has been decreased to half of the starting content. During the next 50 hours, the change slowly changes and when the materials have dried for 100 hours, all the samples have the moisture content less than 10 %. This supports the fact stated in chapter 3.4. The velocity of change in moisture is the fastest during the hours and then it starts do decrease near zero as a square of time.

7.2 Recovered Fuel, REF

The other material that was exposed to the same tests is REF. The aim of the tests was the same as it was for SLF. In the test results most of the figures are simpler than for SLF. This could be because there were only six samples of REF, while SLF had twelve samples. The most complicated figure for REF is figure 17, REF's balling test. The only clear movement is that under 25 % of moisture, the ball does not appear in any samples. Even when the moisture is 20-10 % there are four samples out of six where the ball appears somehow.

All the other three tests, dusting, paper towel test and bottom's state of wetness show clear answers how the material changes during drying. In the dusting test fines start to form when the moisture is below 35 % and continue forming up until the moisture hits

20 %. When the material is drier than water content of 20 %, the fines appear dramatically and the values in the chart are mostly 0 (=Bottom has plenty of fines)

The state of bottom's wetness seems to change dramatically in two stages, first when the moisture is below 35 %, then the actual water disappears and moisture starts to appear on the top. The second change happens when the moisture is below 25 %. Then the moisture from the bottom has disappeared and the only moisture that is left, is absorpted in the material. In the paper towel test the first change happens the same time than in the bottom's wetness. When the moisture is below 35 % fines start to form on top of the paper and when the moisture is below 30 %, the only thing left on the paper is fines so the effect of moisture occurs earlier in the paper towel test than in on the bottom.

REF samples had relatively small amounts of fines compared to SLF. The most fines had sample 1 with 19,97 % of fines and the least had sample 4 with only 7,96 % of fines. These two samples have exactly the same moisture content, so the idea of fines completely determining the moisture content cannot be straight applied here.

The amount of foamed plastic remained straight through all the samples being below 3% in all of the samples. Wood content in the samples on the other hand changed from sample 6's 8,41 % to sample 1's 20,39 %. This does not singlehandedly explain sample 6 being the wettest sample, actually the result is quit unexpected.

Also the contents of paper and other fiber materials, such as cardboard changes in all of the samples rapidly, from sample 1's 18,45% for sample 6's 41,46%. It would be considerable to estimate, that when the material has a lot of fiber material, it could soak up in lots of water, because fiber materials have capillaries, as explained in chapter 3.3. This does not apply in here, as can be seen from the percentages.

Neither do the amounts of fines, foamed plastics and paper follow the moisture content, nor does the contents of wood. Sample 1 has clearly the highest content of wood with 20,39% being at the same time one of the driest samples of three. On the other hand sample 6 has 8,41 % of wood and it's the wettest one of the samples.

The change in moisture content in function of time changes approximately in the same way that it does when drying SLF. REF dries the most during the first 20 hours. Then all of the moisture contents have been decreased to half. After these 20 hours, the drying happens slower and continues to slow down all the way when the moisture content hits zero. When the drying has occurred for 25 hours, all of the moisture contents are below 20 %. When drying has happened for a bit over 50 hours, all the moisture contents are below 10 %. The speed of drying to SLF as well as to REF follows the rule explained in chapter 3.4 (Water evaporation of different heterogenic materials).

The samples of REF were gathered during the week 11 in Lahti, Finland. There are no specific daily statistical information available about the amounts of rain, but in general March seemed a bit dry. The amount of rain during the whole month was less than 10 mm in Lahti-region. (Meteorological office, website)

8 CONCLUSION

With these four tests, balling test, bottom's state of wetness, dusting and paper towel test, there could be found some tools to use, when estimating moisture content of these two materials without drying. In SLF when the moisture is under 30 %, all the water from the bottom has disappeared and you could still somehow form a ball in hand. When the moisture drops down to 25%, the fines are the only thing left in the paper towel test and on the bottom of the sample. When evaluating the moisture content of REF, the percentages are a bit higher than with SLF. Then REF's moisture content is 35 %, all the water from the bottom disappears and in the paper towel test a little moisture can be seen. When the moisture drops below 30 % the only thing left on the paper is fines and at 25 % no ball can be formed and the bottom is completely dry. Estimating moisture content according to these tests the evaluation can be done with accuracy of 5 % and only in the range from 35-20 %. When the moisture content decreases from 20 %, the material stays mostly the same and no differences are shown.

In the earlier chapter a lot of attention has been paid to the fact, that different materials absorb water differently because of various reasons. One of the most observed material is wood due to its organic characteristics, such as capillaries. These capillaries are essential for woods to transport water and therefore photosynthesize. Also other fiber

materials have capillary-like action, such as paper and textiles. Other material is foamed plastics. These plastics can consist up to 50 % of volume that is capable of absorbing water, dust and other small components. (DeGaspari, 1999) Due to this fact, this material could be considered as one of the observable factors when estimating moisture content. Also absorption of fines has been studied in earlier chapters. Due to their big specific surface area, they are capable of absorbing big amounts of water. Also the clumping effect (explained in chapter 3.3) has an effect on the absorption.

According to these results gathered, when estimating moisture content by contents of different materials, there are two factors that should be observed, fines and hard plastics. When observing SLF, the amount of fines has clearly a big effect on moisture content, but surprisingly this does not apply to foamed plastics. The reason for this could be that as stated earlier, foamed plastics can soak up in up to 50 % on moisture, dust and other small particles. While SLF is such a dusty material, it might be that parts of the fines are in the pores of the foams, and therefore they are filled with dust instead of moisture. When it comes to REF, the results are quite clear, not one material has a straight effect on the moisture content. This could be because there were only six samples and therefore there were less evidence than in SLF.

The speed of drying differentiated quite much between these two samples. The main trend after all is that REF dries two times quicker than SLF does. The drying happens in the same sections and quite the way expected. The reason behind the quicker drying could be that REF has clearly less small fraction than SLF. When the material has a lot of fines, the moisture sticks in it more tightly, because of the specific surface area explained in chapter 3.3

By reducing the amount of some materials like wood, foamed plastics and fines, it could be possible to decrease the amount of moisture, which can be absorbed during the process or during storing outdoors. Although decreasing the amount of fines might be a bit tricky, because they only appear when the material is dry. This can be also seen from all of the aesthetical tests made to the materials.

In conclusion it can be stated that there are some ways to estimate moisture content of these heterogeneous material and most of these factors include appearance of fine ma-

terials. This fact supports the idea of physical phenomenon of water absorption and evaporation of materials, which have big specific surface area, mostly fraction sizes below 5 mm. Also it can be stated that these fine materials have essential effect on the velocity of drying process of these materials. When the material has relatively big amount of dust and other fines, the material dries even twice as long as the materials which have only little percentage of fines.

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