COMPARISON OF STANDARD- AND LOW ENERGY EXPANDED POLYSTYRENE

Lahti University of Applied Sciences
Degree Programme in Plastics Engineering

HÄNNINEN, MIIKA: Comparison of standard- and low energy
                     expanded polystyrene

Bachelor's Thesis in Plastics Engineering, 39 pages, 2 pages of appendices

Autumn 2017

ABSTRACT

This thesis was assigned by Bewi Styrochem Oy. The purpose of the work was to polymerize two different expanded polystyrene (EPS) grades in a pilot-reactor and to compare bending strengths of shape molded polymerization samples at different steaming pressures. Material samples polymerized were standard EPS and modified, low energy EPS. The focus was to find out if modified material could be shape molded with lower steaming pressures and save energy, while maintaining required bending strength. Based on the results, estimations of steam usage savings were calculated.

Determined from the results, modified EPS-material samples were stronger than the reference material when using similar steaming pressures. Steaming pressures could be decreased, while achieving still required bending strength values. Shape molding cycle times were also decreased by enabling molding with lower steaming pressures, and by that provided more theoretical molding cycles per day and savings on energy costs by using less steam and time.

This thesis was divided into theory- and practical part. Theory part covers general and more detailed information about EPS manufacturing, further processing and machinery. Practical part contains information about the research, where results based on the measured data are analyzed and as well the summary of the study.

Key words: bending strength, EPS, expanded polystyrene, prefoaming, polymerization, shape molding, steam

Lahden ammattikorkeakoulu
Muovitekniikan koulutusohjelma

HÄNNINEN, MIIKA: Standardi– ja matalaenergisen vaahdotettavan
                       polystyreenin vertailu

Muovitekniikan opinnäytetyö, 39 sivua, 2 liitesivua

Syksy 2017

TIIVISTELMÄ

Opinnäytetyö tehtiin Bewi Styrochem Oy:n toimeksiantona. Työn tarkoituksena oli koepolymeroida kaksi erilaista vaahdotettavaa polystyreeniä (EPS) pilot-reaktorissa, muotovalaa materiaaleista testikappaleita eri höyrytyspaineilla sekä tutkia höyrytyspaineen vaikutusta testikappaleiden taivutusmurtolujuuteen. Materiaalit olivat normaali EPS, sekä modifioitu, matalaenerginen EPS. Modifioidulla materiaalilla säästettäisiin teoriassa energiaa käyttämällä vähemmän höyryä alittamatta vaadittua materiaalin taivutusmurtolujuutta. Tulosten perusteella laskettiin myös arvio höyryenergian säästöistä, kun käytetään alhaisempia prosessointiparametreja.

Tuloksista selvisi, että modifioidusta EPS-materiaalista muotovaletut testikappaleet olivat lujempia samoja höyrytyspaineita käyttäen. Höyrytyspaineita pystyi alentaa vertailumateriaaliin nähden säilyttämällä riittävä materiaalin taivutusmurtolujuus. Samalla saatiin myös sykliaikaa lyhennettyä, enemmän teoreettisia muotovalusyklejä päivässä sekä säästöjä energiakustannuksissa käyttämällä vähemmän höyryä.

Opinnäytetyö on jaettu teoria- ja käytännön osiin. Teoriaosiossa käsitellään muun muassa EPS-tuotteita, valmistusprosessia sekä prosessointitekniikoita. Käytännönosiossa analysoidaan mitattujen tietojen perustana olevat tulokset sekä yhteenveto tutkimuksesta.

Asiasanat: esivaahdotus, EPS, muotovalu, polymerisointi, taivutusmurtolujuus, vaahdotettava polystyreeni

CONTENTS

1 INTRODUCTION

Expanded polystyrene (EPS) is a common insulation and packaging material. It is made by polymerizing styrene and impregnating blowing agent pentane to it. When heated, the pentane in the beads causes them to expand, and the expanded beads can be molded. EPS products are usually relative strong, lightweight, good insulators and packaging materials as well as relatively enviromental friendly to produce.

Bewi Styrochem Oy is one of the leading EPS-manufacturers in Northern-Europe (Bewi Group Oy 2017). It manufactures EPS-raw material as well as does research and development work. The factory is in Porvoo at Kilpilahti industrial area next to Borealis Polymers Oy and Neste Oil Oy refinery.

Bewi Styrochem Oy has started at 1972 as Stymer Oy. Bewi was established later at 1980 and started mainly on packaging and building insulation products. Bewi expanded later to Sweden, and Stymer changed its owner several times. At 2014, Bewi merged into Bewi Styrochem Oy and is now a part of Bewi Group Oy, which manages the chain of insulation and packaging companies from raw-material to finished end products. (Bewi Group Oy 2017.)

In this thesis, a majority of EPS processing technology and machinery information sources are from practical working experience at Bewi Styrochem's research and development team as an engineering summer intern.

2 EXPANDED POLYSTYRENE

2.1 Expanded polystyrene, EPS

Expanded polystyrene (EPS) is a widely used foam-like plastic material. Its main purpose can be found in building and construction applications. In Europe, a great share up to 76 percent of end usage goes to insulation applications and smaller share of 24 percent to packaging and other applications (Johansson 2017, 53). In construction, usage of EPS focuses usually to different insulators, modular elements, sound insulators etc. (Plastics Europe 2017). EPS has many properties that standard, for example injection mouded polystyrene does not have.

EPS has a range of technical properties. It can be used almost anywhere, from simple insulation plates to more complex packaging and special products. It cannot be used in some appliances where it is directly exposed to strong chemicals. EPS can be molded to variable forms with shape - and block molding technology. Due EPS contains mainly air, the material stands out by its thermal conductivity, which makes it an excellent insulation material. Thermal conductivity of EPS is measured with specific machinery, which measures the heat energy passed through the sample. This value is referred as lambda value and the unit is W/mK. The smaller the value is, the less heat it allows through it which makes it a better insulator. EPS has a varying thermal conductivity rate of 0,029 – 0,041 W/mK (Table 1).

Physical Property	Material				
	Glass Wool	Mineral Wool	XPS	EPS	PUF
Density (kg/m^3)*	13−100	30−180	20−80	18−50	30−80
Thermal Conductivity (W/mK)*	0.03−0.045	0.033−0.045	0.025−0.035	0.029−0.041	0.020−0.027
Temperature Application Range (°C)*	−100−500	−100−750	−60−75	−80−80	−50−120
Water Vapor Permeance (Perm-inch)†	118	116	1.2	2.0−5.8	0.4−1.6

TABLE 1. Approximate thermal and water vapor properties of typical construction materials (Kutz M 2011, 555)

2.2 Usage

EPS stands out on its packaging properties. Due its low thermal conductivity rate and it being easily moldable, it is suitable for storing and transporting demanding food products, such as fish and other foods that require cold storaging. EPS is also greatly fit for packacking for its shock absorbing properties and due to its lightness. Light EPS packing products will decrease transporting fees and gives the products extra security from dents. Different special components can be also manufactured from higher densities. (Bewi Group Oy 2017.)

IMAGE 1. Shape molded EPS fish box (WA Polystyrene 2017a)

Insulation plates, or sometimes called slabs, are a very common product made from solid EPS. These are produced with block molding technology and cut to dimensions usually with a hot wire cutter. Insulation plates are used mainly in construction as insulation from all the way from base of the building to cellar, wall, floor and to insulated roofing. By insulating properly on building, complications caused by mold and moisture can be prevented. EPS is suitable for building also by its moisture properties. It repels water, but allow moisture to be absorbed. If, for example, insulation plates are used on outside walls, it repels the water coming outside and

allows the moisture inside to be absorbed, allowing the structure to stay dry and warm. (Bewi Group Oy 2017.)

IMAGE 2. Insulation plates being applied in construction (WA Polystyrene 2017b)

2.3   Extruded polystyrene XPS

Extruded polystyrene (XPS) is a similar material compared to EPS and it produced also from polystyrene and pentane. It differs from EPS in density, look and by moisture- and mechanical properties. Its manufactured by adding a blowing agent and a resin to an extruder process. When the polystyrene is extruded, it melts and is pushed through a die. After its extruded, it swells into a foam as the blowing agent gas will expand (Dyplast 2011).

XPS offers much higher compression strength compared to EPS and it also absorbs less moisture. It is usually used on ground as frost insulation and foundation boards for its great compression strength (Bewi Group 2017).

3   EPS MANUFACTURING PROCESS

3.1   Suspension polymerization

Manufacturing expanded polystyrene is a relatively simple process, but contains several phases. To have a successful process and high-quality EPS raw-material, these phases are precisely determined and monitored.

Expanded polystyrene is produced by polymerizing styrene. Usually suspension polymerization is utilized, where styrene is mixed with water inside a reactor and droplets are being formed from the monomer styrene. By mixing with right temperature, initiator chemicals and other additives such as suspension agents, styrene starts to polymerize in to polystyrene molecules.
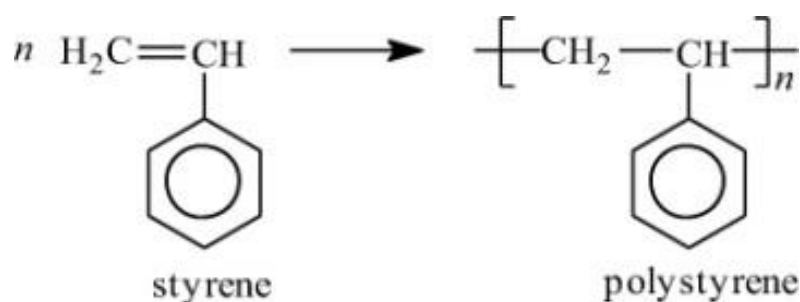

IMAGE 3. Styrene polymerization to polystyrene (Fried 2014, 3)

The process is started by adding a specific amount of water to the reactor. Water helps the suspension to take place as absorbing some of the heat energy forming from the process and acts as an important parameter for stabilizing the process. The water is heated and pH stabilators are added. Stabilizing the pH of the process is crucial for the suspension of water, styrene and additives.

After heating the water, styrene is added to the reactor. Additional chemicals are mixed, to help the suspension take place and to give material different properties. These chemicals are also meant to stabilize the process, control the upcoming bead size and polymers chemical

properties and to give the material different perks, such as fire-retardant properties.

When the main polymerization reaction has taken place, the beads are impregnated with 4–7 % of n-pentane. Pentane acts as a blowing agent when the beads are heated on further processing. These beads can expand up to 50 times from their original size when trapped pentane gas is expanded within them. (Bewi Group Oy 2017.)

After right time and temperature, most of the monostyrene is polymerized and further processing can begin. The EPS beads mixed with water is now pumped into large containers where it stored temporarily and pumped into a dryer. Dryer separates the now unnecessary water from the polymer beads with centrifugal rotation.

The raw dried EPS is now moved into sieving phase. It is a process where raw material is sieved through vibrating, varying size sieves where the different bead sizes are separated and under- and over size grades are removed. Each bead size grade has their own usage and they are pre-expanded to varying densities.

To have successful further processing, the raw material must be coated with precise amounts of coating materials. Coating takes place in large mixers where different coating materials are mixed with given time and amount. For example, they give hydrophobic properties and ease further processing of the raw EPS-beads. If the beads have no coating, the material for example will likely agglomerate in the prefoaming phase. Coated beads are then packed into one-ton octabins and moved on for storing and transport.
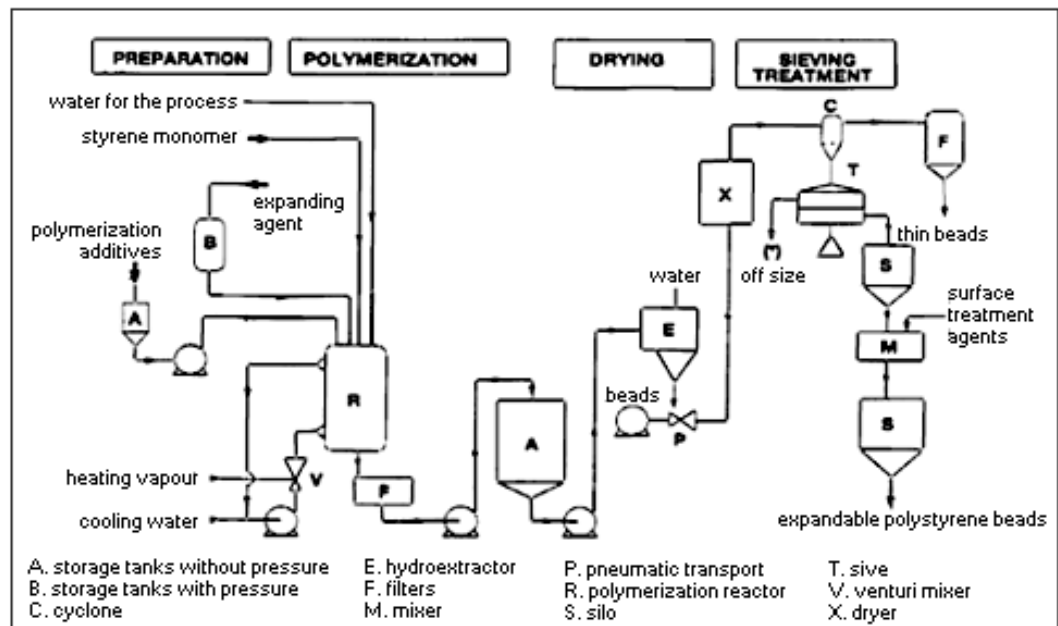
IMAGE 4. EPS suspension polymerization phase diagram (Foam Fabricators 2017)

3.2 Further processing and analysing

Producing raw EPS material is one of the many phases for it to become a fully functional end-product. The pentane inside the beads needs to be expanded with a prefoamer so that they can be molded afterwards.

Bewi Styrochem utilizes a research and development hall and a laboratory, where product development, material strength and laboratory analysis are done. The practical work of this study was done in the pilot hall, where a pilot reactor and other EPS processing equipment are located.

3.2.1 Prefoaming

After production, EPS-prefoamer is one of the most important processing machinery to set properties to the raw beads. Prefoamers purpose is to heat the beads with steam, which causes them to expand due the pentane inside them. Pentane acts as a blowing agent which causes the beads to expand even 50-times their original volume when heated (Bewi Group 2017).

Pre-expanders usually work by measuring a batch of raw material from a hopper to the steaming chamber. Raw beads are now steamed with given pressure and time, which causes the beads to expand (IMAGE 5). After expansion they are moved to fluidized bed where some of the moisture is removed. After that, they are moved on to silos for conditioning.

IMAGE 5. Prefoamed EPS-beads (Bewi Group Oy 2017)

3.2.2   Molding

Shape molding is a very common way to process EPS. It resembles some way like an ordinary injection molding process, only in this one steam is brought to the mold as well and there is no screw to melt and mix the material. Prefoamed EPS is injected by pressurized air in to the mold where hot steam is pressurized to set pressure. This causes the prefoamed beads to melt partly, adhering them together, causing a smooth surface and a solid product. Generally, the more the beads in the mold are pressurized with steam, the firmer and stronger the product is. In some cases, vacuum is applied to the mold cavity, which allows steaming to be more effective (Nurminen 2005).

After the steam has been pressurized in set time and pressure and the product is now solid, cooling phase starts. The pressure is slowly released as the product and the mold cools down. The main cooling is done usually with water spray inside the mold.

Due to expanded polystyrenes low thermal conductivity, it takes some time to cool the product before it can be removed from the mold. If the product is not cooled enough it will likely bend and distort after it has been ejected.

Shape molding phases:

1. Closing and preheating the mold
2. Filling the mold with prefoamed EPS-beads.
3. Steaming and increasing the mold pressure and temperature, EPS-beads adhere to each other
4. Releasing some of the pressure
5. Cooling the mold
6. Molded EPS-pieces surface pressure increases in the mold
7. Opening mold, ejecting molded piece of EPS when surface pressure has decreased enough.

Block molding works mainly by a same principle as shape molding. Difference is that blocks are larger, solid pieces of EPS. These blocks are then cut into shapes and dimensions, usually with a hot wire cutter.
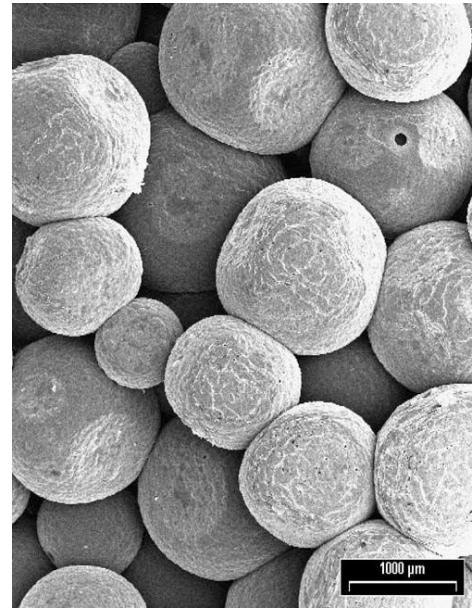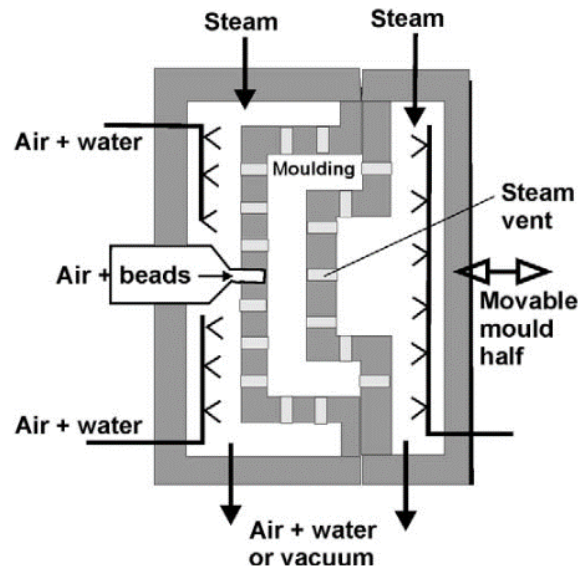
IMAGE 6. Mold structure used on EPS shape molding (Mills 2005)

IMAGE 7. Microscopical picture of the EPS beads structure (Rossacci & Shivkumar 2003, 2)

IMAGE 8. Solid blocks of EPS made with block molding technology (WA Polystyrene 2017b)

3.2.3 Laboratory analysis of EPS

The cellular structure of the EPS product is often observed with a microscope. This can give an estimate of EPS materials properties, such as from thermal conductivity. If the cells are similar and intact, it is usually a good sign of the properties.

Gas chromatography is used to determine pentane and residue monostyrene levels from the EPS-beads. With pentane being important chemical for successful prefoaming, the pentane levels of the raw – and prefoamed beads are monitored by taking small samples to research and development. The levels affect directly how the material behaves in the prefoamer. Roughly the more pentane, the more the molding parameters are affected.

Residual monostyrene is styrene that has not been polymerized in the process and is an unwanted residual material now. Low residual monostyrene levels are crucial especially for the food packaging products. Regulations do not allow over a certain limit of ppm (parts per million) residual monostyrene, as it might contaminate the food products for styrene being a hazardous material for health.

Diluted solution viscosity of EPS samples offers information about the mechanical and chemical properties of the EPS material. Polymers change the viscosity of the fluid in which they are diluted, and molecular weight can be determined from the change in viscocity. Lower viscosity value means the polymer has smaller molecular weight, which affects its properties. Higher viscocity is based on materials longer polymere chains, which usually sticks to each other more, causing the flow to be slower, more viscous. (Hester 2016.)

4   TEST MATERIALS

4.1   Pilot polymerizations

Bewi Styrochem research and development utilizes a pilot reactor. It is a smaller 310-liter reactor, where variable EPS polymerizations are tested. The main usage is researching and developing ways to improve the EPS-products in every way, as well as testing new additives and production parameters before applying it to the full-scale production plant. The pilot polymerization process is mainly manual, but the most important values can be observed from a display such as temperature, pressure, moment of the mixer etc.

The practical part of the study started by finding out the polymerization recipe of interest. Previously, some low energy EPS experiments had been done using a X polymerization recipe. The material is used mainly for insulation purposes. For this study, it was chosen to use a a different, so called standard recipe, as there appears to be no vast differences in shape moldings energy usage compared to the previous material (Nurminen 2017). Later it was decided that the grade size used was the X-classified grade for it being most used one, which bead size varied from X to Y mm (Julku 2017).

To compare the results, two references and two modified polymerizations were made in the pilot reactor. The EPS-polymerization process has many variables which can alter the end results, so the key factor was to minimize the margin of error to ensure the results are truly compatible. This was done by using same batch of each chemical in every polymerization. The reference polymerizations were done sequentially and low energy polymerizations after them.

4.2   Low energy polymerizations

Low energy polymerizations based on the standard recipe, but some modifications to the polymerization reciope were made. With these

modifications, the material could be more easily molded in theory due to its classified properties (Nurminen 2017). Presenting these modifications on the public version of this thesis was prohibited.

4.2.1 Coating and sieving

Right after drying, the material was sieved and approximately 15 kilograms of sieved beads were collected and coated with a precise recipe.

The working principle of the coating machine is simple. A blade is mixing the materials in a container at set rotations per minute. Cooling can be also applied. Mixing time for the studys materials was agreed to be 10 minutes, as this would be enough time for a small set like this to be properly mixed. All the coating materials were applied to the mixer at once too. Coating material recipe was decided from the main productions recipe. (Julku & Nurminen 2017.)

5   PREFOAMING

5.1   Parameters

Prefoamer used was HIRCH PREEX 1000 – EPS batch pre-expander
(Image 9). It is a modern machine compared to older prefoamers found at
the R&D hall. Smaller and heavier densities can be achieved by its
automated raw material batch measuring and beads expansion sensor
technology.

IMAGE 9. HIRSHC PREEX-1000 (HIRSCH Maschinenbau GmbH 2016, 6)

It was decided to use already available prefoaming recipe, which is used
for the standard product for 20 kg/m^3 densities. Steaming time and amount
of material in one cycle did not had to be altered.

Steaming time was set to X seconds, steaming pressure to X bar and
material feed to X kg/cycle. Seven to nine kilograms of raw material were

prefoamed in to a silo to get plenty of testing material for the shape molding phase.

Density was achieved within margin of error in every test material. The margin of error was 0.6 kg/m^3 which was determined from the differences in highest and lowest density and from density-volume-weight tables scaling accuracy. Accuracy of the table was ± 0.1 kg and the density variable between samples by 0.4 kg/m^3.

TABLE 2. Densities of the prefoamed EPS beads.

PREFOAMED SAMPLE	DENSITY [kg/m^3]
STANDARD 1	19,6
STANDARD 2	19,8
LOW ENERGY 1	19,9
LOW ENERGY 2	19,5

5.2 Conditioning

To have realistic and comparable results, real life EPS-production had to be imitated. Material is aged for the pentane and other residue substances to settle down and evaporate partly in time. If material is prefoamed and molded right after polymerization, it will behave undesirable compared to aged ones. Pentane levels are the primary affecting cause on this.

The material in this study was aged seven days after polymerization before prefoaming in a silo. According to Nurminen (2017), minimum aging time after prefoaming would be 20-24 hours. After prefoaming, material was aged in a silo for 20 hours before shape molding.

6   SHAPE MOLDING

Shape molding machine used was the Erlenbach Maschinen EMMotion EHV-C-E (Image 10). It is a modern shape molding machine capable of molding EPS and EPP (expanded polypropene) materials.

IMAGE 10. Erlenbach Machinen EPS shape molding machine (Erlenbach Machinen 2017, 1)

Based on previous material development work, it was chosen to use at least five different steam pressures for each material. From each steam pressure, five cycles were done. Two test plates would have been enough to cut the bending – and compression test pieces, but three extra cycles were used to make sure there were no huge differences in molding parameters, such as in cooling time. Last two cycle's test plates were saved, and the parameters were compared to other cycles ones. The parameters did not vary a lot and the results were comparable to other steam pressures.

The mold used was for the rectangle shaped 300 x 600 x 50 mm testing plate. The volume of the mold is 9000 cm^3. The steam pressures used were determined from previous material development work and from the cooling times. Pressure used varied from 0.40 to 0.80 bar at 0.10 bar gaps. It was not desirable to use too much steam pressure when the cooling times would have been too long for realistic production use. No stabilization time were used. Stabilization time allows the steam pressure in the moud to be released in slower time phase. This can help the molded material from bending when its cooling after ejecting. (Ronkainen 2017.)
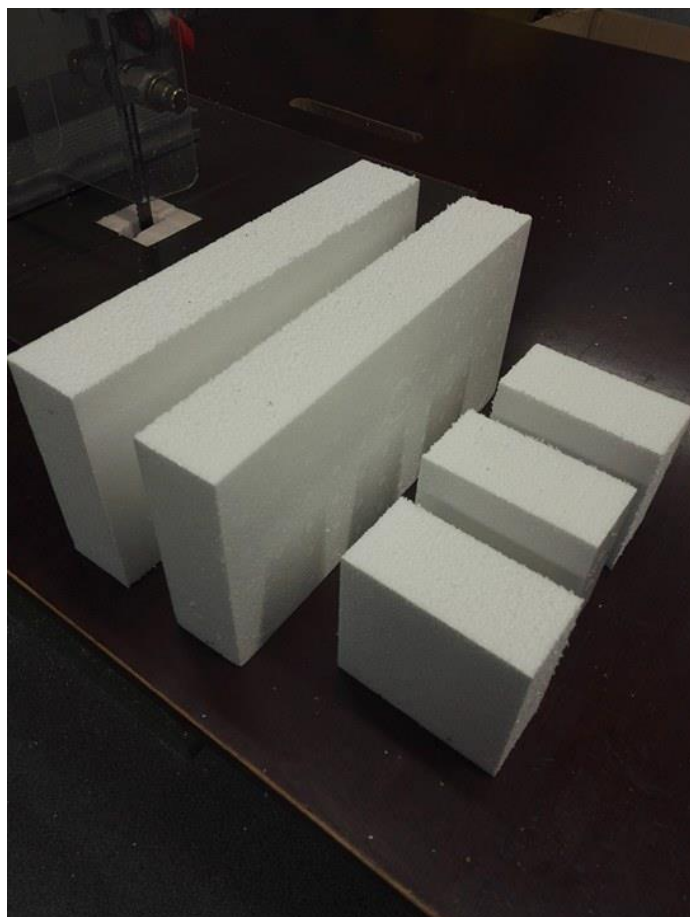
IMAGE 11. Shape molded EPS plate sawed to bending strength and compression stress samples.

7   RESULTS

7.1   Measuring methods

Materials were tested with Lloyd Instruments LR-10K Plus machine.
Bending strengths were tested with three-point test method, where
material is supported from different sides and force is applied to the middle
(Figure 1). Test samples were prepared for to match the standards in use
at Bewi Styrochem Oy. Required amount of 300 x 150 x 50 mm bending
strength and 100 x 100 x 50 mm 10% compression stress test samples
were sawed (Image 11). Six 10% compression stress and four bending
strength test pieces were sawed and tested from each pressure and
material.

Before testing bending strengths and compression stresses of the
samples, they were stored for seven days at standardized conditions,
where the room temperature and moisture conditions were similar for each
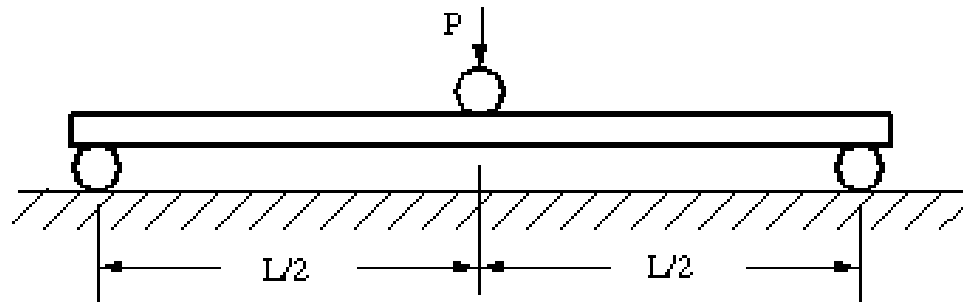sample.

FIGURE 1. Three-point bending strength method (Rusmee 2005)

7.2 Standard products molding and strength parameters

Shape moldings parameters, such as cooling time are affected by steaming pressures. Bending strengths are also increased, as the molding pressures are raised. Bending strength / 12 * ρ value of the tables is covered more on chapter 7.4.1. Compared to modified, low energy materials bending strengths and cycle times, differences can be pointed out. (Table 3; Table 4.)

TABLE 3. Average values of standard test materials steam pressures, densities, bending strengths and cycle times.

STEAM PRESSURE [barg]	DENSITY [kg/m³]	BENDING STRENGTH [kPa]	BENDING STRENGHT/12*ρ	CYCLE TIME [s]	CYCLES/HOUR	COOLING TIME [s]
0,40	21,7	193	0,74	35,4	102	4,0
0,50	22,1	213	0,80	35,8	101	4,0
0,60	21,7	232	0,89	35,9	100	4,0
0,70	20,9	247	0,99	40,5	89	8,9
0,80	21,1	287	1,13	80,6	45	52,1

7.3   Modified, low energy products molding and strength parameters

From low energy products molding parameters table, lowest steaming pressure value achieving the required bending strength / 12 * ρ value is achieved at 0.70 bar. Cycle times at 0.70 bar steaming pressure sets to an average of 63.9 seconds. With this method, at lower 0.60 bar steaming pressure, minimum reference value of 1 is almost achieved. (Table 4.)

TABLE 4. Average values of low energy materials steam pressures, densities and bending strengths and cycle times.

STEAM PRESSURE [barg]	DENSITY [kg/m³]	BENDING STRENGTH [kPa]	BENDING STRENGHT/12*p	CYCLE TIME [s]	THEORETICAL MAX. CYCLES/HOUR	COOLING TIME [s]
0,40	21,2	214	0,84	35,4	102	4,0
0,50	21,3	226	0,88	35,8	101	4,0
0,60	20,6	239	0,97	37,4	96	5,4
0,70	20,5	267	1,08	63,9	56	31,9
0,80	20,6	298	1,21	142,5	25	110,5

7.4   Bending strengths compared (kPa)

Average of each sample sets bending strengths results were calculated and both materials average values were compared (Figure 2). Low energy samples were stronger on average of 6.4 % (19 kilopascals).
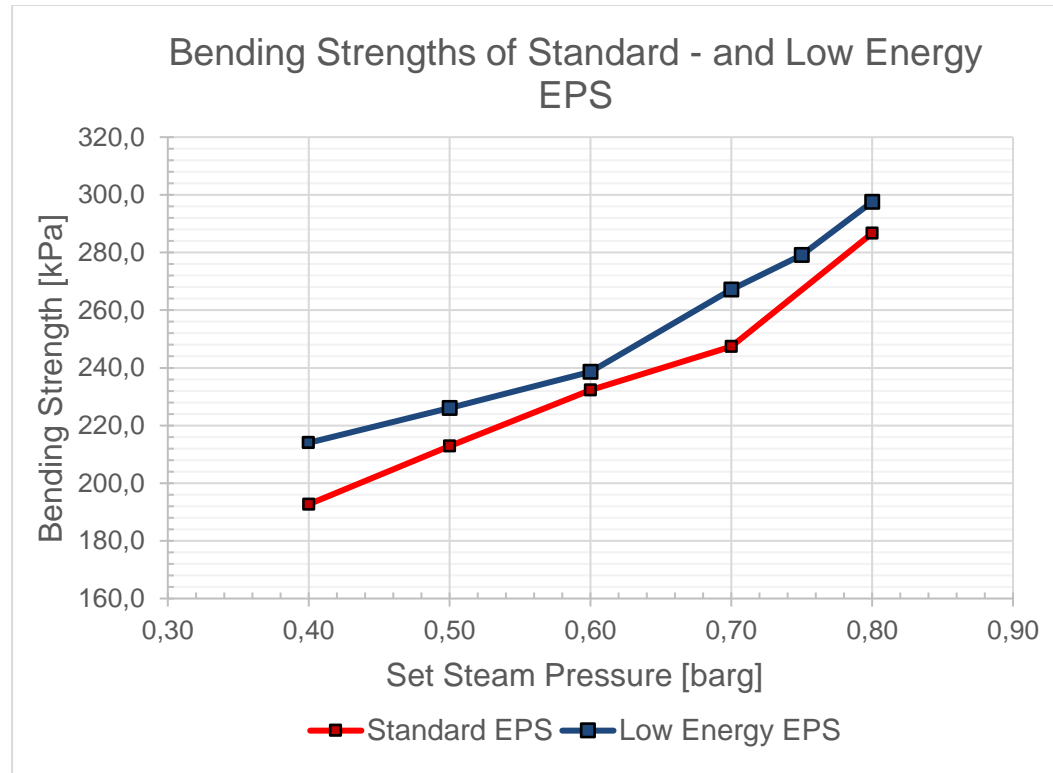

Figure 2. Average bending strengths results on both materials.

7.4.1   Bending strength value taking density into account

For more realistic bending strengths results, Bewi Styrochem´s R&D utilizes formulas for more accurate results, instead of only using the raw kilopascal value. It takes also into an account the density of the test sample, which affects its strength. More dense samples are generally stronger. By using this method, a realistic and describing value is achieved and bending strengths are comparable despite of their slight density changes. The limit value for acceptable bending strength with this method is 1.0. (Julku & Ronkainen 2017.) (Formula 1.)

$$R = \frac{Bending\ strength\ (kPa)}{12 * \rho} \qquad (1),$$

FORMULA 1. Formula for calculating more accurate value to describe bending strengths of EPS-samples (Bewi Styrochem 2017).

Averages from each standard – and low energy's bending strengths and densities results were calculated together to get an average comparison of the two products by taking into an account both polymerizations instead of laying results based on one polymerization.

Based on the results, low energy products bending strengths were stronger with every set steam pressure than standard products ones. The reference values error margin of 0.07 is exceeded between every corresponding steam pressure (Figure 3).
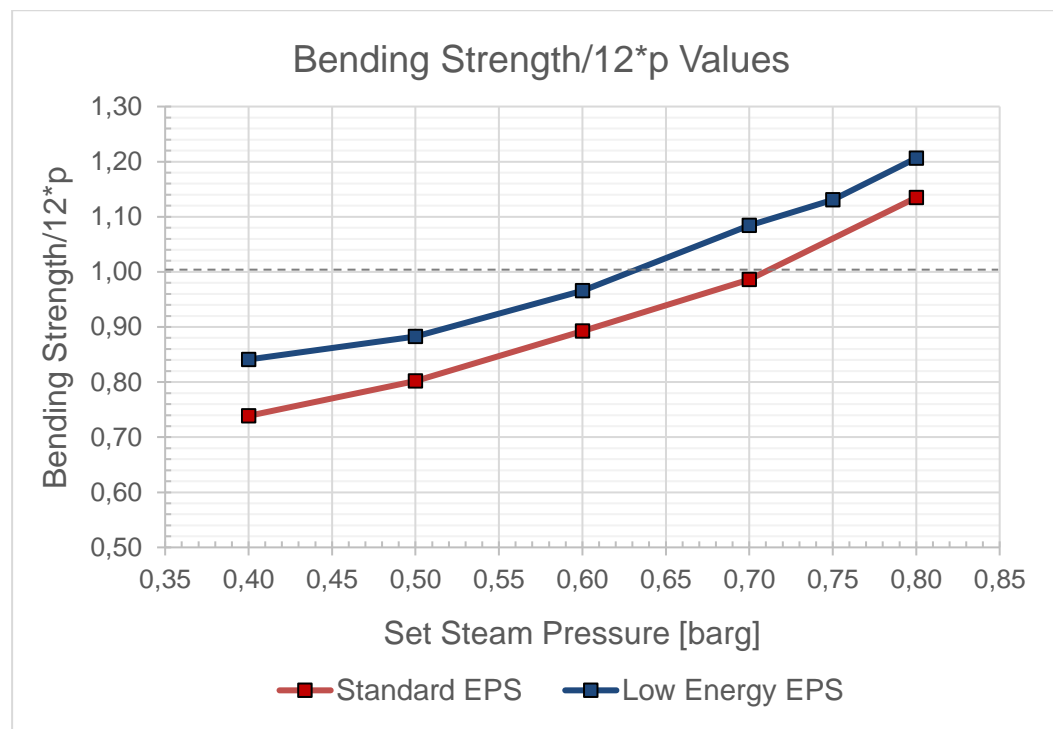

FIGURE 3. Comparison of bending strength and steam pressure values from combined reference – and low energy bending strength results

7.4.2 Bending strength reference value

Even more accurate reference value to describe the realistic bending strengths were calculated from results and compared to standard material

(Figrure 4). This more accurate graph was formed from a classified formula and for those reasons presenting it on the public version of this thesis was not allowed.

Reference value fluctuated between same polymerizations shape molded samples at maximum of 1.20 units. When compared between standard- and low energy materials, values exceeding this were considered as valid results. Between these materials, difference to reference value of 1.20 was exceeded with every tested sample.
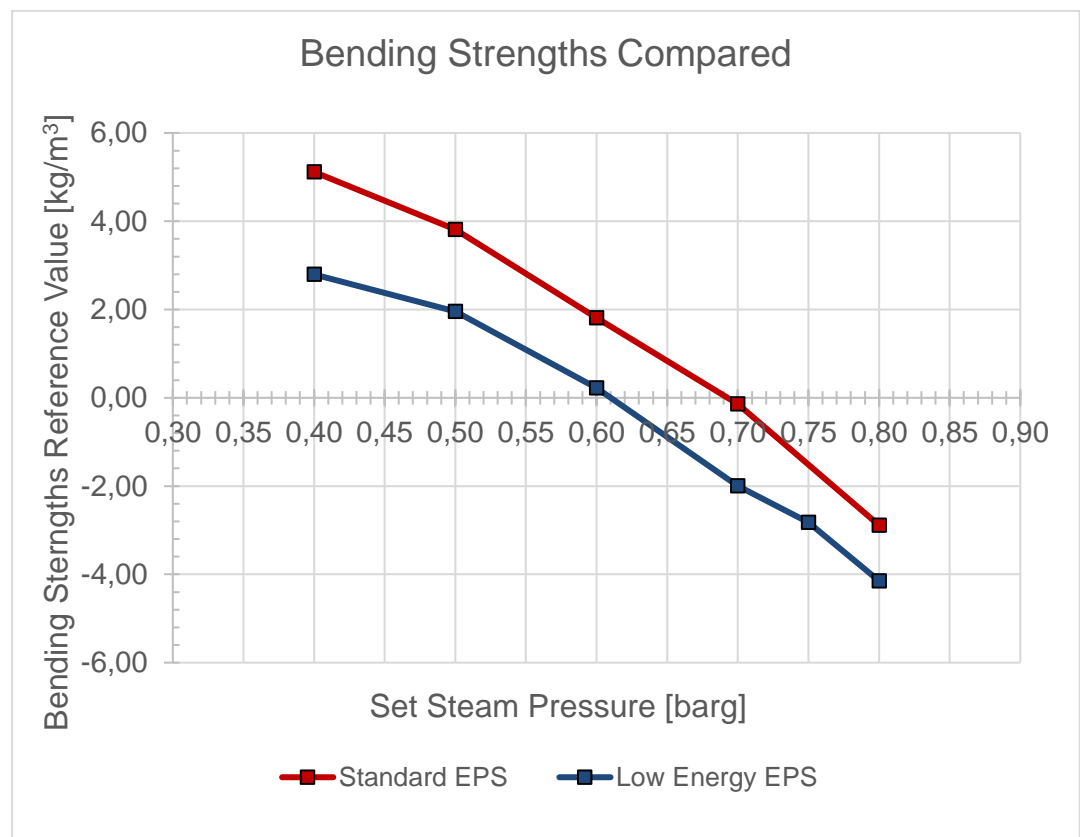

Figure 4. Reference value for bending strengths in correlation with set steam pressures.

From the figure, steam pressure points where bending strengths are crossing the x-axel can be determined. Also, the difference on strengths at same steaming pressures can be seen. With this reference value formula and method, required strengths with standard materials are achieved precisely at 0.70 bar molding pressures. With low energy samples, the strengths were achieved with 0.70 pressures as well. However, at that

pressure, low energy material is 1.85 units stronger, which means steam pressure could be decreased.

It can be read from the figure, that the realistic required bending strengths for low energy materials would be achieved somewhere at 0.61 to 0.62 bar. Steam pressures were altered by 0.10 bar gaps, so the closest value for calculations was used, which was at 0.60 bar pressures parameters. Also at 0.60 bar, low energy materials average strengths are very close to the required value and was achieved on one of the tested polymerization sample materials.

At 0.60 steam pressure, low energy materials perks are seen. The bending strengths difference can be compared to standard materials strength at higher, 0.70 bar. The difference to the standard materials 0.70 bar bending strength is only 0.08 units.

7.4.3 Comparison between same polymerizations bending strengths

Two same polymerizations were also compared in between. Largest fluctuating on bending strengths were at 0.80 bar test samples by a 0.07 bending strength / 12 * ρ value. Even between same products results, some fluctuating is happening and for reliable results, this fluctuation would have to be considered as normal variable and values over this would be taken into an account when comparing in between standard and low energy´s bending strengths. Graphs between same materials samples can be found from appendices.

7.5 Compression stress at 10% relative deformation

For this for this study, bending strengths were the point of interest, as it is the most common way the material is stressed on the final form as a packaging product.

10% compression stresses were measured as well as the results were somewhat interesting to see. As the end results came by, it was noticed

that there were no marginal differences in between materials or steaming pressures, they were not a point of interest anymore. Figure for compression stresses at 10% relative deformation between testing materials can be found on appendices.

8 ESTIMATED SAVINGS ON ENERGY

8.1 Steaming

As a secondary part of the study, it was interesting to see an estimate of energy usage difference with these two materials. Focus was to see, if low energy material would save energy and how much compared to the standard reference material. This would be achieved by using lower steaming pressures in shape molding process. The molding machine used in this study had a build in steam usage display, which is a computational and calculational data of the usage. The calculation is a computional phase from steaming valves position. However, the steam usage is also affected by the size and length of the piping in the machinery and the size of the mold. By adjusting steam pressure and steaming times, this consumption can be decreased. In this study, steam pressures to the fixed and moving part of the mold were adjusted. (Erlenbach Machinen 2017.)

Steam came to the R&D hall with 3.7 bar of pressure from which it was decreased to 2.3 bar pressure to the shaping machine. From this pressure, steaming pressure for fixed and moving part of the mold can be adjusted. On this study, test pieces were molded with a steam pressures varying from 0.40 to 0.80 bar gauge, by increasing pressure by 0.10 bar gaps. For steaming baseline, parameters shown on table below were used (Table 5).

TABLE 5. Steaming parameters. Steams pressure were changed for fixed and moving part of the mold.

Rinsing moving side	0,5 s	0,30 Bar
Rinsing fixed side	0,5 s	0,30 Bar
Steaming autoclave 1	0,0 s	0,0 Bar
Steaming autoclave 2	0,0 s	0,0 bar
Cross steaming 1	4,0 s	0,55 Bar
Cross steaming 2	4,0 s	0,55 Bar
Steaming moving side	4,5 s	-
Steaming fixed side	3,5 s	-

8.2 Estimated savings based on steam usage and theoretical production capacity increase

The estimated steaming energy was calculated by adding energy required to heat given mass of water to steams temperature and adding energy required to evaporate given mass of steam at 0.60 bar gauge of pressure. Mass of the steam used based on the data from shape molding machine's steam usage at used steaming pressures which achieved required bending strengths. The difference of maximum capacity cycles steams usage between test materials was the steam mass saved daily by using low energy products molding parameters, and so on.

The given mass of steam was converted to energy units by calculating estimated amounts of heat energy on that mass, temperature and pressure. Quantities of energy, Q_1 and Q_2 were calculated (Formula 2; Formula 3).

$$Q_1 = cm\Delta T \qquad (2),$$

Where Q is quantity of energy, m is mass of the steam, c is specific heat capacity of the substance and delta T temperature rise of the substance.

$$Q_2 = mh_{fg} \qquad (3),$$

Where h_{fg} is specific enthalpy of evaporation of steam. (Spirax Sarco 2017).

The Q_1 and Q_2 energy were added as Q_{total}, which was the estimated energy brought to used steam. Delta t value for Q_1 was determined by using measured steam temperature value at 0.60 bar of 112 ^oC and from room temperature of 22 ^oC. At Q_2, the specific evaporating temperature was verified from steam tables to be 2220 kJ/kg at 0.60 bar (Engineering Toolbox 2017).

After calculating estimate of energy savings by using the lower steam pressure and by that achieving decreased cycle time, and steam usage, it was transformed to kWh and the possible savings on energy fees was calculated. The price of electricity is an estimate, based on examples found on similar calculations and for that, it is only showcases the scale and do not represent any real numbers, as it would require more detailed survey and realistic production data. The calculated estimations were catered in a table (Table 6).

TABLE 6. Estimated savings on energy in shape molding by using low energy products

TIME	DAY (24H)	WEEK (5 D)	MONTH (22 D)	YEAR (226 D)
SHAPE MOLDING CYCLES MORE WITH LOW ENERGY PRODUCT	177	884	3890	39 960
STEAM USAGE WITH STANDARD PRODUCT [kg]	2560	12 800	56 320	578 560
STEAM USAGE WITH LOW ENERGY PRODUCT [kg]	2480	12 420	54 640	561 2550
SAVE COMPARED TO STANDARD PRODUCT [kg]	77	380	1 690	17 310
STEAM ENERGY SAVE Q_{TOTAL} [kJ]	200 400	996 700	4 385 000	45 049 000
SAVE ON kWh*	56	277	1220	12 500
SAVE ON ENERGY, ONE SHAPE MOLDING MACHINE [€]	7	36	158	1 630
SAVE ON ENERGY, 20 MACHINES [€]	145	7120	3 170	32 500

SAVE ON ENERGY, 5 MACHINES [€]	36	180	790	8 130
* (ESTIMATED PRICE 0,13€/kWh)				

8.3 Maximum molding capacity

By molding with lower steam pressure, savings on steam consumption can be determined. On this study, savings were calculated from the parameters by decreasing the steam pressure from 0.70 to 0.60 bar. Cooling and cycle times are not tremendously different at these pressure changes, but difference is still notable. Cooling times are major part of the cycle time, and by that production capacity. As cycle times are decreased, molding capacity is increased. In this study, molding capacity was increased from 2133 cycles to 2310 cycles a day with one machine, or 8.3 %.
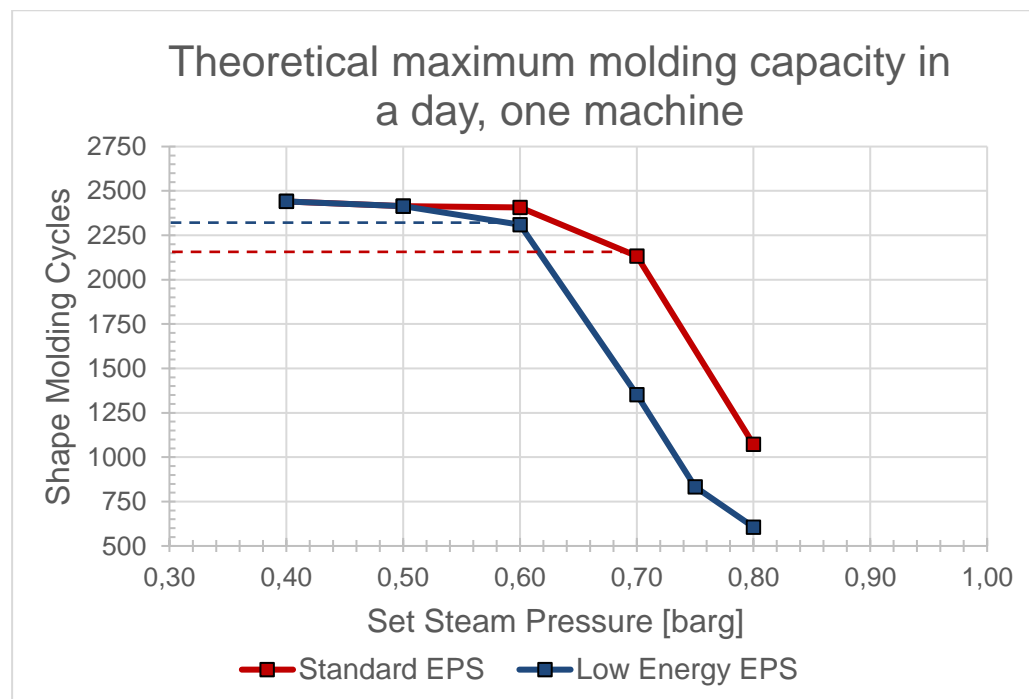

Figure 5. Horizontal lines indicate points where average minimum bending strengths are achieved.

8.4   Cooling times

In this study, cooling times and surface pressure varied some between the reference, standard products and the varying cooling and surface pressure values between low energy products did not exceed these values.

Cooling times increased, as steam pressures were raised. At lower pressures, both materials cooling times were similar, but when increased beyond 0.70 bar, it started to increase rapidly and more with low energy material, which adds up to longer cycle time. The standard materials cooling time was on average of 8.9 seconds and low energy's 5.4 seconds. At 0.70 bar, low energy materials cooling times increased significantly up to 30+ seconds, while standard's cooled faster (Figure 6).

Test materials hit their longest cooling time at highest tested pressure of 0.80 bar. Standard samples peak of average maximum cooling time was 52.1 seconds, where low energy cooled in 110.5 seconds (Figure 7).
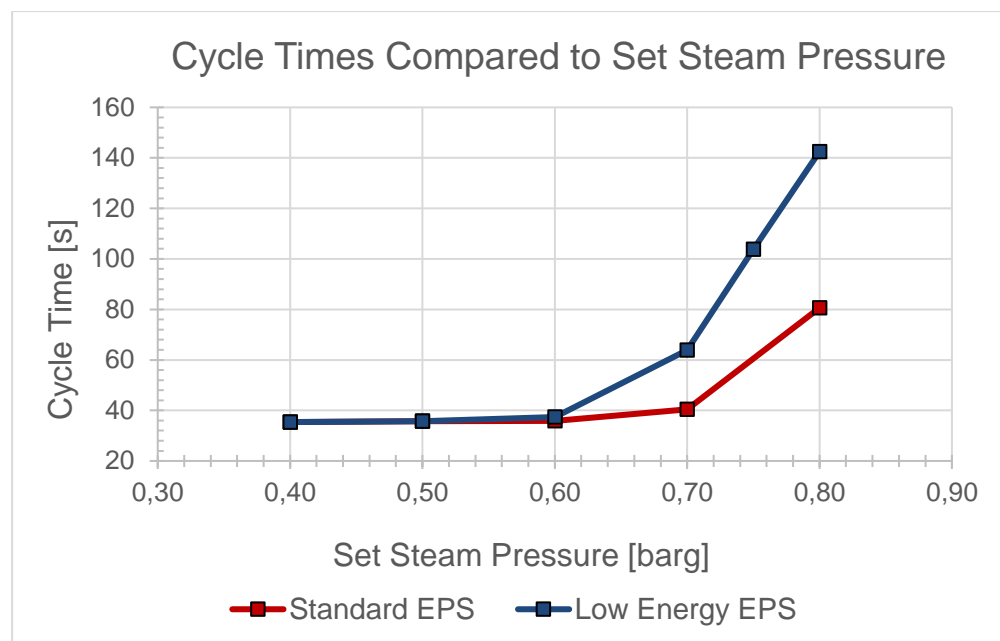

Figure 6. Cooling times of sample materials correlated with set steam pressure.
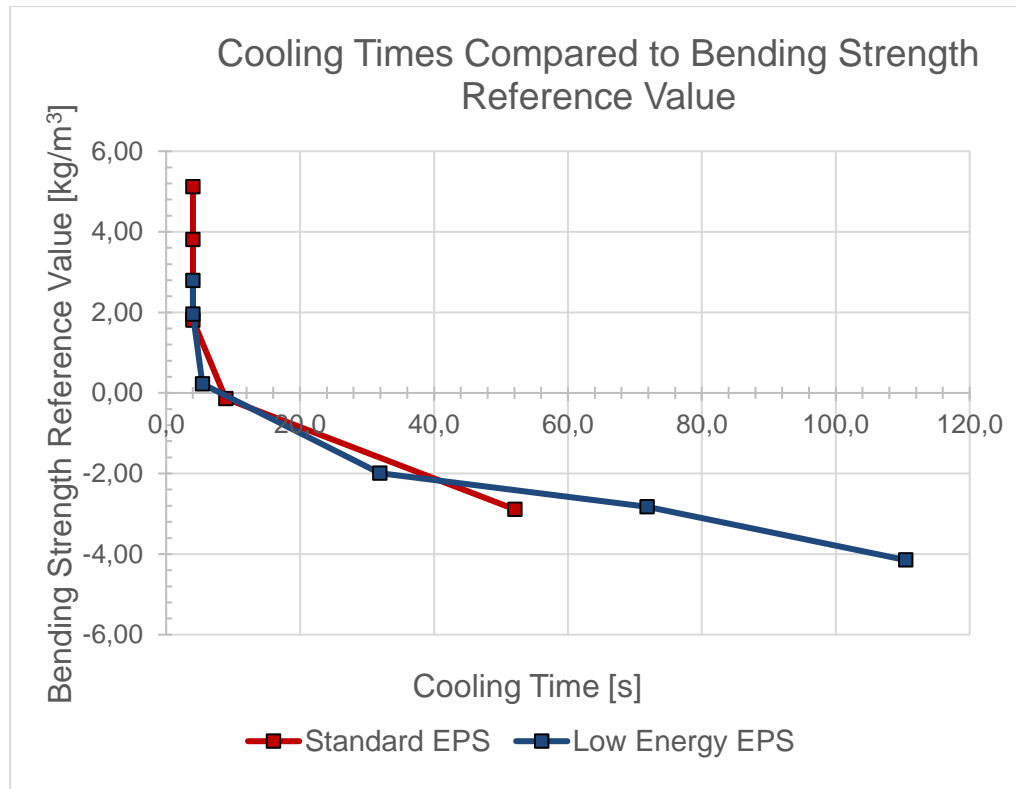
Figure 7. Cooling times of sample materials correlated with bending strengths reference value.

8.5 Theoretical example of steam usage in a EPS shape molding factory

As a part of the study, steam usage in a shape molding factory were estimated. Example was used for a factory producing a similar volume product as in this study at 9 liters. In this example, 20 shape molding machines are running and used on three shifts a full day. A shape molded product taken for an example is a lid for sturdy fish box, or a smaller fish box.

Using the low energy EPS, 0.60+ bar of steaming pressures can be used. At that pressure, a rate of one lid in every 37 seconds is produced. In a day ~ 2310 cycles are produced with one machine and approximately 46 200 cycles with 20 machines. Steam is being used approximately 50 820 kg.

Compared to standard EPS material, where 0.70 bar of steaming pressure is required, at that pressure a rate of 40 + seconds per a cycle, 2130

cycles with one and 42 660 cycles with 20 shape molding machines can be molded in a day. Steam is being used similar amounts, slightly more of about 51 190 kilograms. Notable is, that similar amount of steam is being used, even with 5000 cycles less. Cycle amounts per day are increased up to 8.3% by using low energy EPS.

To compare steam usage, same amount of shape molding cycles would be done with each material. If standard materials 42 660 cycles are molded in a day with low energy materials parameters, 46 930 kg of steam is used. Steam is saved 4260 kg or 9.7% (from 51 190 kg to 46 930 kg with same amounts of cycles) (Figure 8).
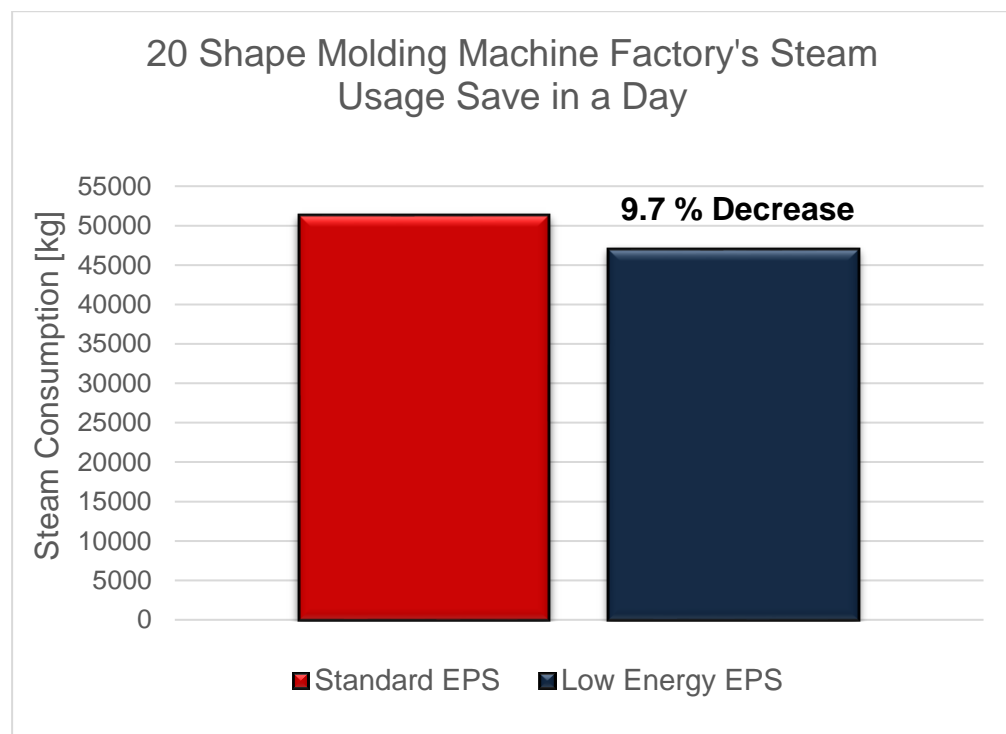

Figure 8. Steam usage with 20 shape molding machines in day, while same amount of cycles molded

Saving were also converted into percentages to express the them in another way (Table 7). These are the savings, when same amount is moukded with both test materials. Production capacity increase percent represents the increase in maximum amount that products can be molded in a day. Steam can be saved, while cycle time decreases and production capacity increases, when more products can be molded in a day.

Table 7. Estimated savings in shape molding production using the low energy EPS material.

Savings compared to reference material	
Steam	- 9.7 %
Cycle time	- 7.5 %
Production capacity increase (If theoretical maximum amount per day is molded with both materials)	+ 8.3 %

9   SUMMARY

From the results it can be determined, that by processing low energy EPS-material according to this study's molding parameters, steaming pressures could be decreased approximately 0.10 bars, from 0.70 to fair 0.60 bar pressures. Low energy test samples were 6.4 % stronger on average at bending strengths when compared between every similar steaming pressures samples to reference material.

Also by using low energy EPS-material, cycle times increased, but when decreasing the steaming pressures to 0.60 bar and comparing it to the reference material at 0.70 bar, cycle times decreased on average of 7.5%. This correlates also to 8.3% molding production capacity increase. In addition, by decreasing steaming pressures from 0.70 to 0.60 bar, steam can be saved up to 9.7%.

By doing two polymerizations with each product, an estimate of the materials properties was formed. However, as the results were analyzed, it was noted that due the slight changes in density, processing times between same materials and bending strengths, more polymerization samples could be needed to form a solid and truly reliable data. It would be interesting to see, how low the steam pressure could be decreased, if the polymerization recipe would be modified even more.

Calculating extremely realistic steam flow and energy usage at mouding would have been particularly demanding, due to complex piping layout and steam transfer system to the shape molding machine. Energy is lost at piping due the heat transfer through it. Incoming steams properties to the R&D hall were known, but pressures were decreased to the shape molding machine with a valve and after this, steam properties could not be measured without excessive dismounting of piping. Also, as the steam was brought from a power plant to the study's shape moluding machine, it is not identically similar compared to the common boiler and steam accumulator system found at shape molding factories. Fortunately, temperature of the incoming steam to the mold was able to be measured,

and the shape molding machine had a modern technology build in steam usage sensor and display which enabled and provided data, and estimations based on that data were formed.

To make even more accurate estimate of the energy savings, more factors than difference in steaming pressures could be considered. For example, steaming times to the mold could be altered in similar ways as the steaming pressures were. In addition, the genuine cost of the modified polymerizations could be calculated and compare it to the possible benefits available from lowering steaming pressures.

REFERENCES

Printed Sources

Hautala, M. & Peltonen, H. 2011. Insinöörin (AMK) FYSIIKKA OSA 1. 10th edition. Saarijärvi: Lahden Teho-Opetus.

Johansson, T. 2017. Soluuntuva polystyreeni, EPS. In Järvinen, P. Muovit ja muovituotteiden valmistus. Porvoo: Bookwell Oy.

Digital sources

Bewi Group Oy. 2017. Bewi [accessed 11.10.2017] Available: http://bewi.com/fi/

Dyplast. 2011. A Comparison of Expanded Polystyrene (EPS) and Extruded Polystyrene Insulation (XPS). [accessed 20.11.2017] Available: https://dyplastcorefoam.com/files/103/Technical-Bulletins/52/A-comparison-of-Expanded-Polystyrene-(EPS)-and-Extruded-Polystyrene-Insulation-(XPS).pdf

Engineering Toolbox. 2017. Properties of saturated steam. Engineering toolbox.com [accessed 15.11.2017] Available: https://www.engineeringtoolbox.com/saturated-steam-properties-d_101.html

Falaise, J-P. 2017. VS: EMMotion EHV-C-E Steam usage display. Email correspondence. Recipient Hänninen, M. Sent on 17 October 2017.

Fried, J. 2014. Polymer science & technology, 3rd edition. Book sample. Massachusetts: Pretince Hall. [accessed 19.10.2017] Available: http://www.informit.com/articles/article.aspx?p=2235827

Hester, R. 2016. Molecular Weight Determination by Dilute Solution Viscosity Measurements [accessed 16.11.2017] Available: http://www.pslc.ws/macrog/lab/dsvh.htm

HIRSCH Maschinenbau GmbH. 2016. Why Hirsch Pre-Expanders. Austria. Brochure [accessed 14.11.2017] Available: http://www.hirsch-gruppe.com/_Resources/Persistent/9cd911778d1d1052ddfce248cc52810 0d765aa0a/HIRSCH%20Preexpanders%202016.pdf

Kutz, M. 2011. Typical thermal and vapor barrier properties of common insulation materials [accessed 27.10.2017] Available at: https://masto.finna.fi/Record/nelli16_phkk.2670000000099800

Mills, Nigel J. 2005. Mold structure used in EPS shape molding. [accessed 27.10.2017] Available: https://masto.finna.fi/Record/nelli16_phkk.1000000000350685

Nurminen V., & Julku, P. 2017 VS: Matalaenergisen tuotteen resepti. Email correspondence. Recipient Hänninen, M. Sent on 27 September 2017.

Nurminen, V. 2015. Koeajosuunnitelma 01/17. Directive/production plan.

Nurminen, V. 2007. EPS työstö ja siihen vaikuttavat tekijät. PowerPoint slideshow.

PlasticsEurope. 2017. Expanded polystyrene [accessed 2.11.2017] Available: http://www.plasticseurope.org/what-is-plastic/types-of-plastics-11148/expanded-polystyrene.aspx

Ronkainen, A. 2017 VS: Jälkipolymerointiaika. Email correspondence. Recipient Hänninen, M. Sent on 2 October 2017.

Rossacci, J. & Shivkumar, S. 2003. Bead fusion in polystyrene foams. Journal of materials science. 38, 201-206 [accessed 11.11.2017] Available at: https://link.springer.com/article/10.1023/A:1021180608531

Rusmee, P. 2005. High strength composites [accessed 25.10.2017] Available: http://www.mech.utah.edu/~rusmeeha/labNotes/composites.html

Spirax Sarco. 2017. Methods of estimating steam consumption. [accessed 1.12.2017] Available:
http://www.spiraxsarco.com/Resources/Pages/Steam-Engineering-Tutorials/steam-engineering-principles-and-heat-transfer/methods-of-estimating-steam-consumption.aspx

WA Polystyrene. 2017a. Esky ice box 15 kg. [Accessed 27.11.2017] Available: http://www.wapolystyrene.com.au/products/esky-ice-box-11kg/

WA Polystyrene. 2017b. Wall insulation. [Accessed 27.11.2017] Available: http://www.wapolystyrene.com.au/products/polystyrene-sheets-blocks-sl-grade/
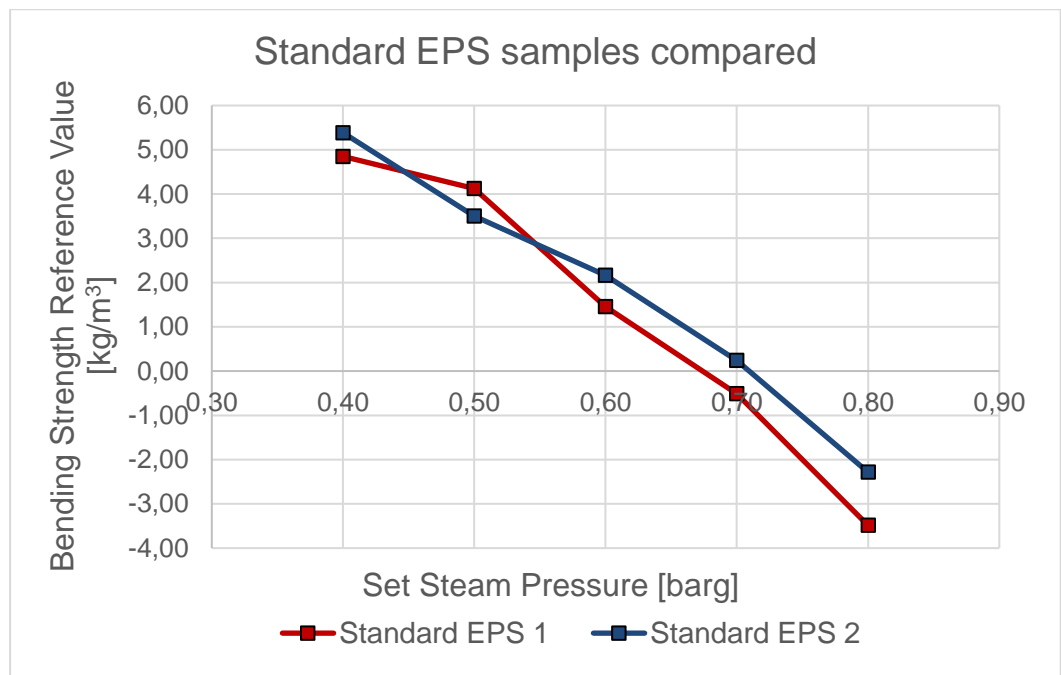
APPENDICES

APPENDIX 1. Compression stress at 10 % relative deformation of standard and low energy samples compared.
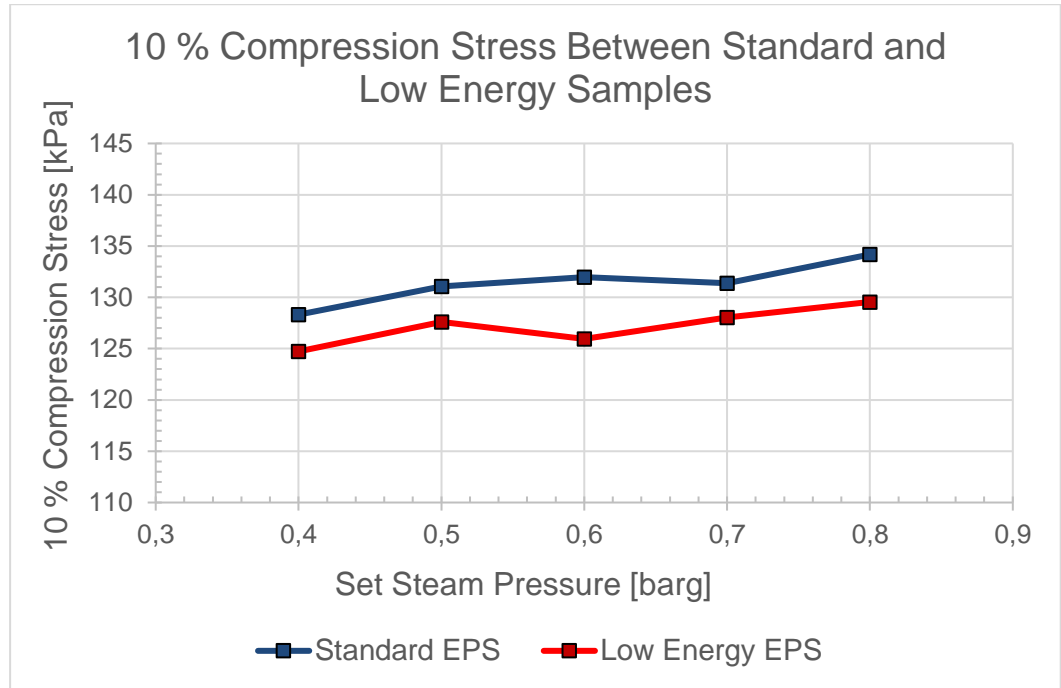
APPENDIX 2. Comparison of bending strength and steam pressure values from standard bending strength results

APPENDIX 3. Low energy bending strengths compared in between

Low Energy EPS Samples Compared