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ASSESSMENT OF FACTORS AFFECTING PRODUCTIVITY OF BRIQUETTING PRESSES AND QUALITY OF BRIQUETTES

Dissertation Thesis

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Declaration

I hereby declare that I have done this Thesis entitled **"Assessment of factors affecting productivity of briquetting presses and quality of briquettes"** independently, all texts in this Thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague 30th of May 2020

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Alexandru Muntean

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Abstract

The solid biofuel represents an affordable and efficient alternative of fossil fuel that makes its use very attractive in many countries. Considering this fact it is necessary to pay a special attention to the problems related to the quality and production efficiency of densified biofuel in the form of briquettes.

The work represents the practical and theoretical research directed to the increasing of the production efficiency of high-quality briquettes on the screw and piston briquetting presses taking into consideration different factors. All used biomass was initially processed - ground by the hammer mill in three fractions and dried. For the efficient use of equipment, there was evaluated the work and determined optimal operation modes with the application of the possible settings. An important part of the work was devoted to the study of temperature influence on the densification process of biomass and the determination of the optimal working temperature of the briquetting equipment.

In the framework of the research there were determined the properties of obtained solid biofuel and evaluated their interrelation with the properties of initial raw material and the specific working conditions (parameters) of equipment. In the result of the research performed, it was found that biomass with particles of small size is more suitable for the production of briquettes. Smaller particles permit to obtain briquettes with dense structure and high durability. The use of biomass of smaller fraction size that has a homogeneous structure can prevent the segregation of the particles during the densification. The studies demonstrated that densification of the raw material of smaller fraction has a positive impact on the rise of the temperature during the briquetting process that has a positive effect on the quality of biofuel. The performed research has indicated that for the production of high-quality solid biofuel on the piston briquetting press, the fibrous or wooden materials of high density are more suitable. The most proper operational speed of the screw as well as the optimal working temperature for the screw briquetting press were determined in the research, too.

Key words: Agglomeration, densification, solid biofuel, briquettes, screw briquetting press, piston briquetting press, biomass, operational temperature, segregation of particles

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List of symbols and abbreviations

AC – Ash content

ATPW - Apple tree pruning waste

BD – Bulk density

BP - Briquetting press

C – Carbon

Cl – Chlorine

cm^3 – Cubic centimetre

CO_2 – Carbon dioxide

CV - Calorific value

°C – Degree Celsius

d.b. – Dry basis

DU - mechanical durability

g – Gram

$g.cm^{-3}$ – Gram per cubic centimetre

GCV – Gross calorific value

GHG - greenhouse gases

H - Hydrogen

HBP - Hydraulic briquetting press

HP - Hemp (Cannabis Sativa)

$J.°C^{-1}$ – Joule per degree Celsius

$J.g^{-1}$ – Joule per gram

$kg.h^{-1}$ – Kilowatt – Hour per tone

$kg.m^{-3}$ – Kilogram per cubic meter

kW – Kilowatt

m^3 – Cubic meter

mm – Millimetre

MBP - Mechanical briquetting press

MC - moisture content

MG - Miscanthus Giganteus

$MJ.kg^{-1}$ – Mega joule per kilogram

MS - Miscanthus Sinensis

N – Nitrogene

NCV_{ar} - Net Calorific value as received

NCV_d – Net Calorific value dry basis

O – Oxygen

PM - Pellet mill

PSD - particle size distribution

RBP - Roller briquetting press

S – Sulphur

SB – Solid biofuel

SBP - Screw briquetting press

V1 – The mode of working speed 1

V3 - The mode of working speed 3

WS – Working speed

1. INTRODUCTION

At the present time, renewable sources of energy received wide distribution in the world and became an integral part of the energy sector in many countries. This trend happened thanks to the need for access of the people in many countries, not only to simple and cheap sources of energy but also for access to ecologically friendly and sustainable sources of energy that can have a positive social and economic impact on the development of countries. Replacement of fossil fuels and traditional sources of energy by renewables and their large implementation in practical use represents a priority of national politics for highly developed countries and also for developing countries of the world. Fossil fuels cannot guarantee anymore for humanity sustainable development. Even if the use of fossil fuels still dominates in entire world, the share of renewable energy sources in global energy production grows year by year thanks to high investments in renewables.

Creation of enterprises that are involved in biomass processing, biofuel production and production of bioenergy offered the possibility for the access to clean fuel for transport, sustainable production of electricity and thermal energy for industrial and residential consumers (Swaaij & Kersten 2015). Solid biofuel is important source of renewable energy, which plays an important role in the global and European energy markets (Palz 2015). Since ancient times when solid biofuel became the first type of fuel used by humanity, it still remains a reliable source of energy at the present.

Densified solid biofuel it is the most promising sources of renewable energy obtained from biomass. This type of biofuel became an affordable alternative to fossil fuels in many countries that do not have own energy resources but have significant quantities of accessible biomass from agriculture or wood processing(Abdoli et al. 2018). Recently in European countries, a large number of company producers were established activity in the production of densified solid biofuels such as briquettes or pellets.

These companies manufacturing solid biofuels from raw materials of various kinds, in different forms and are using in production process very different technologic equipment. All these factors have an influence not only on the quality of the final products but also have a direct contribution on their final price. Many producers cannot use efficient raw materials in briquettes production due to the lack of knowledge about their properties. Producing of the densified biofuel fuel of high price is difficult to sell on the market and it is not suitable for the needs of potential clients that are looking for cheap and efficient analogue instead of the traditional fossil fuel. Also, it is difficult to sell fuel briquettes of low quality due to that densified biofuels in many countries is made in accordance with standards for quality that prescribe for every type of solid biofuel, minimal requirements, necessary for getting to the market and buyers usually, prefer to buy a product of high quality.

Increasing quality of briquettes and reduction of their price is possible through the meeting of following measures as improving technological equipment design; optimization of particles' size and composition of used raw materials of vegetal origin; use of the most appropriate raw materials for a particular briquetting technology.

The most suitable and reliable way, which can have an influence on the quality of briquettes is the optimization of particles' size and use raw materials with optimal density for a given briquetting technology. But for that it is necessary to make more thorough research of densification process and analysis of existing densification technologies.

2. LITERATURE REVIEW

2.1 Renewables and biomass

Climate change caused by the intensive use of fossil fuel, which is considered as one of the main reasons, makes the use of renewables more relevant (Gough et al. 2018).

According to the scenarios made by the year 2040, a consumption of energy resources will increase. And, it is expected that fossil fuels like oil and natural gas will remain the most used fuel types (International Energy Agency 2018). Contrary, the consumption of coal will decrease due to many reasons. The share of renewables in energy production will increase, especially in developed countries. In the present, energy production is still focused on fossil fuel (see **Figure 1**), but the trend indicates that the share of renewable in world energy production and consumption is increasing (Palz 2015).

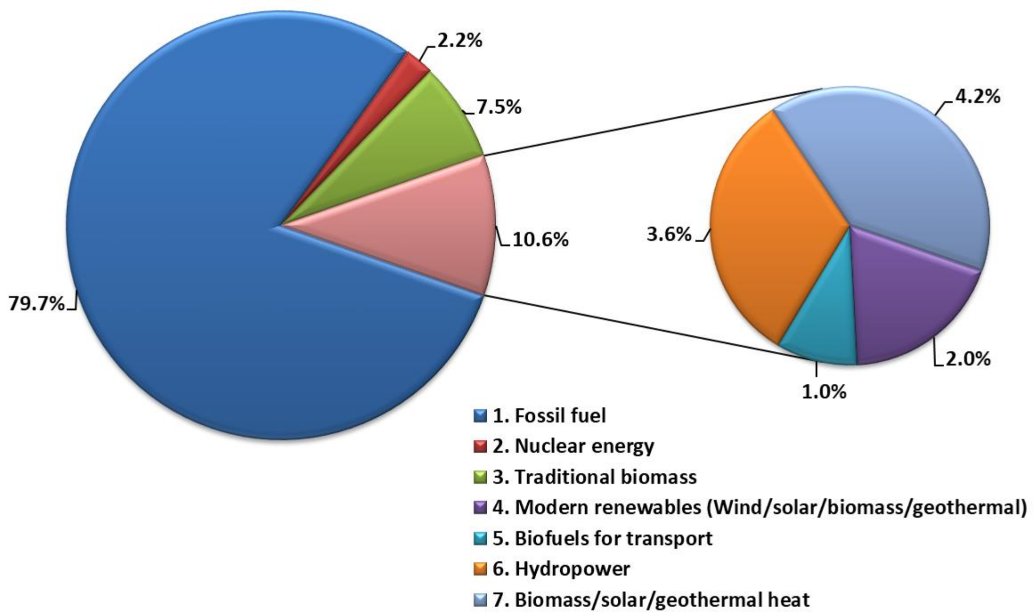


Figure 1. World estimated renewable share of total final energy consumption, 2017

Source: REN21 Renewable Global Status Report (2019)

During the last decade, the development of renewable technologies and their use increased rapidly (Swaaij & Kersten 2015). Especially fast development has received the technologies that refer to the energy obtained from the conversion of biomass (Palz 2015). Even though in the present the most investments are directed in the development of such renewables like solar energy and wind energy production, biomass energy also is promising and advantageous (Jones et al. 2014).

Unlike other renewables, biomass energy technologies are more reliable and accessible. This can be explained by the fact that many biomass conversion technologies (for production of bioenergy) were developed many years ago (or even centuries) (Swaaij & Kersten 2015). Biomass can be used in an initial form for energy purposes or can be processed for the production of efficient forms of biofuel: solid biofuel, liquid biofuel, and gaseous biofuel (Jones et al. 2014).

Have to be mentioned that currently, the process of energy production from biomass provided the possibility to create more than three million working places for the people in the energy sector (see **Figure 2**).

Figure 2. Jobs in Renewable Energy, 2018
Source: REN21 Renewable Global Status Report (2019)

The application biomass energy technologies were limited and their usage mainly was at the level of family farms or small rural communities. For many years the lack of interest in a large-scale production of bioenergy and biofuels was conditioned by a number of factors; and the main was the inability of biofuel to compete with fossil fuel (Kopetz 2015). Currently, favourable conditions for the development of bioenergy on a large scale appeared and production of biofuels at the industrial level began.

2.2 Agglomeration process

2.2.1. Agglomeration: fundamentals, history and development of technologies

The principle of production of densified solid biofuel is based on the phenomenon of agglomeration. The word "agglomeration" has origins from the latin *agglomerare* that has a meaning - to join ("Merriam-Webster's Collegiate Dictionary" 2001). Agglomeration represents a process that consists in enlargement of small particles size and transforming in a body of bigger size than it was initially, and of different shapes (Cleveland & Morris 2015).

The agglomeration is a complicated process, the key role in which belongs to the interactions between particles of materials subjected to this process. According to the classification elaborated by H. Rumpf, following binding mechanism (interactions) between particle sare possible (Pietsch 2005): solid bridges (**Figure 3 A, B, C, F**); adhesion and cohesion forces (**Figure 3 B, F**); surface tension and capillary pressure (**Figure 3 C, F**); attraction forces between solids (**Figure 3 D**); interlocking bonds (**Figure 3 E**)

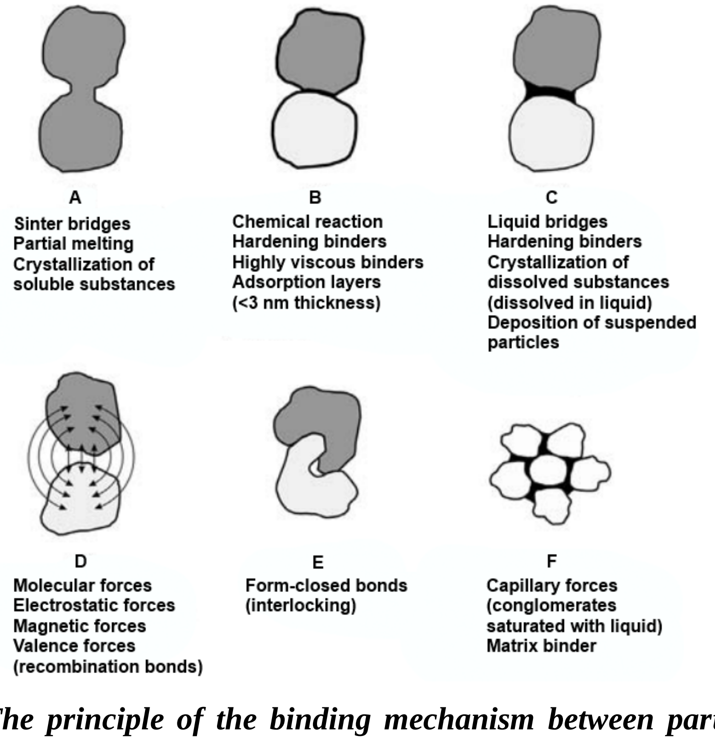


Figure 3. The principle of the binding mechanism between particles during the agglomeration

Source: Pietsch (2005)

The mechanism of agglomeration is different and depends on the environment in which it takes place, size and shape of particles, type of processed material, temperature, the technology of agglomeration, etc. (Rumpf 1990; Mani et al. 2003).

On the Earth, the agglomeration appeared in a natural way, once with the formation of the rocks, stones, and soil. In nature, there are a lot of examples of the agglomeration, e.g. (termites, yellow potter wasp, and dung chafer) are using it for protection or feeding purposes. The same this principle is applied by the birds for construction of the resistant and safe nests (Red ovenbird) (**Figure 4**).

Figure 4. Agglomerated nest of red ovenbird and nest of yellow potter wasp made from clay and parts of the plants

Source:https://commons.wikimedia.org/wiki/File:Rufous_hornero_(Red_ovenbird)(Furnarius_rufus)_and_nest_(2).JPG and http://www.brisbaneinsects.com/brisbane_vespoidwasps/MudDauber.htm (accessed February 2018)

First processes, where humanity applied the agglomeration principle, were the construction of the houses from the clay, making of bricks and tiles from the clay, glassmaking, and pottery forming. Cooking of the bread also can be attributed to this process, where the main material - flour was bonded by the binder agent – water (Capes et al. 1980; Pietsch 2002).

Industrial application of the agglomeration process began in the middle of the nineteenth century with its usage in the technology of densification of coal fines that were accumulated in the process of coal mining (Capes et al. 1980; Pietsch 2002). For few centuries coal was the main fuel used for various purposes, in different industries and for residential use. In the mining process of the different types of coal, there were remaining the significant quantities of unused wastes of a fine coal that were not possible to use due to the danger of its explosion and spontaneous combustion. The problem related to the utilization of fine coal wastes was solved by its densification in the form of briquettes with adding of a pitch in the quality of binding agent. Densification was done by special equipment called in this time “briquetting machine” which was driven into the action by steam (Wright 1907). In some cases, densified fuel obtained after briquetting was better by its properties than an initial fuel. For example, this type of fuel was resistant to weather action and had a long time of burning. For this reason, many railroads and steamship companies preferred to use densified coal instead of wood or coal (Wright 1907).

Countries that actively participated in the developing and producing of briquetting equipment for coal were Great Britain, France, and the United States of America. Nevertheless, as the country-discoverer which had the biggest contribution to the apparition and development of agglomeration technologies has to be considered Germany. Thanks to German scientists, the agglomeration appeared for the first time as an independent field of science from the 1950s with the creation of the scientific school that had the contribution in the formation of such scientists like H. Rumpf, W. Pietsch, E. Hoffman, H. Schubert.

Today agglomeration received widespread in such areas like food processing and production industry, pharmaceutical industry, metallurgy, agriculture, etc. Development of different types of industries had a direct impact on increasing application and development of agglomeration technologies in many areas of human activity. Agglomeration technologies have many positive aspects of their large application in the practice but the main purpose of their use is improving the properties and quality of final products, enhancing the density of the products, improving conditions for better manipulation, storage, and transport of products (Capes et al. 1980) .

Existing agglomeration technologies that are applied in the different areas of production can be divided by:

- The domain of application
- Type of processed material
- Method (technique) of agglomeration

Classification by domains of application of agglomeration technologies is made based on where they are applied. There are many areas where these technologies are used but the most important are: pharmaceutical production, food industry, animal feed production, fertilizers and agrochemicals production, production of building materials and ceramics, mining industry (minerals and ores), metallurgical industry, solid fuels production, powder metallurgy, recycling (Pietsch 2002).

Application of agglomeration technologies is made based on the type of the raw material applied in the production. Classification of agglomeration technologies, in this case, is done according to the provenience of raw material, proprieties of processed raw material, size and structure of the raw material.

The classification based on the method (technique) of agglomeration means dividing existing agglomeration technologies according to the principle of their working process. The classification based on the method (technique) of agglomeration made by Capes et al. (1980) is as following:

- Tumbling agglomeration
- Mixer agglomeration
- Agglomeration from liquids
- Pressure agglomeration
- Dispersion and spray agglomeration
- Thermal agglomeration

The more detailed classification and description of used equipment, of the existing agglomeration technologies, which was carried out and described by Pietsch (2002), is shown in the Table 1 below.

Table 1. *Classification and description of used equipment, of the existing agglomeration technologies.*

The main agglomeration technologies	The subcategory of the main agglomeration technology	The main agglomeration equipment
Tumble or growth agglomeration	High-density tumbling bed High-shear tumbling bed High-density/high-shear with abrasion or crushing transfer Low-density fluidized bed Low-density particle clouds Agglomeration in stirred suspensions Immiscible liquid agglomeration	Rotating inclined pan Cone agglomerator Drum aglomerator Deep pan or disk agglomerator Mixer agglomerator Fluid bed agglomerator Tumbler aglomerator Rewet agglomerator Spray fluidizer Steam jet agglomerator
Pressure agglomeration	Low-pressure agglomeration extrusion through screens	Screen and basket extruders

	Medium-pressure agglomeration pelleting, extrusion through perforates die plates High-pressure extrusion High-pressure agglomeration –in confined spaces, punch-and-die pressing, tableting –in confined spaces, isostatic pressing –in semi-confined spaces, roller presses	Radial, axial and dome low pressure extruders Flat die extruders Pellet mill Moist granulator Gear pelletizer Axial medium pressure extruder Ram extrusion press/piston press Axial high pressure extruder Punch-and-die press Roller press
Agglomeration by heat or sintering	Agglomeration of stationary particle beds by sintering Bonding of pre-agglomerated bodies or parts during post-treatment to obtain final product properties, Agglomeration and bonding during special pressure agglomeration processes (i.e., hot isostatic pressing).	Bell type furnace Elevator type furnace Tunnel kiln Mesh-belt sintering furnace Continuous pusher furnace Continuous roller hearth sintering furnace Walking beam sintering furnace

Source: Pietsch (2002)

From all existing agglomeration technologies, the most suitable for the densification of biomass, for energy purposes, is the pressure agglomeration (densification, briquetting, pelletizing, compacting). For the production of the solid biofuel (SB) in the form of pellets is applied medium-pressure agglomeration and for production of the SB in the form of briquettes is used high-pressure agglomeration (extrusion).

2.2.2. Densified solid biofuel

The use of biomass (uncompacted) for direct burning is possible and is widely applied for the production of energy. But this way of biomass use is considered as not efficient. This is related to the fact the biomass has a low density, that creates difficulties in handling and storage, and requires additional costs for transportation (Mani et al. 2003). Direct use of biomass can create operational difficulties for the burning equipment and can decrease its working efficiency (Abdoli et al. 2018).

The processing of biomass by densification can essentially improve the efficiency of its use (Chen et al. 2015a).

The brief description of the common types of solid biofuels is presented below.

Bales

Bales are SB produced by compressing of biomass. To keep their shape and the biomass more compressed the bales are bound. Production of the bales is performed by the machines called balers (Dyjakon 2018). The weight and the size of bales are different. The shape of bales can be rectangular or cylindrical (is related to the type of machinery applied for baling). Usual bales are made from the straw of cereal crops (preponderantly wheat straw), but for energy purposes, bales made from energy crops, orchard and vineyard prunings, forest wastes (tops and branches of the trees, etc.) can be used successfully (Lavoie et al. 2007; Vanbeveren et al. 2017; Dyjakon 2018). The density of bales is lower in comparison with briquettes and pellets.

Briquettes

Briquettes represent a densified SB with a diameter higher than 25 mm. The shape of the briquettes usual is cylindrical, but in the dependence of the production equipment can have also cubic, rectangular, polyhedral shape EN ISO 16559 - 2014. The briquettes are obtained on briquetting presses (BP).

Pucks

Pucks are very similar to briquettes. They are produced by the same equipment with briquettes. The main difference in comparison with briquettes is the size. The pucks have a cylindrical shape but are thinner then briquettes and look like disks(Abdoli et al. 2018).

Pellets

Pellets are densified biofuel with diameter not bigger than 25 mm, mainly of cylindrical shape but also can be met with another shape EN ISO 16559:2014. Pellets are obtained on a pellet mill (PM). The specific of the pellets is that for their production is required raw material with particles of small size (Döring 2013).

Cubes

Another densified biofuel are cubes. They are similar to pellets and briquettes, but their shape is only rectangular. Cubes by the size are something intermediate between pellets and briquettes, but their density is lower (Abdoli et al. 2018).

2.2.3. Modern biomass densification technologies

Pelletizing is called the compacting process of biomass particles, by giving them the shape of pellets (granules) of various sizes and increasing of their density, made for energy (fuel) purposes (Chen et al. 2015b; Cleveland & Morris 2015). The history of pellets started at the end of the 19th century when they were used initially in the quality of fodder for animals. The first use of pellets (were made from the sawdust) as a fuel began in the twenties of the 20^{th} century in North America (Kocsis & Csanády 2019).

The main equipment used in the production of pellets is PM, that has an identical principle of agglomeration process but differ in construction, productivity, size and shape of the obtained products. In the process of the biomass pressing, the main working parts of the PM that are involved in the pelletizing process are rollers and a die (Koshelev & Glebov 1986).

The process of pellet production is the following: initial crushed material gets on the die where, under the influence of the moving rollers, the material is pressed under pressure into the channels of the die. Due to the friction force that appears from the movement of the particles of raw material, the main working parts and the pressed feedstock are heated up. **Under the action of high temperature as well as the pressure** that arises in the channels of the die, **the process of densification of raw material particles and formation of pellets take place** (Koshelev & Glebov 1986; Bernardes & Aurélio 2011; Kocsis & Csanády 2019).

Often for the production of pellets of high quality, a hydrothermal processing of raw material is used. Immediately before the densification process, liquid (more often water) or steam is added into the biomass. In consequence of the hydrothermal treatment, the biomass is exposed to biochemical and structural-mechanical changes that have a positive impact on the efficiency of a pressing process. In case of using the raw material of low quality, different binder substances can be applied for the pelletization process (Koshelev & Glebov 1986; Bernardes & Aurélio 2011; Lu et al. 2014).

Briquetting **of SB** is called the **densification process of biomass particles, by giving them the different shapes** (cylindrical, cubiform and prismatic) of various sizes made for energy (fuel) purposes EN ISO 16559:2014.

In the process of briquettes production densification technologies of high pressure agglomeration are applied. For briquettes obtaining are used BP that differ by the technology of production, main working parts, productivity, construction, shape and size of the final product. At present exist many briquetting technologies but the main technologies are: the briquetting technology with a piston (punch or ram), roller and screw briquetting technology (Kristoferson & Bokalders 1986; Kuchinskas et al. 1988; Pietsch 2002, 2005).

Difference between this technologies of briquetting is that briquetting by piston press is a discontinuous process of pressing whereas briquetting by roller (with some exception) and screw press is a continuous process pressing (Kristoferson & Bokalders 1986).

In comparison, the other briquetting technologies, the densification process in the roller press (RBP) is simpler. The pre-processed biomass (ground, dried) is added by feeder between two counter-rotating rollers. The rollers usual are of cylindrical shape with deepenings on the lateral surface. The deepenings are moulds that confer the shape to the raw material. Thanks to the developed pressure by rotating rollers, the biomass during the passing between them is densified (Kitani 1999; Bembenek 2017; Abdoli et al. 2018).

Active pressing parts of piston BP that are involved in the process of densification, are piston (punch or ram) and cylindrical die with an open channel. Usually can be used cylindrical or conical dies (Pietsch 2005).

The principle of biomass densification in piston BP is following: raw material is added into the pressing chamber where it is pressed by the moving piston (ram) into the cylindrical die. During every movement of the piston, a new quantity of raw material is added into the pressing chamber until it will cover all the space of the die. The pressure from the piston is transmitted to the raw material. With increasing the quantity of raw material, begins to increase the axial force that pushes it through the cylindrical die. Thanks to the friction force that appears from the movement of the particles of raw material, the cylindrical die heats up. Due to the influence of the high pressure and high temperature in the die, the process of densification with the formation of briquettes occurs (Kristoferson & Bokalders 1986; Pietsch 2002; Tumuluru et al. 2011). The piston presses can be divided into hydraulic BP or mechanic BP. The cyclic principle of biomass densification, in the hydraulic briquetting press (HBP), permit to obtain briquettes of determined length without any additional cutting of them.

Unlike to the piston BP, in the screw BP main parts that are involved in the process of densification are a screw and die with an open channel. The used die can be of a cylindrical shape or of a conic shape (Pietsch 2005).

There is not only the difference in construction between ram briquetting press and screw briquetting press but also there is different principle of the biomass densification (Kristoferson & Bokalders 1986). In the working process of the screw press, the raw material is supplied into the pressing chamber, where it is taken by the rotating screw and it is directed to the die. The screw by continuously forcing of the biomass through the die increases the pressure. The raw material is exposed to a pressure that is caused mainly by friction forces. As a result, the die is heated up. Due to the high pressure and high temperature, the densification process of the raw material takes place (Kuchinskas et al. 1988; Grover & Mishra 1996; Pietsch 2002).

It should be noted that, due to highly developed pressure by the friction forces in the channel of the die, the extrusion of the briquettes can be difficult. For this reason at the end of the die, it is installed an external heater which has the main destination to heat up the die in order to reduce the friction and to facilitate the output of briquettes from the channel of the die (Grover & Mishra 1996).

2.2.4. Principle of briquetting

The main aim of the densification is the creation of compact structure, with strong bonds and a reciprocally fixed position between particles, without voids (Rumpf 1990; Mani et al. 2003). This is possible only in the case of a careful study of the densification process on specific equipment (Adapa et al. 2009). For a better evaluation and study of the process of pressure agglomeration, it is preferable to perform the theoretical analysis. As an example it can serve the analysis of the briquetting on the HBP (**Figure**

5), the theoretical analysis of which is presented based on the previously published results of the author (Muntean et al. 2010; Ivanova et al. 2013).

The main working tools of the HBP are pressing piston and cylindrical die with an open channel. The die has variable geometry that gives the possibility to change its shape from cylindrical to the conical shape.

The biomass is dosed by the feeding screw from the hopper into the pressing chamber (noted *0*), the length of which corresponds to the length of the piston stroke L. In the pressing chamber, the initial compacting of the raw material happens under the action of the piston.

The part of initial raw material V_0 under the influence of externally applied forces, change the structure from the bulk ρ_0 (with voids) into the more compact. The particles start to rearrange but do not change their shape and size (see **Figure 6**). At this stage, the degree of the densification depends more on the bulk density of the particles and their size (Pietsch 1997, 2005). Under the influence of axial pressure P_a, created by the action of the hydraulic cylinder, the material is forced by the piston into the die which is divided into two areas *I* and *II* (the area *I* has a more cylindrical shape and area *II* has a conical shape). The value of the pressure in this part is $P_{x.0}$. In the area of contact between the piston and the end face of briquettes acts the distributed pressure p. The areas of the die *I* and *II*, for more careful study are divided into sub-areas X, dx and sections $l_{x1} \ldots l_{x6}$. The material receives the shape of the briquettes in area *I* of the die, where the volume decreases until V_1 and the density increases ρ. The pressure in the briquette rises to $P_{xI} = P_{x.max}$ (Muntean et al. 2010; Ivanova et al. 2013).

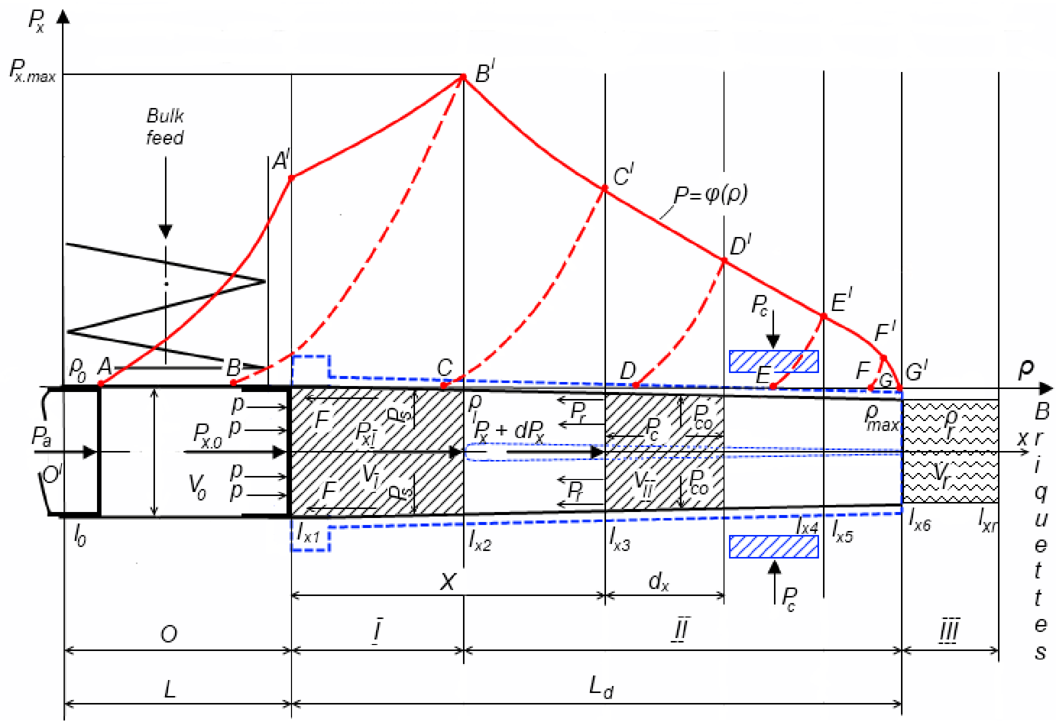


***Figure 5**. The theoretical model of the pressing process of biomass in the HBP*
Source: Ivanova et al. (2013), Muntean et al. (2010)

At this step, partial break and deformation of the brittle and malleable particles take place (see **Figure 6**) (Pietsch 1997, 2005). As a consequence, residual pressure (section l_{x1} and l_{x2}) appears in the densified material and the briquette exerts lateral pressures on the walls of the die P_{sI} ($P_s = f(P_x)$). Throughout the sub-area X, dx the pressure P_x+dP_x acts on the briquette. The horizontal axis is characterized by increasing of the density of briquettes ρ. On the vertical axis should be noted the change of the character of pressure P_x. Following the results of the pressure study (Muntean et al. 2010; Ivanova et al. 2013), it is necessary to create a diagram *AA'B'C'D'E'F'G'* that will reflect interrelation $P_x = \varphi(\rho)$ between compacting pressure and density of the briquettes.

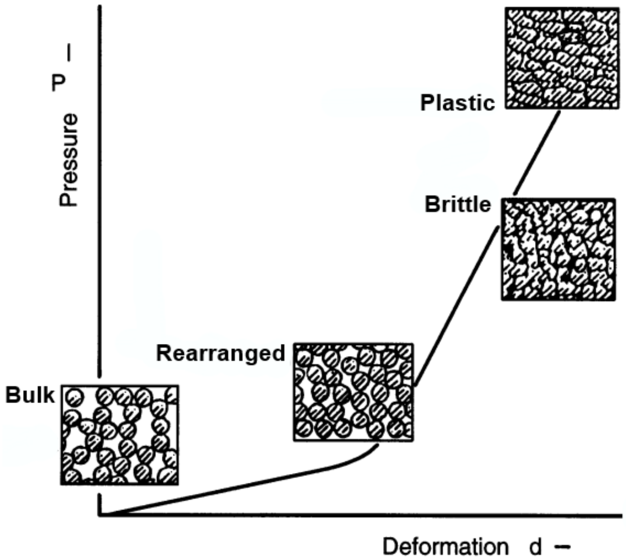


Figure 6. The mechanism of the particles densification (pressure agglomeration)
Source: Pietsch (1997)

It is seen that for the curves *BB'...GG'* (**Figure 5**) are characteristic the regularity of the density increase with decrease and increase in pressure for each subsequent portion of briquettes.

The resistance of the material movement in the channel is assured by the friction forces *F* between briquettes and the walls of the die, appearing in the result of the lateral pressure P_S. The lateral pressure is developed by the action of the material on the walls of the die. Also, additional resistance (counter pressure) P_r is created by the briquettes already formed in the die. The particles shape and size is changing by deformation and breakage (Figure 6). Take place the plastic deformation of particles (Pietsch 1997, 2005).

All densified material is forced from the area I into the area II of the die, which has a conical shape. The change of the shape is possible thanks to the construction with a slit that die has and the clamping device. Under the action of the clamping device with effort P_c on the side of the die with the slit (area *II*), the change of the shape from cylindrical into a conical happens. As a result, there is developed additional friction force and the resistance of the material's movement. The internal pressure in the briquette P_{co} and resistance to deformation become more pronounced. Sequentially the volume V_{II} of briquette decreases and the pressure P_{xII} is decreasing as well (according to the diagram *B'C'D'E'F'G'*). The final formation of the briquette occurs, with the creation of strong bonds between particles. The briquette's density achieves the value ρ_{max}.

After the exit of the briquette from the die (area *III*), the pressure P_x significant falls. The obtained briquettes pass through the cooling line (vibration damper), where they are cooled, stabilisation of their density ρ_r takes place as well as decreasing of internal stress. The additional holding time of the briquettes in the cooling line under the load help to prevent the relaxation (Faborode & O'Callaghan 1987). The volume of the briquette slightly rises to the value V_r.

2.3 Sources of biomass used for solid biofuels production

On the Earth, there are a lot of biomass sources that can be applied as a raw material for the production of different forms of biofuels. Unfortunately, it is impossible or difficult to use in the present all these sources of biomass for many reasons: difficult access to the harvesting of biomass, too expensive processing of some sources of biomass, etc. (Tripathi et al. 1998). Access to biomass also can be seasonal or during the whole year depending on, in which part of the world is located the country where is grown source of biomass. Countries that have warm climate during the whole year have more possibilities to use vegetal biomass due to longer vegetation period of different plants. Countries with cold climate (or seasonal warm climate) have fewer possibilities to use vegetable biomass and need to create necessary stocks of biomass for use in the cold season (Grammelis et al. 2011).

According to many authors of scientific works, exist many of ways of biomass classification. But most often biomass can be classified by the origin or type (Grammelis et al. 2011; Oakey et al. 2016). By the origin biomass can be formed in:

- Agriculture
- Forest
- Aquaculture
- Processing
- Energy crops growing

Wood obtained mainly from forest exploitation is considered to be the most popular source of biomass used as a solid fuel, thanks to high properties. Even today, wood remains a very important solid fuel for many developing countries from Latin America, Asia, and Africa. Uncontrolled cutting of forests has a negative impact on the environment. Deforestation at the present became a considerable problem in the number of developing countries. Even though as the main reason for deforestation is considered the extension of lands for agriculture, fuel wood harvesting also have an immense negative impact on reducing of forests' area (Kitani 1999). Usually for production of the solid biofuel, from viewpoint of sustainability, are preferable wood residues derived from forest cutting (Oakey et al. 2016). For energy purposes can be used such part of trees and wood residues as wood chips, stem wood or round wood, bark, offcuts, sawdust, shavings. Even such residues as tree leaves also can be used for the production of densified solid biofuel (Malak et al. 2016).

Countries that do not have access to the biomass of wood origin are using for energy purposes much more accessible and cheap biomass derived from the agricultural activity (Karaosmanoğlu 2000). The type and amount of agricultural wastes obtained is different and depends on the specific cultivated crops in a certain country or world region (Hakeem et al. 2014).

One of the best, type of raw material that originate from agriculture, are the pruning residues. Pruning residues are considered as a good feedstock for production of densified SB (pellets, briquettes, rolls, and bales) or for energy purposes used in an unprocessed form, thanks to high properties like high calorific value (CV), low ash content. Modern technologies offer possibility of efficient harvest and processing of residues obtained after seasonal pruning of fruit trees and vineyards (Pari et al. 2017).

The most cultivated agricultural crops worldwide are cereals. A considerable quantity of the waste from their cultivation and processing are obtained yearly. With the increasing of the demand for food, caused by population rise, the cultivation areas of the cereals will extend and as a result more wastes will be produced (Lestander 2012).

Straw of cereal crops is also an important source of biomass. It should be noted that straw can be used not only as important forage for cattle but also as efficient fertilizer that can contribute to increasing of soil structural stability. All of this points to the fact that straw has to be considered more as an agricultural secondary product than the residue. In Denmark and Sweden, a straw of cereal crops is considered as one of the most important sources of agricultural biomass due to the accumulation of its big quantities every year (Bentsen et al. 2018).

Application of wastes obtained from rice cultivation for briquettes production also is a widespread practice in the world (Brand et al. 2017).

Residues obtained after harvesting of corn which includes cobs, husks, leaves, and stalks can serve as a good feedstock for production of solid biofuel (Kaliyan & Morey 2010a).

Aquaculture in present is considered as a promising source of biomass destined for energy purposes (Hakeem et al. 2014). The high content of fatty oil in the algae makes them a valuable feedstock for the production of liquid biofuel (Lestander 2012). But also their application in the production of solid biofuel is possible. For the production of fuel from aquatic biomass are used algae, water hyacinth, lake and sea weed, and reed. Application of reed for the production of high-quality briquettes is possible according to (Cosereanu et al. 2011).

After the processing process, in different industries (for example food processing, wood processing) are accumulated residues that can be successfully, used for solid biofuel production. From residues obtained after processing of some oil crops like rapeseed, oil palm it is possible to produce densified SB of high quality in form of briquettes (Karaosmanoğlu 2000; Nasrin et al. 2008). Another promising source of biomass originated from food processing is pulp of potato (residue obtained in process of starch production) and tea waste (obtained in the process of tea leaves processing) that were studied for applying in SB production (Demirbaş 1999; Obidziński 2012).

For the briquetting can be also applied such wastes as furniture waste and municipal waste (Prasityousil & Muenjina 2013; Moreno et al. 2016).

Energy crops are crops that are intentionally grown for energy purposes. A characteristic feature of these crops is that they grow fast, have high yield, low production costs as well as they are characterized by resistance to pests and drought, simple cultivation without intensive use of pesticides and fertilizers (Singh B. 2013; Tumuluru & Heikkila 2019). Energy crops that received widespread in present are: poplar, willow, reed canary grass, miscanthus, hemp. These crops can be efficiently applied for production of densified solid biofuel (Rechberger et al. 2009; Karlen 2014; Daraban et al. 2015; Miao et al. 2015).

Clear and understandable classification by the type of biomass is described in standard EN ISO 17225–1:2014 (more detailed it is presented in the Table 2):

- Woody biomass

- Herbaceous biomass
- Fruit biomass
- Aquatic biomass

Table 2*. Classification of biomass by the type according to standard EN ISO 17225–1:2014.*

Type of biomass	Origin of biomass	Source of biomass	Used parts of biomass
Woody biomass	Forest, plantation and other virgin wood	Whole trees with or without roots Segregated wood from gardens, parks, roadside maintenance, vineyards, fruit orchards and driftwood from freshwater	Stem wood Logging residues Stumps/roots Bark (from forestry operations) Broad-leaf
	By-products and residues from wood processing industry	Chemically untreated or treated wood by-products	Residues Broad-leaf with bark Fibers and wood constituents
	Used wood	Chemically untreated or treated used wood	Wood with or without bark Bark
Herbaceous biomass	Herbaceous biomass from agriculture and horticulture	Cereal crops Grasses Oil seed crops Root crops Legume crops Flowers Segregated herbaceous biomass from gardens, parks, roadside maintenance, vineyards and fruit orchards	Whole plant Straw parts Grains or seeds Husks or shells Stalks and leaves Root Fruit Pods
	By-products and residues from food and herbaceous processing industry	Chemically untreated or treated herbaceous residues	Whole plant Straw parts Grains or seeds Husks or shells Stalks and leaves Root Fruit Pods
Fruit biomass	Orchard and horticulture fruit	Berries Stone/kernel fruits Nuts and acorns	Whole berries Whole fruit Whole nuts Flesh Seeds Stone/kernel/fruit fiber Husks
	By-products and	Chemically untreated or	Whole berries

	residues from food and fruit processing industry	treated fruit residues	Whole fruit Whole nuts Flesh Seeds Stone/kernel/fruit fiber Husks Crude olive cake Exhausted olive cake
Aquatic biomass	Algae	Micro algae Macro algae	
	Water Hyacinth		
	Lake and sea weed	Lake weed	
		Sea weed	Blue sea weed Green sea weed Blue-green weed Brown sea weed Red sea weed
	Reeds	Common reed	
		Other reed	

Source: EN ISO 17225–1:2014

Animal biomass also can serve as a source of feedstock applied for the production of densified solid biofuel. Animal biomass used in the production of solid biofuel consists of solid wastes obtained from livestock breeding (manure). Animal manure in most cases is used as an additive to other feedstock in the production process of solid biofuel due to its good binding proprieties but low calorific value (Shuma & Madyira 2017).

Reduction of greenhouse gases (GHGs), accessible fuel, friendly for the environment, energy independence and safety - all this makes biofuel attractive and popular in many countries. At the same time, there are risks exist when the use of biofuels can have a negative impact. This is possible in a case of the application of agricultural products for obtaining biofuels or use of land with agricultural destination for the growing of energy crops. In this case, the production of biofuel can create food shortage and as a result negative social consequences. This is the main argument of biofuel's enemies (Singh B. 2013). Sustainable use of biofuels can be considered in case of non-food biomass application in production (for example various wastes) or use of energy crops cultivated on non-agricultural lands (or left/marginal lands).

In addition to the biofuel production, energy crops can be grown to maintain or reduce the concentration of CO_2 in the atmosphere in a sustainable way. This can be achieved by the intensification of bioenergy use, instead of fossil fuel. Furthermore, active use of the energy crops for energy purposes and capture of GHGs from the atmosphere with their following geological storage are more efficient ways of the CO_2 reduction in the atmosphere (Gough et al. 2018).

2.4 Influence of different factors on the quality of briquettes

The agglomeration of densified solid biofuels is a complicated process, which can be influenced by many factors. Each technology used in the production of densified SB has its specific features of the work. On the work of the equipment as well as on the quality of the final product have influence many factors that have to be taken into consideration. The main factors are following:

- **Properties of a raw material**:

Factors that relate to properties of the raw material (density, type of biomass, the level of content of C,H,N, moisture content (*MC*), ash content (AC), use of additives etc.) (Kaliyan & Morey 2010b).

- **Pre-processing of a raw material**:

Main factors related to the pre-processing of raw material (the degree of grinding (particles size), the degree of drying and mixing of biomass, etc.) (Matúš et al. 2014).

- **The principle of the agglomeration process of used pressing equipment**:

Factors that relate to the design feature and principle of the agglomeration process of used pressing equipment (the shape and size of the die, working pressure, working temperature of the main pressing parts, etc.) (Tumuluru et al. 2011).

2.4.1. Properties of a raw material

The physical and chemical properties of the raw material are crucial for the production of high-quality SB. Each type of biomass has specific properties and content in a different amount of such components like C, H, N, ash, moisture, etc. (Lestander 2012; Vassilev et al. 2012).

In many cases, the properties of biomass are in strong relation with the economic reasonability of the use of some specific feedstock. For example, it is preferable to use biomass that has high CV, high density, low AC and MC but at the same time requires less pre-processing costs (Stolarski et al. 2013).

The quality of biomass that has low physical and chemical properties can be improved by adding additives/ binding agents, by the creation of blends with other materials. The additive can have the influence on the quality of produced biofuel, for example, it can increase CV, reduce emissions, reduce ash content, improve ash melting behaviour, increase the strength of the product, or enhance the efficiency of the production process (Wang et al. 2017b). According to the standard EN ISO 17225–1:2014, the additives are considered substances (materials) the share of which in the production structure is less than 20 % from the mass of the used raw material. If the share of added material in the structure of the pressed feedstock is more than 20% this material is already considered as a blend.

Many producers are using binding agents in the production process in order to increase the strength of densified SB. In the quality of binding agents are used gelatine, starch, molasses, bentonite, protein, fat, oil, modified cellulose, etc. (Thapa et al. 2014; Jittabut 2015; Rajaseenivasan et al. 2016).

It should also be noted that some used binding agents in the production process are not environmentally friendly and can contribute to the pollution of the environment (Garrido et al. 2017).

Adding of binder agents in the production process has a positive impact on the quality of SB but at the same time it has a negative influence on the increase in the price of the final product. Due to the high price of some binding agents or absence of the access to them on the market, many producers of densified solid biofuel prefer to use an alternative of the binder agents, i.e. adding in the production process of another materials that have different structure or properties than initially used feedstock (Muazu & Stegemann 2015).

In many scientific sources it is mentioned that the most easier and popular way of improving the quality of densified SB, made from biomass of low density, is the application as an additive in the production process, the raw material with high density such as wood (products or wastes that derived from wood processing). For example, rice straw is feedstock with a low density from which it is difficult to obtain briquettes of satisfactory quality but with adding of wood sawdust the quality will become better (mechanical durability, calorific value) (Rahaman & Salam 2017). Wood biomass has a high content of lignin. Lignin serves as a binder substance in the agglomeration process of SB in form of pellets and briquettes (Voicea et al. 2015) and it is considered one the best natural binding agents (Lu et al. 2014). After the action of temperature and applied pressure, cooled lignin and additional organic components keep the particles bonded and as a result the shape SB (Tabil et al. 2011a).

Improving the quality of the briquettes also is possible by the use as a binder of algae (Muazu & Stegemann 2017). Adding of algae powder in the production process can increase the strength of briquettes made from miscanthus (Thapa et al. 2014).

Using of neem powder contribute to higher strength, water resistance but reduce calorific value of briquettes (Rajaseenivasan et al. 2016).

Some research work demonstrated the possibility of plastic waste (from electrical and electronic equipment) application as additive that can improve the quality of briquettes, decrease their price. But at the same time burning of briquettes made from biomass with plastic waste additives will contribute to air pollution (Garrido et al. 2017).

Some sources of biomass used for the production of briquettes have low calorific value, unsatisfactory for many consumers. Increasing of calorific value it possible by adding of other sources of biomass with higher calorific value or by adding of fossil solid fuel - coal (Ávila et al. 2012).

2.4.2. Pre-processing of a raw material

Pre-processing (or preparation of raw material before pressing) of biomass applied for production of biofuel is very important. According to the requirements for used feedstock in the production, the type of produced SB, pressing equipment, number and type of biomass pre-processing operations varies (Tabil et al. 2011b).

Pre-processing can consist of sorting of biomass, grinding (particle size reduction), drying, sieving, mixing, etc. The basic and most important technological operation are drying and seize reduction (Jacob et al. 2013), where size reduction of raw material usually is made in one or two steps (initial and final or coarse and fine crushing) for feedstock applied in briquettes production. In the case of pellets, their production requires the use of feedstock with smaller particles size, as a result, two or three steps of size reduction it necessary (Tumuluru & Heikkila 2019). Particle size can have impact on the densification process of SB and as a result, on the quality of final product (Matúš et al. 2014). The particle size of feedstock is decisive for the pressure agglomeration, influencing the homogeneity, bulk density, rheological behaviour of the material, the strength and density of the biofuel, etc. (Mani et al. 2003).

High moisture content in raw material also can have a negative influence on the quality of SB in a form of briquettes (Wang et al. 2016). For this reason is important to accord special attention to the drying of raw material. The level of moisture content in a feedstock and the applied technology for drying depending on the properties of the processed biomass, type of produced SB and used equipment for densification, etc. (Döring 2013).

In some case is required to use the mixing of the feedstock, especially when it represents a multicomponent mixture composed of several different materials or adding of binders. The mixing of components can improve the homogeneity of the feedstock structure (Gyenis 2001).

For the production of the SB with high CV and hydrophobic properties, the feedstock can be exposed to the thermal treatment - carbonization or torrefaction (Chen et al. 2015b). But that requires addition spends of energy.

In some case adding of water or steam can make the feedstock more pliable that will contribute to better densification process (Tabil et al. 2011b).

2.4.3. The principle of the agglomeration process of used pressing equipment

The positive impact of high temperature on the densification process of biomass was mentioned in the result of many studies (Orth & Löwe 1977). Usually, the high temperature is applied for the treatment of biomass during the compaction process, but in some case, biomass can be initially preheated. Preheating can improve the quality of briquettes (Bhattacharya et al. 2002)

The shape and the size of the main pressing parts also can have decisive value in the process of pressing. (O'Dogherty & Wheeler 1984) found that with decreasing of the die diameter of the BP it is required less applied pressure for the densification of biomass (in the die with a closed channel).

The increasing of the density of briquettes is also possible by the increase of the pressure during briquetting process of biomass (Panwar et al. 2011; Thabuot et al.

2015). The necessary working pressure applied for the densification of biomass vires and depends on technology of briquetting, type of processed material, etc. (Adapa et al. 2009). There are the direct interrelations between the applied pressure and the density of obtained SB (Mani et al. 2003). However changing of the pressure of briquetting equipment contributes to the increase of the energy consumption in the pressing process (Rajaseenivasan et al. 2016). The change of working pressure can be realised by the adjustment of briquetting equipment or adjustment and connection of special means with which is equipped BP. The change of working pressure has to be done only in limits recommended by the producer of BP. In some case changing the working pressure of equipment it is not recommended or it is prohibited by the producer companies due to the negative impact on the correct work of equipment, reliability and service life of the equipment, the hazard for life and health of the working personnel. Also changing the working pressure on pressing equipment, it is difficult or impossible to make due to design features, lack of special tools (maintenance equipment) or qualified workers (Kuchinskas et al. 1988; Pietsch 2002).

The hold of the material longer time under load can prevent such negative effect as relaxation and as a result to increase the density of biofuel (Faborode & O’Callaghan 1987).

The efficient production of high-quality SB and correct work of the equipment can be achieved only by the respecting of the requirements related to the properties and pre-processing of feedstock, selecting of suitable working modes of the equipment. This, in turn, needs to be studied more carefully.

3. OBJECTIVES AND HYPOTHESES

3.1. General objective of the Thesis

The main objective of the present work is theoretical and practical (experimental) research of production efficiency of briquettes on hydraulic piston and screw briquetting presses with respect to optimization of particle size, use raw materials with optimal density and their pre-processing treatment in order to guarantee briquettes' quality.

3.2. Specific objectives

In order to fulfil the main aims of the research work should be taken a number of additional objectives:

- to define the influence of different important factors on the quality of densified biofuel;
- to prepare the raw material and create necessary conditions for the carrying of research work;
- to process the studied raw material, of different fractional size, into briquettes with the registration of working parameters of equipment;
- to evaluate the work of the pressing equipment and determine optimal working parameters for efficient densification of biomass;
- to investigate by the thermal analysis the influence of temperature on the briquetting process and to define suitable working temperature;
- to determine properties of obtained SB and to evaluate their interrelation with the specific working conditions (parameters) of equipment.

3.3 Hypotheses

Hypothesis 1

By the choice of material with optimal fraction for each type of studied briquetting technology is expected to obtain briquettes with much more dense structure without additional grinding of raw materials.

Hypothesis 2

After the selection of raw materials more suitable for densification on each type of briquetting press, is expected to obtain high-quality briquettes with increased strength.

4. METHODOLOGY

The experimental research in the framework of this Dissertation Thesis was realised in the laboratories of the Czech University of Life Sciences Prague (Laboratory of biofuels at the Faculty of Tropical AgriSciences and laboratories of the Faculty of Engineering) as well as in the Bioenergy Centre of the Research Institute of Agricultural Engineering Prague.

4.1 Materials

Four types of raw biomass materials with different structure and density were used for the research purposes of the present Dissertation Thesis:

- Residual wood biomass (apple tree branches obtained after pruning - ATPW);
- Fibrous biomass material (industrial hemp *Cannabis sativa* L. - HP);
- Herbaceous biomass (two varieties of miscanthus: *Miscanthus* × *giganteus* and *Miscanthus sinensis* – MG and MS).

The designation of tested samples of biomass and biofuel:

ATPW**12** - Apple tree pruning waste with **fraction size of 12 mm**

ATPW**8** - Apple tree pruning waste with **fraction size of 8 mm**

ATPW**4** - Apple tree pruning waste with **fraction size of 4 mm**

MG**12** - Miscanthus Giganteus with **fraction size of 12 mm**

MG**8** - Miscanthus Giganteus with **fraction size of 8 mm**

MG**4** - Miscanthus Giganteus with **fraction size of 4 mm**

MS**12** - Miscanthus Sinensis with **fraction size of 12 mm**

MS**8** - Miscanthus Sinensis with **fraction size of 8 mm**

MS**4** - Miscanthus Sinensis with **fraction size of 4mm**

HP**12** - Hemp crushed with **fraction size of 12 mm**

HP**8** - Hemp crushed with **fraction size of 8 mm**

HP**4** - Hemp crushed with **fraction size of 4 mm**

ATPW**12V1** - Briquettes made on **SBP at working speed 1 from ATPW of 12 mm fraction**

ATPW**8V1** - Briquettes made on **SBP at working speed 1 from ATPW of 8 mm fraction**

ATPW**4V1** - Briquettes made on **SBP at working speed 1 from ATPW of 4 mm fraction**

MG**12V1** - Briquettes made on **SBP at working speed 1 from MG of 12 mm fraction**

MG**8V1** - Briquettes made on **SBP at working speed 1 from MG of 8 mm fraction**

MG**4V1** - Briquettes made on **SBP at working speed 1 from MG of 4 mm fraction**

MS**12V1** - Briquettes made on **SBP at working speed 1 from MS of 12 mm fraction**

MS**8V1** - Briquettes made on **SBP at working speed 1 from MS of 8 mm fraction**

MS**4V1** - Briquettes made on **SBP at working speed 1 from MS of 4 mm fraction**

HP**12V1** - Briquettes made on **SBP at working speed 1 from HP of 12 mm fraction**

HP**8V1** - Briquettes made on **SBP at working speed 1 from HP of 8 mm fraction**

HP**4V1** - Briquettes made on **SBP at working speed 1 from HP of 4 mm fraction**

ATPW**12V3** - Briquettes made on **SBP at working speed 3 from ATPW of 12 mm fraction**

ATPW**8V3** - Briquettes made on **SBP at working speed 3 from ATPW of 8 mm fraction**

ATPW**4V3** - Briquettes made on **SBP at working speed 3 from ATPW of 4 mm fraction**

MG**12V3** - Briquettes made on **SBP at working speed 3 from MG of 12 mm fraction**

MG**8V3** - Briquettes made on **SBP at working speed 3 from MG of 8 mm fraction**

MG**4V3** - Briquettes made on **SBP at working speed 3 from MG of 4 mm fraction**

MS1**2V3** - Briquettes made on SBP at **working speed 3 from MS of 12 mm fraction**

MS**8V3** - Briquettes made on **SBP at working speed 3 from MS of 8 mm fraction**

MS**4V3** - Briquettes made on **SBP at working speed 3 from MS of 4 mm fraction**

HP**12V3 -** Briquettes made on **SBP at working speed 3 from HP of 12 mm fraction**

HP**8V3** - Briquettes made on **SBP at working speed 3 from HP of 8 mm fraction**

HP**4V3** - Briquettes made on **SBP at working speed 3 from HP of 4 mm fraction**

ATPW**H12 -** Briquettes made on **HBP from ATPW of 12 mm fraction**

ATPW**H8** - Briquettes made on **HBP from ATPW of 8 mm fraction**

ATPW**H4** - Briquettes made on **HBP from ATPW of 4 mm fraction**

MG**H12 -** Briquettes made on **HBP from MG of 12 mm fraction**

MG**H8** - Briquettes made on **HBP from MG of 8 mm fraction**

MG**H4** - Briquettes made on **HBP from MG of 4 mm fraction**

MS**H12** - Briquettes made on **HBP from MS of 12 mm fraction**

MS**H8** - Briquettes made on **HBP from MS of 8 mm fraction**

MS**H4** - Briquettes made on **HBP from MS of 4 mm fraction**

HP**H12** - Briquettes made on **HBP from HP of 12 mm fraction**

HP**H8** - Briquettes made on **HBP from HP of 8 mm fraction**

HP**H4** - Briquettes made on **HBP from HP of 4 mm fraction**

According to many studies, perennial grasses are attractive for energy purposes thanks to their high yield, and special attention is payed to miscanthus (*Miscanthus spp*.). For the research, in order to understand better the impact of a material's structure on the quality of briquettes, two plant materials were selected from the same species with very similar morphological characteristic, but different by the structure (of a dry material). *Miscanthus × giganteus* is characterized by the long, wide leaves and stem of approximately 9 mm in diameter. *Miscanthus sinensis* has narrower leaves and stem of 4-5 mm in diameter. *Miscanthus × giganteus* has a soft and brittle structure of leaves and stem. *Miscanthus sinensis* has a more rigid structure of stem and leaves (dry biomass) with the yield 18-40 $t.ha^{-1}$ (Fike, Parrish 2013). Both varieties are widespread nowadays.

Another promising energy crop is hemp. Hemp is interesting first of all thanks to its fibres that are possible to use in many areas. Especially biomass obtained from hemp cultivation, represent interest for energy production. Yield of hemp biomass varies in dependence of cultivation condition and cultivated species, and can be 8-21 $t.ha^{-1}$ (Dahlquist & Bundschuh 2012).

The orchards of fruit trees are an important part of modern agriculture. In addition to fruits production, orchards are the source of the wood biomass that is accumulated yearly in plenty as a result of pruning operations. The particularly immense quantity of the waste is formed in the apple orchards due to their large cultivation areas (Dyjakon et al. 2016). The annual amount of the accumulated pruning waste of apple orchard varies about 0.6-5 $t.ha^{-1}$ depending on the type of orchard, age of trees, etc. (Cichy et al. 2017). This waste can be easy transformed into a valuable type of fuel in the form of briquettes.

4.2 Methods

4.2.1 Pre-pressing treatment of raw materials

Material grinding

The particles size of the biomass applied for energy purposes is very important. Based on this it is necessary to select the equipment suitable for obtaining ground material of wanted size with a homogeneous structure. Does not exist universal grinders that are able to process all kinds of biomass efficiently, but it can be selected an optimal equipment that can process the feedstock with required parameters. For the grinding of studied materials, the optimal solution was the use of hammer mill.

Figure 7. Hammer mill STOZA ŠV 15 (left image) and process of the drying of biomass (right image)

Tested materials were initial ground on hammer mill 9FQ – 40C with the energy input is 5.5 kW, by use of the sieve with openings of diameter 40 mm. The secondary grinding was done on the hammer mill STOZA ŠV 15 with energy input 15 kW (see **Figure 7** left). All tested materials were ground using three sieves with openings of diameters: 4 mm, 8 mm and 12 mm.

Material drying

The high moisture content present in raw material makes it utilisation for briquetting difficult or even impossible. For this reason, it is necessary to reduce the moisture content at the certain admissible limit in the material before densification. For this purpose, raw material preliminary is exposed to the drying process that can be natural or artificial (forced) (Abdoli et al. 2018).

The artificial drying or also called forced implies the use of special equipment for a generation of heat (thermal agent - hot air, hot water or hot flue gases) applied for reduction of moisture. This way of drying permit to make biomass to dry fast, with the possibility of control the drying process and final moisture of dried material. In this case, the drying can be done in a short time but requires financial investments for equipment, qualified personal (Döring 2013).

The natural drying does not require the use of special equipment for the reduction of the moisture in the raw material. This method is based on the utilisation of the direct solar radiation or of hot air (heated up by the sun) for the drying process. It is a cheap and simple way of drying but at the same time it is considered not efficient, requires a longer time for drying and it is dependent on the climate conditions.

For moisture reduction of the tested material was used the natural way of drying (**Figure 7** right. The process of material drying was carried out during the summertime when the temperature values are high and air humidity is low. All dried up material was placed into hermetic plastic bags to prevent contact with atmospheric air. Tested material before briquetting was exposed to the mixing on the mixer MJ-75.

4.2.2 Densification of biomass

Hydraulic briquetting press

Two briquetting technologies were tested in the framework of this research, i.e. hydraulic piston press and screw press. Both types of equipment were produced by the Briklis Company, Malšice, Czech Republic.

The HBP (hydraulic driven briquetting press) HLS 50 represents a serial equipment for biomass densification, which has been being produced by the company for many years, well known on the market thanks to its reliable work (see **Figure 8** and **Figure 9**). In the present, the continuation of this type of press is improved press of series Brikstar (Brikstar 30, 50, 70) with the same principle of work. The press is equipped with hopper, conical agitator with vanes, feeder, electrical switchboard with control panel, transducers, electric motor, and hydraulic drive system.

Figure 8. Hydraulic briquetting press Briklis HLS 50

The main pressing parts are hydraulic cylinder with piston, die, pressure adjusting cylinder (clamp cylinder), and the cooling line (vibration damper). HBP Briklis HLS 50 has input power of 4.6 kWh, approximately productivity of 50 $kg.h^{-1}$, diameter of briquettes 65 mm with length 30-50 mm.

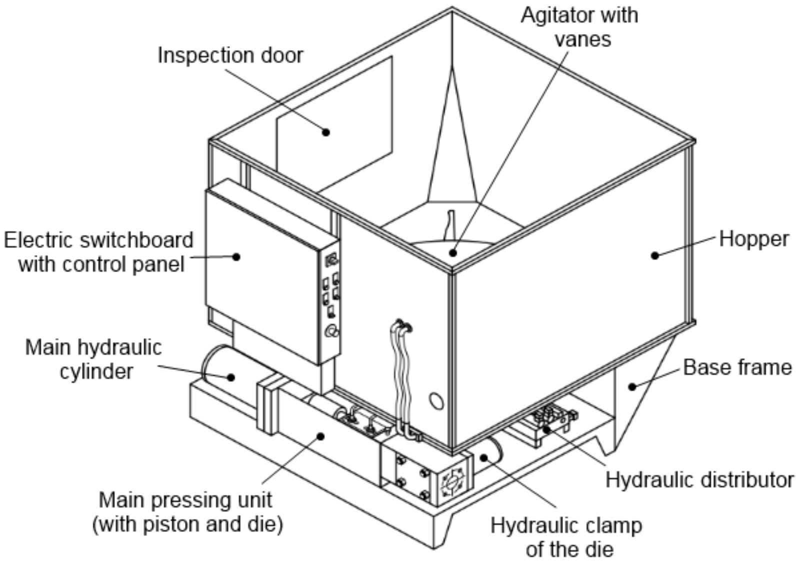


Figure 9. The main component parts of HBP Briklis HLS 50

The work principle of HBP is analogic for all types of such equipment. The raw material is added into to the hopper, is continuously mixed and after that fed into the pressing chamber. The biomass is cyclic pressed by the piston through the cylindrical die. The die is with variable geometry that permits to change the shape from cylindrical to the conical. Obtained briquettes are retained and cooled in the cooling line. The obtained briquettes are of cylindrical shape.

Screw briquetting press

Another equipment used for research was SBP Briklis BSL (Šnekový briketovací lis). The press is illustrated in the **Figure 10**. Unlike the previously mentioned briquetting press, that represents the main equipment produced by the Briklis Company for many years, the screw press can be considered more as an experimental equipment released in limited quantity. SBP Briklis BSL has installed input of 22 kW, with the productivity around 300 $kg.h^{-1}$, diameter of produced briquettes 80 mm. The screw press consists of a hopper with vane agitator, main electric motor, reducer, electrical switchboard with control panel, heat transducer.

Figure 10. Screw briquetting press Briklis SBL.

The main pressing parts are screw, forming die and heating die (heating tube), the heater of the heating die, and cooling line with a pressure adjusting screws.

The work principle of the press is simple and is typical for the work of many other extruders. The initially added biomass into the hopper is mixed and fed to the pressing screw which continuously forces the raw material through the forming and heating dies.

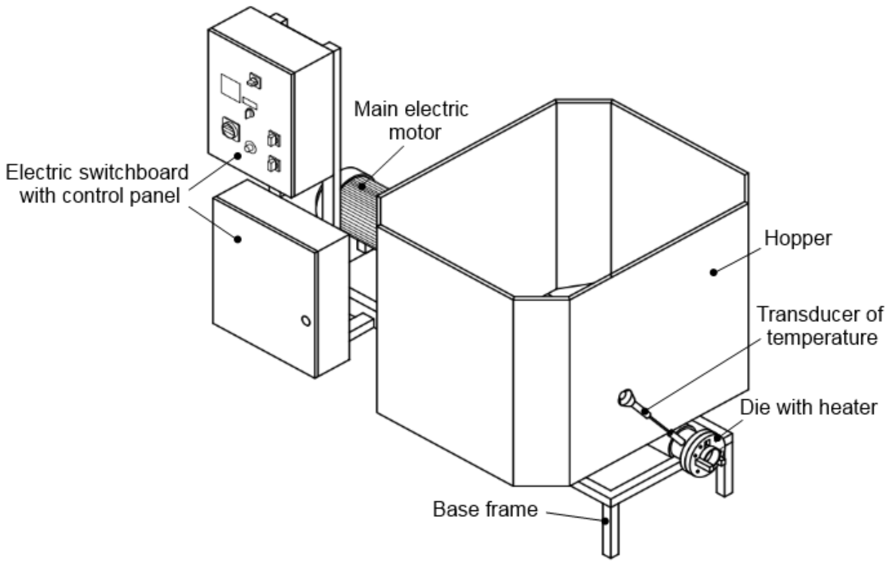


Figure 11. The main component parts of SBP Briklis BSL

The obtained biofuel is retained and cooled in the cooling line. The produced briquettes are of cylindrical shape with an aperture in the centre (channel) and have a slightly carbonized surface.

Thermal analysis

In many studies (Bhattacharya et al. 1989; Rynkiewicz et al. 2013; Okot et al. 2018), was mentioned the importance of temperature during the briquetting process. During the work, the temperature in briquetting equipment can achieve different values, depending on the technology of densification, type of equipment, etc.

Thus, based on the importance of temperature for the briquetting, the thermal analysis of the process was carried out. The research was performed during the work of both briquetting presses. For the determination of the raw material’s influence on the level of heating of the main pressing parts of HBP, the temperature was measured during its work. The measurements were carried out during 60 minutes of the equipment’s work for each fraction of each material apart. The registration of temperature values was done every 10 minutes of work, in the specific parts of the equipment (main pressing parts) - pressing chamber (measuring points P1, P2, P3), the die (measuring points D1, D2, D3), cooling line (B1, B2, B3, B4 - produced briquettes). All points of measurements could be seen on the **Figure 12**.

Figure 12. Areas of the measurements of the temperature during briquetting on HBP

Determination of the temperature was made by the contact thermometer THERM 2246 with a range of measure -5-100 °C with an accuracy of 0.1 °C (the main measuring device). Also, for the measurement it was used a contactless thermal imager Testo 875 (see **Figure 13**) with a range of measure -20/+280 °C (maximal 320 °C) with an accuracy 2 °C. The data obtained by thermal imager were processed with the software IRSoft version 4.5.

Figure 13. Thermal imager Testo 875

For obtaining high precision data the device allows to take into account the emissivity (the capability of objects to emit electromagnetic radiation) and the reflection temperature of the body of studied objects. The coefficient of emissivity for studied equipment was selected 0.95 and reflection temperature 22 °C. An example on measurement is presented on **Figure 14**.

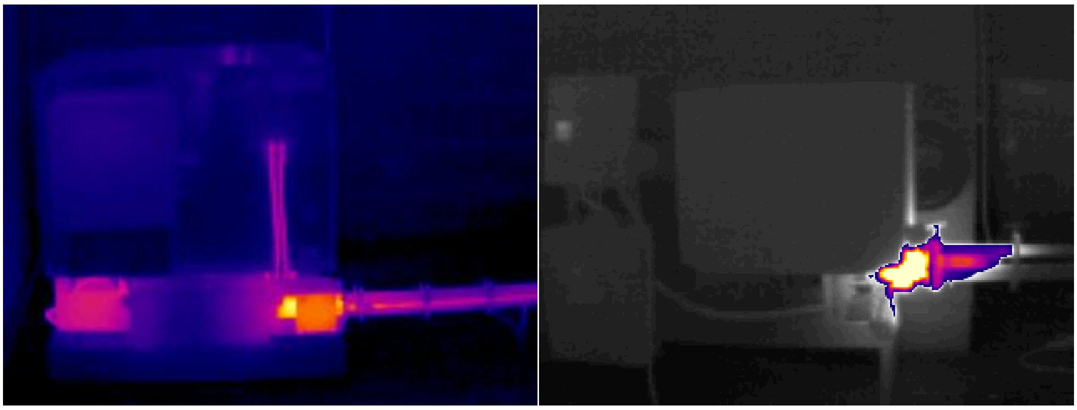


Figure 14. The image of HBP (left image) and SBP (right image) made by thermal imager.

For the determination of an optimal temperature during the work of SBP, only contactless thermal imager Testo 875 was used. The measurement for each material was performed for 60 minutes of the equipment's operation as well.

4.2.3 Determination of properties of raw biomass and obtained briquettes

All measurements of physical, mechanical and chemical properties of produced briquettes were conducted strictly according to the methodology of the International and European standards for SBs.

- ***Preparation of analysis samples***

According to the requirements for the determination of the properties of SB, all samples have to be initially prepared in analysis samples. The procedure of preparation of the samples is realized in accordance with standard EN ISO 14780: 2017. Solid biofuels - Sample preparation.

The samples of raw material and briquettes were cut, divided (by tools like saw, gardening shears) and coarse ground by microfine grinder IKA MF 10 Basic applied for the first step of grinding. For the second step of grinding (fine comminution) was used laboratory knife mill RETSCH GRINDOMIX GM 200. The obtained sample received a homogenous structure with the biomass particles size 1mm.

- ***Determination of moisture content***

The determination of moisture content was performed for raw material and obtained briquettes regarding the standard EN ISO 18134-3:2015.

Studied samples of material were placed into the drying oven MEMMERT UFE 100–800 and dried up at the temperature of 105 °C until achieving constant weight (for about 2-4 hours). The moisture content was determined by the equation:

$$MC_{ad} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \quad (1)$$

where:

MC_{ad} – moisture content as analysed, %;

m_1 – mass of an empty dish and lid, g;

m_2 – mass of a dish and lid with a sample before drying, g;

m_3 – mass of a dish and lid with a sample after drying, g.

- ***Determination of ash content***

The determination of ash content was performed for the feedstock and obtained briquettes. The ash content was determined in accordance with the standard EN ISO 18122:2015. The analysed sample of material, initially dried at 105 °C in a drying oven, was placed in a muffle furnace LAC LH 06/13. Each sample was exposed to the heat influence at the temperature of 550 °C for an established limit of time. For the weight of the samples was used analytical balance KERN ABJ - 120 NM. Ash content of each sample was found as a mean of three repetitions. The result was calculated by the following formula:

$$A_d = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \quad (2)$$

where:

A_d – ash content on a dry basis, %;

m_1 – mass of an empty dish, g;

m_2 – mass of dish with a sample, g;

m_3 – mass of dish with an ash, g.

- ***Determination of total content of C, H, N, S and Cl***

For the study of carbon (*C*), hydrogen (*H*), nitrogen (*N*) the content in the biomass and biofuel was applied special equipment - an automatic Determinator LECO CHN628 Series. The measurements were made according to the standards EN ISO 16948:2015. In the initially calibrated equipment was placed the analysed sample (wrapped in aluminium foil). The sample is combusted in the burning chamber of the device (with the access of the oxygen) at a temperature around 1,050 °C. The results were calculated automatically and expressed as % by mass.

Content of sulphur (*S*) and chlorine (*Cl*) was performed by following the standard EN ISO 16994:2016. The *S* content was measured by application of the combustion method in the special *S* add-on module component part of the Determinator LECO CHN628 Series. The *Cl* content was determined by the titrimetry technique.

- ***Determination of calorific value***

The measurement of the CV of the raw material and briquettes was done by the standard EN ISO 18125:2017. Was determined the gross calorific value. Also were determined net calorific value of a dry sample (dry basis) and net calorific value at the required moisture content (as received) but based on the results of gross calorific value.

All tested samples of biomass (with the weight of 0.5 g each) were burned in the high-pressure combustion bomb, fulfilled initially with oxygen. The burning and determination of temperature were performed by use of calorimeter.

Figure 15. Calorimeter LAGET MS – 10A

For the research was used calorimeter LAGET MS-10A (**Figure15**). After the complete combustion of the sample, the value of temperature rise is shown on the calorimeter's display and gross calorific value is then calculated as:

$$Q_{v.gr} = \frac{\varepsilon \times \theta - (m_{ign} \times Q_{ign} + m_{cb} \times Q_{cb})}{m_s} \qquad (3)$$

where:

$Q_{v.gr}$ – gross calorific value of a biofuel sample, $J.g^{-1}$;

ε – effective heat capacity of calorimeter, $J.°C^{-1}$;

θ – corrected temperature rise, °C;

m_{ign} – mass of an ignition wire, g;

Q_{ign} – gross calorific value of an ignition wire (6,000 $J.g^{-1}$ for nickel-chromium), $J.g^{-1}$;

m_{cb} – mass of a combustion bag, g;

Q_{cb} – gross calorific value of a combustion bag (16,279 $J.g^{-1}$ for paper), $J.g^{-1}$

m_s – mass of a biofuel sample, g.

Afterwards, ***Net calorific value*** of a dry sample (dry basis, in dry matter) was calculated by the equation below:

$$Q_{net.d} = Q_{v.gr} - 212.2 \times w(H)_d - 0.8 \times [w(O)_d + w(N)_d] \tag{4}$$

where:

$Q_{net.d}$ – net calorific value of a dry sample of biofuel, J.g^{-1};

$w(H)_d$ – hydrogen content of a dry sample of biofuel, %;

$w(O)_d$ – oxygen content of a dry sample of biofuel, %;

$w(N)_d$ – nitrogen content of a dry sample of biofuel, %.

Net calorific value of a wet/initial sample or a sample at required moisture content (as received) was calculated as:

$$Q_{net.ar} = Q_{net.d} \times (1 - 0.01M) - 24.43 \times M \tag{5}$$

where:

$Q_{net.ar}$ – net calorific value at a required moisture content (as received), %;

M – moisture content for which the calculation is required, %;

24.43 – enthalpy of vaporization for water at 25 °C, for 1% of moisture, J.g^{-1}.

Conversion of analytical results from one basis to another was performed in accordance to the standard EN ISO 16993:2016 using the following equation:

$$w(O)_d = 100 - w(C)_d - w(H)_d - w(N)_d - w(S)_d - w(Cl)_d - w(A)_d \tag{6}$$

where:

$w(O)_d$ – oxygen content of a dry sample of biofuel, %;

$w(C)_d$ – carbon content of a dry sample of biofuel, %;

$w(H)_d$ – hydrogen content of a dry sample of biofuel, %;

$w(N)_d$ – nitrogen content of the a sample of biofuel, %;

$w(S)_d$ – sulphur content of the a sample of biofuel, %;

$w(Cl)_d$ – chlorine content of the a sample of biofuel, %

A_d – ash content on dry basis, %.

- ***Determination of bulk density***

Determination of bulk density of produced briquettes' samples was performed in accordance with International standard EN ISO 17828:2015 Solid Biofuels – Determination of bulk density. The bulk density was performed for the biomass of different fraction size of the particles. For the test was used the cylindrical container with a volume of 50 l.

Then the biomass is placed in the container which is dropped from a high of 150 mm onto a wooden board (this action is repeated 3 times). Afterwards, the container is refilled and adjusted until the rim level using a scantling. After weighing of the container the result is determined by the following formula:

$$BD_{ar} = \frac{(m_2 - m_1)}{V} \quad (7)$$

where

BD_{ar} – bulk density as received, kg.m^{-3};

m_1 – mass of an empty container, kg;

m_2 – mass of the container with biomass, kg;

V – net volume of the container, m^3.

- ***Determination of particle density***

Particle density (volumetric mass density**)** of tested briquettes was measured following the standard EN ISO 18847:2016 Solid biofuels – Determination of particle density of pellets and briquettes and calculated as:

$$DE = \frac{m_b}{V_b} \quad (8)$$

where:

DE – density of a sample (briquette), g.cm^{-3};

m_b – mass of a sample (briquette), g;

V_b – volume of a sample (briquette), cm^3.

Stereometric volume V_b of the briquettes of cylindrical shape (produced by the hydraulic piston press) was estimated as:

$$V_b = \frac{Dem^2 \times \pi \times L}{4} \tag{9}$$

where:

Dem^2 – mean value of 6 measurements of external diameter of a sample/briquette (two measurements at both ends and in the middle at ½ L), mm;

L – length of a sample (2 measurements per briquette, each with 90 degrees offset), mm.

Stereometric volume V_b estimation of the briquettes of cylindrical shape with a channel (produced by the screw press) was done as:

$$V_b = V_e - V_i \tag{10}$$

where

$$V_e = \frac{Dem^2 \times \pi \times L}{4} \tag{11}$$

and

$$V_i = \frac{Dim^2 \times \pi \times L}{4} \tag{12}$$

where:

V_e – external volume of a sample, cm^3;

V_i – volume of a sample's channel, cm^3;

Dim^2 – mean value of 4 measurements of internal diameter of a sample (two measurements at both ends), mm;

Dem^2 – mean value of 6 measurements of external diameter of a sample (two measurements at both ends and in the middle at ½ L), mm;

L – length of a sample (2 measurements per briquette, each with 90 degrees offset), mm.

The measurements of dimensions were carried out by a digital vernier calliper (model MITUTOYO ABSOLUTE IP66). The mass of the samples was weighted on a digital laboratory scale KERN ABJ 120 – 4NM with readout of 0. 1 mg.

- ***Determination of mechanical durability***

The determination of mechanical durability (DU) was done by the use of international standard EN ISO 17831-2:2015 Solid biofuels – Determination of mechanical durability of pellets and briquettes – Part 2: Briquettes. The main equipment applied for the research was rotating drum for determination of DU (**Figure 16**). Each portion of briquettes with the weight of approximately 2 kg was placed into the drum and rotated 105 times during 5 min.

Figure 16. Drum for the determination of mechanical durability

Afterwards, the abrasion was sieved and the mechanical durability of the briquettes was calculated as follows:

$$DU = \frac{m_A}{m_E} \times 100 \quad (13)$$

where:

DU – mechanical durability, %;

m_E – mass of sieved briquettes before the drum treatment, g;

m_A – mass of sieved briquettes after the drum treatment, g.

- ***Determination of particle size distribution***

The determination of particle size distribution for all fractions of studied biomass was done according to the standard EN ISO 17827-1:2016 Determination of particle size distribution for uncompressed fuels - Part 1: Oscillating screen method using sieves with apertures of 3.15 mm and above. For the test was used horizontal vibrating sieve shaker RETSCH AS 200 with a set of 7 standard calibrated sieves. The sieves have a diameter of 20 cm and openings with a size of 8.0, 6.70, 5.60, 4.50, 3.15, 2.50, 1.0, 0.63 mm, and the collecting pan. During the analysis, a tested weighed sample was placed into the top sieve with the largest screen opening size, and 10-minute sieve shaking mode with amplitude 1.5 mm was applied. In consequence of the sieving process, the material retained on each sieve was weighed and the percentage of particles' weights retained on the sieves was determined as:

$$\%\ \text{Retained} = \frac{W\ sieve}{W\ total} \times 100 \tag{14}$$

where:

w_{sieve} – weight of a material in a sieve, g;

w_{total} – total weight of a material, g.

Three repetitions were performed for each fraction (with sieving loss error approx. 0.3%) and the average value was considered as the final result.

- ***Image analysis of the macro structure of briquettes***

For the image analysis of the briquettes was used wood biomass from spruce, that was divided in three fractions (**Figure 17**) that consist of the particles with size – big (particles with a size of 40 - 15 mm), medium (particles with a size of 15 - 7 mm) and small (particles with a size less than 7 mm).

Figure 17. The used for the research work, coloured fractions of material

The fraction of the bigger size was coloured in blue colour. A small fraction was coloured in red colour. Middle fraction remained uncoloured (**Figure 18**). For the colouring of biomass was used water-based paint Creall with a neutral effect on the agglomeration process of particles or properties of biomass. Tested material before use was dried.

Figure 18. The image analysis of the coloured fractions of material

The macroscopic analysis was performed by the USB microscope Chronos DigiScope with a maximum magnification 200×. But for the research, mainly magnification 25× was used, that was enough for analysis of the macro structure.

4.2.4. Statistical data analysis

In addition to the laboratory measurements of the biomass and study of the densification process, the statistical data processing was performed.

One part of processed data refers to the results of the temperature measurements (thermal analysis) of HBP and obtained SB during briquetting briquetting process.

Another part is attributed to the statistical processing of the results received from the measurement of *GCV*. The detailed calculation of *GCV* it is related to its high impact on the later calculation of NCV_d and NCV_{ar}.

For the processing of data the software Microsoft Office Excel (version 2016) with analysis tool pack ANOVA was used. The obtained data of *GCV* were additionally processed by determination of standard deviation, confidence coefficient, confidence interval, upper and lower bound, minimum and maximum values, range.

In the consequence of the analysis, there were determined the average values, variance, sum of the squared deviations, degree of freedom, mean squares, F value, P-value, F critical value.

5. RESULTS AND DISCUSSION

5.1. Evaluation of the briquetting process

5.1.1. Evaluation of the work of hydraulic briquetting press

Briquetting presses with the die with open channel type and/or with the die with closed channel.

The process of briquetting on the equipment is automated and requires minimal operator involvement when working. From one side, that creates conditions for comfortable work and makes the process less laborious. But at the same time, that's limit the possibility to use more means for adjustment and control of the production process. There is possible to make only a few adjustments during the pressing: Selecting of the working mode - manual or automatic; connection of pressure adjusting cylinder of the die; adjusting of the springs of the cooling line. For obtaining of the briquettes with high density it is necessary to use turned on adjusting cylinder of the die and to adjust the springs of the cooling line.

It is possible to change the pressure in the hydraulic system for increasing the action of the piston's pressure on the biomass. The rise of the applied pressure positively affects the density of solid biofuel (Mani et al. 2003). However, this measure is not recommended by the producing company due to the high risk of the equipment's damage and reduction of its service life. Also, it represents a danger for the operating personnel. There are no other options to influence the compaction level of the material.

Additional way to control the process and the quality of produced biofuel remains the optimization of the use of feedstock with the most suitable properties (moisture content, bulk density, size of particles, etc.)

During the briquetting, the negative effect of the agitating on the particle distribution was observed. The influence of the agitation on the distribution of the particles was mentioned in many studies, and this is the problem for various types of briquetting presses (Chaloupkova et al. 2016). Importance of the distribution of particles for the quality of the briquettes, is presented and discussed in more details in the results of macroanalysis of the briquettes' structure.

The HBP is easy to operate, and it is less power intensive. As a drawback, but not so essential, it can be considered a high level of noise in the operation of the equipment.

In the framework of the research there were not observed any significant deviations in the work of the equipment. In general, the work of the press can be characterised as stable and reliable.

5.1.2. Evaluation of the work of screw briquetting press

In comparison with the hydraulic press, the work on SBP was not an easy task. At the initial stage of the equipment operation, frequent failures in the work occurred, e.g. clogging or fall out of material, ignition or detonation of biomass, crumbling of briquettes, etc. This is not related to the technical malfunction of the press. The test of equipment work in idle (without material) has shown that equipment is working correctly.

The problem relates to the lack of reliable information about the efficient work with the equipment during the densification of different types of raw material at specific operation modes. In the scientific literature there is a lack of relevant information about the suitable working temperature for briquetting (on SBP) of a specific type of biomass, with certain bulk density and particles size. In order to assure acceptable work of the equipment and to eliminate the aforesaid flaws, the control of the working process and exploitation of SBP was examined more in detail.

The equipment has many options for adjustment during the working process. From one side that gives the possibility to adjust and to optimise the press for the work with a wide range of raw materials. From the other side, the adjustment of equipment for the proper work with a specific type of processed material can be done only by experienced personnel. Also, too many working adjustments take more time. It is possible to set up the necessary temperature of the heating die; to choose rotation speed of the screw; to change the pressure by using adjusting screws (clamping screw) of the cooling line; to select the desired length of produced briquettes.

The control and settings of an operating mode of SBP are made from the electric switchboard with the control panel including the following parts: switch of the connection to electrical grid; switch of the main electric motor; switch for the selecting of the direction of the screw’s rotation; switch of the agitator; unit for temperature setting and control with a display; controller of the screw rotation speed; switch of the die heater (**Figure 19**).

The beginning of the work starts with the pre-heating of the die by the heater, the temperature of which should be set up from the unit for temperature setting and control. The **heating rate** developed by the heater is about **8 °C/min^{-1}**.

Figure 19. Setting up of the working temperature (left image) and selecting the rotation speed of the pressing screw (right image)

In the frame of the research was found problems with a working temperature of SBP and the heat treatment of the briquettes. The information about the optimal working temperature received from the technical staff of the company producer of equipment was not sufficient for proper work. The recommended temperature for the efficient work was 90 °C. But in a practice, this temperature was not sufficient for the proper work of the press.

Figure 20. The laborious cleaning process of the forming and heating die.

According to the results present in the literature, suitable temperature for the densification varies 20 – 60 °C (Rynkiewicz et al. 2013), 20 – 80 °C (Okot et al. 2018) 2018, 85 °C (Kaliyan & Morey 2010c) 135 °C (Demianiuk & Demianiuk 2016), 300 °C (Bhattacharya et al. 1989). **Furthermore, the low temperature was the reason for the clogging of the biomass in the die** (**Figure 20**), blocking the rotation of the pressing screw and total stop of the electric motor work. Further launch of the work is impossible until the complete cleaning of the forming and heating die from the raw material.

After series of trials it was found that the **sufficient temperature for the stable work** and production of high-quality briquettes has to be not lower than **160 °C**.

Too high temperature also has negative consequences on the production process. The excess of the high temperature can cause the large amount of flue gases or even the ignition of the briquettes (**Figure 21**). Thus, based on the research, it was experimentally indicated that the optimal working temperature of the heating die for the work has to be in limits of 160 – 215 °C.

Figure 21. The consequences of high temperature excess on the production of the briquettes

Another problem was that the time for the connection of the heater (in automatic mode) was very long and it had a negative impact on the quality of the obtained briquettes. As a result, one part of briquettes was produced with a too carbonised surface, another one was low thermally treated (see **Figure 22**). The main reason was the slow time of temperature transducer's reaction, its incorrect location or its incorrect work. In consequence, the work of the heater of the die was inadequate.

Figure 22. The view of produced briquettes obtained in the result of unsatisfactory work of transducer of the heat

Maintain of the necessary temperature was done mainly manual (by the connection of the heater).

Some data related to the evaluation of the work of thermal transducer are presented in the results of the thermal analysis.

It was found that on quality of the produced briquettes has an impact not only the high external temperature created by the heater and heating die but also internal temperature generated by the friction between screw and biomass (see **Figure23**).

Figure 23. The impact of high temperature (inside the briquettes) obtained in the result of high friction between screw and biomass

Briquettes which were exposed only to the external thermal influence (by the heater of the die) differ by the quality in comparison with briquettes that were exposed to internal and external thermal influence.

The research has indicated that the rotation speed of the pressing screw is important. By **increasing the rotation speed of the pressing screw** it is possible to **increase the productivity of SBP** and to improve **the quality of briquettes** by application of additional heat thanks to the high friction. This is possible by the changing of the screw's working speed (WS). In the option of the speed working mode of the equipment, there is a possibility to select the working speed of the screw from the values 0 to 11.

Based on the practice, the speed modes from 1 until 3 are the most suitable and safe for the work. For the evaluation of the influence of different working modes on the quality of solid biofuel, the briquettes were produced at the working speed mode 1 (noted with abbreviation V1) and at the WS mode 3 (noted with abbreviation V3).

At WS V1 it is possible to obtain briquettes that will be exposed to thermal influence only at the surface. The rotation speed in this mode is not enough to treat thermally the internal side of the briquettes. The revolution speed of the screw in working mode 1 is 102 rpm^{-1}. But the longer holding time of the briquettes under the load and high temperature contributes to better densification of particles and increase the density of briquettes(Faborode & O'Callaghan 1987; Demianiuk & Demianiuk 2016). In general, the biofuel obtained from thermally treated biomass has better chemical and physical properties (Araújo et al. 2016).

At WS V3 it is possible to obtain briquettes exposed to the action of the high temperature not only at the surface but also inside (in the internal channel). The revolution speed of the screw in working mode 3 is 135 rpm^{-1}.

Figure 24*. *Work of the press at the high speed and the low speed (optimal speed).

Use of working mode higher than speed 3 is not suitable for production. First of all, due to the fast displacement of the material through the die the formation of the briquette does not occur, and all material falls out from the die (see **Figure 24**). One more reason against the use of the high working speed is the risk of biomass detonation. At the detonation the smouldering fragments of briquettes can injure the working staff.

Figure 25. The clog of the channel of briquette (left image) and fragment of briquette after detonation (right picture).

An important factor for the process of briquetting is the presence of sufficient pressure, applied on biomass during densification, especially for raw material with low density (O’Dogherty & Wheeler 1984; Mani et al. 2003; Adapa et al. 2009). The main pressure during the densification is made by the pressing screw. Additional, acceptable working pressure can be created by the device (mechanism) for additional pressure control and adjustment of the cooling line. The adjustment of the pressure for raw material is different and it is done in accordance with properties of processed biomass (moisture content, density, the origin of raw material, etc.).

Figure 26. The adjustment of clamping screws of the cooling line.

In the present, the adjustment is complicated due to the lack of a calibrated scale on the clamping screw of the device for pressure adjustment. In order to improve and to simplify the pressure adjustment, it is necessary to create a calibrated scale on the clamping screw of the device for pressure adjustment (**Figure 26**).

As a positive side of the SBP, it can be mentioned a simple design which allows quick replacement of the main active working parts and easy maintenance which reduces the equipment's downtime. Comparing with the HBP, the SBP is not equipped with a feeder. The function of the feed is realised by the pressing screw that feeds the biomass continuously.

The drawback of SBP is high wear of the main pressing parts. As difficult and dangerous in the operation, it is possible to be used only by the experienced personnel. Additionally, during the work the use of the aspiration system for the flue gas is required.

5.2 Evaluation of the properties of raw material and briquettes

5.2.1 Moisture content

Unprocessed (not densified) biomass is more sensitive to the air humidity changes, because of the characteristic structure (hygroscopic) with high porosity that can absorb and accumulate the moisture (Kocsis & Csanády 2019). **Densified biomass** is **less exposed** to the influence **of humidity changes**. But, it should be noted that briquettes produced by the technology of briquetting without high temperature (cold briquetting) or of low density are also able to absorb in some limits moisture. High values of moisture content present in the raw material can influence the density and integrity of the structure of densified solid biofuel (O'Dogherty & Wheeler 1984). As a result of **high *MC***, the **binding of the particles is low** and obtained fuel has fragile structure and crumbles (**Figure 27**) (Kocsis & Csanády 2019).

***Figure 27**. The influence of the high moisture on the quality of briquettes*

In the same time, moisture has a significant role in production of some types of SB and lack of moisture makes the process of densification difficult or even impossible (in case of pellets production) (Tabil et al. 2011a). Some studies demonstrate the importance of the MC on the specific energy consumption. **The raise of MC** in the material **decrease energy consumption during densification**, make it more soft and pliable for pressing (Jianjun et al. 2013).

The result of the analysis of MC of the tested biomass and SB is presented in **Figure 28.**

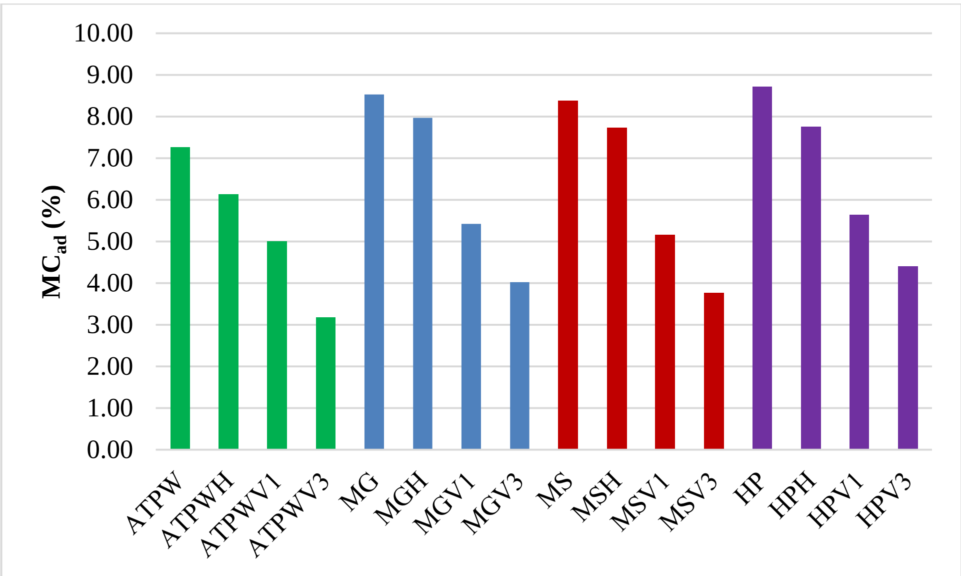


***Figure 28**. The moisture content of the tested biomass and SB*

The ***MC*** of tested biomass **did not exceed** the value of **9 %** (**maximal** was in case of the **HP 8.72 %**). But even this highest value of the determined *MC* is considered admissible for the production of densified SB. According to the many research results, the suitable *MC* in biomass applied for the production of SB can be 12 % (Mani et al. 2006). Have to be noted that there **was not found a big difference of *MC* between the fractions of the same materials**. However, there is **difference in the *MC* of briquettes**. The difference between initial raw material and briquettes obtained on HBP is not so big and is approximately 0.5 - 1 % of *MC* (maximum value is between **ATPW and ATPWH - 1.13 % of *MC***, minimal value between **MG and MGH - 0.56 % of *MC***).

The **significant difference in *MC*** is between initial biomass and **briquettes obtained on SBP**. The best result is marked for the briquettes made on SPB at working speed 3 (for example initial raw material of **ATPW has 7.27 % of *MC*** but of briquettes **ATPWV3 has 3.18 % of *MC***). That was possible thanks to the influence of high temperatures in the briquetting process.

Losing of moisture content during the briquetting happens thanks the high temperature developed by the friction or external heating (Bhattacharya et al. 1989).

Lower moisture content has only the torrefied SB. But its production requires the use of special technological equipment and additional spends for heat treatment (Chen et al. 2015b).

5.2.2 Ash content

Importance of the ash content (*AC*) in biomass consists of the influence on the work of the combustion equipment (Cichy et al. 2017). Ash obtained from biomass after its burning represents mainly inorganic remained part. The ***AC* in biofuel can be influenced by** the **specific content of substances** in raw material, by the **contamination of biomass with** the **inorganic matter or organic matter** (sand, soil, particles of the biomass of various origin or other ash forming matter) (Lestander 2012). Plants have a property to accumulate, in some of their parts higher content of (like branches, bark, stumps, leaves) inorganic matter. Lestander et al (2012) underlined that ***AC* in wood biomass can be influenced by the content of the bark**. The high content of bark of the biomass will increase the ***AC*** (Lestander 2012). That's why exists opinion in the scientific literature that some parts of the plants, which are low valuable biomass are less preferable to use for the production of SB Doring 2013.

In **Table 3** are presented results of the ***AC*** measurements. The **highest *AC*** from all tested materials was found in biomass of **HP**. The research performed by Rice (2008) and Prade et al. (2012) also indicated the high ***AC*** of the hemp applied for energy proposes – 3 - 4%. Both types of miscanthus as well have high ***AC***. As well as in the case of the hemp, the high ***AC*** of both types of miscanthus biomass is a common occurrence (Obernberger et al. 2006; Abdoli et al. 2018). The **lowest values of *AC*** were found in the **ATPW**. Low ***AC*** of SB makes easier operation and maintenance of heating equipment (Tabil et al. 2011a).

The content of the ash of biomass from ATPW lower in comparison with another tested type of feedstock, but it is high for wood material. Usual the A_d of wood biomass is lower (Obernberger et al. 2006).

(Royano et al. 2018) reported that the ***AC*** of biofuel made from prunings of fruit tree branches is higher due to the presence of bark.

5.2.3 Content of C, H, N, O, S, Cl (chemical composition)

The composition of the biomass depends on the provenience of biomass, plant species, growing condition, application of fertilizers and pesticides for cultivation, age of plants, harvesting time, growing in an environment with pollutants, etc. (Vassilev et al. 2012). As a result, this can influence the properties of biofuel (for example calorific value, ash content) (Lestander 2012).

The content of *Cl* and *S* in biomass is commonly not high (for example, the typical content of *Cl* is not higher than 2%). But despite that, the presence of these constituents can have the essential impact on the formation of deposits and corrosion in the boilers during the burning process (Jones et al. 2014).

Table 3. The chemical composition of investigated biomass

Type of tested biomass	C (%)	H (%)	N (%)	S (%)	Cl (%)	O (%)	Ash content AC (%)
ATPW	49.63	5.86	0.74	0.03	0.014	41.826	1.90
MG	48.57	5.91	0.56	0.068	0.13	42.142	2.62
MS	48.22	5.90	0.59	0.061	0.18	42.209	2.84
HP	46.96	5.96	0.55	0.035	0.09	43.445	2.96

ATPW, MG and **MS** have **higher content of *C***, that has a positive influence on the calorific value (see **Table 3**) (Abdoli et al. 2018). The **lowest *C*** content was determined in a sample of **HP**. Also not high values of *C* content for biomass from HP were mentioned by (Kraszkiewicz et al. 2019).

The **lowest content of the *Cl*** is marked for the biomass of **ATPW** and **HP**. *Cl* content in the wood biomass is in the limit of 0.01 - 0.05 %, and an exception can make the tree bark (in some case the level of *Cl* can be 0.26 %) as it was stated by (Vassilev et al. 2012). The content of *Cl* in the biomass obtained from HP usual is in the limit from 0.03 % (Rice 2008) until 0.5 % (Prade et al. 2012) and depends on the variety, age of crop and period of the year when the harvest was performed E(El Bassam 2010). The high content of the *Cl* in both types of miscanthus can be considered as a drawback. However, high values of the *Cl* content are typical for the herbaceous biomass (Obernberger et al. 2006).

Content of *N* in HP, MG, and MS was in limit of 0.55 % - 0.59 %. In the same time, sample of the tested **wood biomass contains a higher amount of *N (see Table 3)***. (Vassilev et al. 2012) has also reported a high content of *N* in the wood biomass.

During the analysis, the **highest values of *S*** content were found in **MS** and **MG**. The **lower content of *S*** is in **ATPW** and **HP**. The *S* content in the biomass of hemp usual is low - 0.056 % (Kraszkiewicz et al. 2019), 0.06 % (Prade et al. 2012).

In the frame of research was not found any difference in the content of *C, H, N, O, S, Cl* and *AC* of initial biomass and briquettes for each type of tested biomass.

5.2.4 Calorific value

The *CV* represents one of the most important properties of the biomass that have a decisive place for the application for energy purposes. The agricultural and wood biomass of high values of *CV* is more preferable for the production of the SB (Stolarski et al. 2013).

***Table 3**. The results of the test for the calorific value*

Type of tested biomass and solid biofuel	Gross calorific value of the sample of biomass/biofuel GCV ($MJ.kg^{-1}$ d.b.)	Net calorific value of the dry sample of biomass/biofuel NCV_d ($MJ.kg^{-1}$)	Net calorific value at a required moisture content NCV_{ar} ($MJ.kg^{-1}$)	Moisture content MC (%)
ATPW	19.55	18.27	16.76	7.27
ATPWH			17.00	6.14
ATPWV1			17.23	5.00
ATPWV3			17.61	3.18
MG	18.73	17.45	15.75	8.53
MGH			15.86	7.97
MGV1			16.37	5.42
MGV3			16.65	4.02
MS	18.60	17.32	15.66	8.38
MSH			15.79	7.73
MSV1			16.30	5.16
MSV3			16.57	3.77
HP	18.29	16.99	15.30	8.72
HPH			15.48	7.75
HPV1			15.89	5.64
HPV3			16.14	4.40

In the **Table 3** are indicated the results of the measurement of *CV*. During the research of *CV*, a difference of gross calorific value (*GCV*) between initial biomass and the densified biofuel was not found for each type of tested material. It should be noted that *GCV* of all tested biomass indicated high results. However, the **highest result of** *GCV* **belongs to** the biomass of **ATPW**. High calorific value is typical for the wood biomass (Stolarski et al. 2013). The results for the biomass of both types of miscanthus are similar (slightly higher in case of MG) and are close to the values of *GCV* presented in the results of other studies (El Bassam 2010; Döring 2013). The **HP has the lowest** *GCV*. The results of many research works indicated that the *GCV* of the industrial hemp vires around 18.08 - 18.5 $MJ.kg^{-1}$ (Rice 2008; Prade et al. 2012; Kraszkiewicz et al. 2019), and it was confirmed here.

Taking into account the importance of the *GCV* for the research and its later use for the determination of net calorific value, a more detailed calculation was performed in order to assure the high precision results. The example of the calculation (for ATPW) is presented in the **Table 4**. The results for all studied types of biomass are presented in the **Annex 2**.

Moreover, **a difference in the results of net calorific value in a dry base** (*NCV_d*) between initial material and solid biofuel **was not found**. The difference in the results was observed only for the net calorific value determined as received (***NCV_{ar}***) with the calculation of moisture content (**Table 3 and Figure 29**).

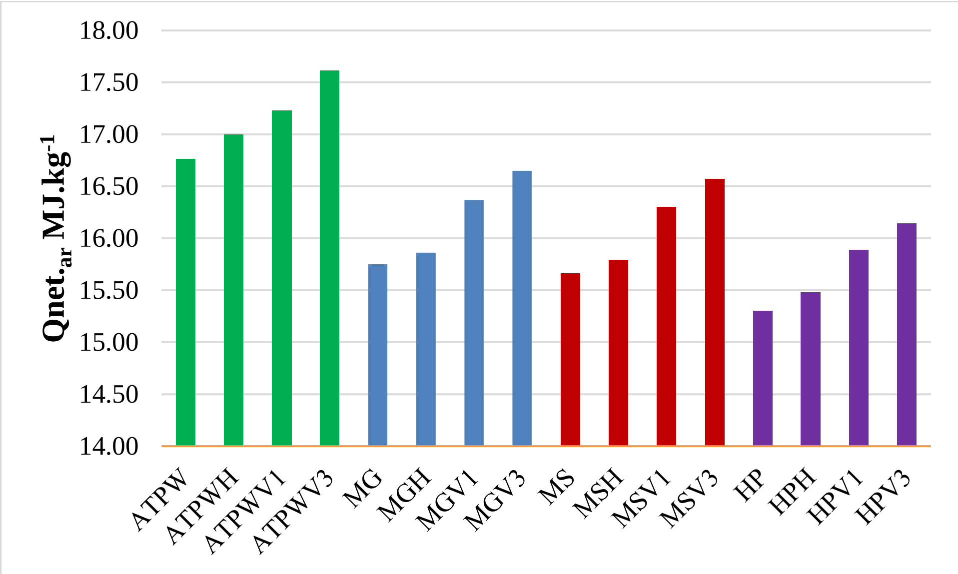


Figure 29. The net calorific value (as received) of initial material and biofuel.

The high ***MC* negative affects the *CV*** of the biofuel (Kocsis & Csanády 2019).

The **higher values of *NCV_{ar}* have briquettes** obtained on SBP at high temperatures (**obtained at WS V3**). The same briquettes have lower *MC*. Briquettes or biomass exposed to the action of high temperature during the production, have higher *CV* (Wang et al. 2017a) (Tabakaev et al. 2017). The **best result of *NCV_{ar}*** was achieved by briquettes made from **ATPWV3 (17.61 MJ.kg^{-1})**. Can be marked as well the result of briquettes **MGV3 (16.65 MJ.kg^{-1})** and **MSV3 (16.57 MJ.kg^{-1}).** Even though the herbaceous biomass has a low density, the CV of the briquettes made from miscanthus can be high (Urbanovičová et al. 2017). The briquettes **HPV3** have little lower ***NCV_{ar}* – 16.14 MJ.kg^{-1}**.

The obtained briquettes at high temperature have a slightly carbonized surface and are very close to the mild torrified biofuel. Torrefaction represents the thermal treatment of biomass at the temperature of 290-300 °C at a certain time (usual 20-30 minutes) in consequence of which increases its CV (energy density). Another result of this thermochemical process is decreasing of moisture content and reduction of hemicellulose content (Jones et al. 2014).

Table 4. *The detailed determination of gross calorific value*

Type of tested biomass or solid biofuel	Number of repetitions	The mass of ignition wire (g)	The mass of combustion bag (g)	The mass of sample (g)	Corrected temperature rise (°C)	Effective heat capacity of calorimeter (J.°C^{-1})	Gross calorific value of ignition wire (J.°C^{-1})	Gross calorific value of combustion bag (J.°C^{-1})	Gross calorific value of the sample (J.°C^{-1})	Average value of gross calorific value of the sample (J.°C^{-1})
ATPW	1	0.0085	0.0613	0.5547	1.30946	9099	51.0	997.9027	19588.74	19551.17
	2	0.0087	0.0620	0.5400	1.27703	9099	52.2	1009.298	19552.22	
	3	0.0089	0.0608	0.5627	1.32134	9099	53.4	989.7632	19512.55	
Standard deviation										38.1078
Quantity of samples										3
Confidence coefficient										1.96
Confidence interval										43.12304
Upper bound										19594.29
Lower bound										19508.04
Max										19588.74
Min										19512.55
Range										76.19388

5.2.5 Bulk density

The bulk density (BD) of the biomass is a property that has to take into account in case of the research of the densification process due to its high impact on the process. The BD of the feedstock depends on many factors like MC, size of particles, type of biomass, etc.(O'Dogherty & Wheeler 1984; Chevanan et al. 2010).

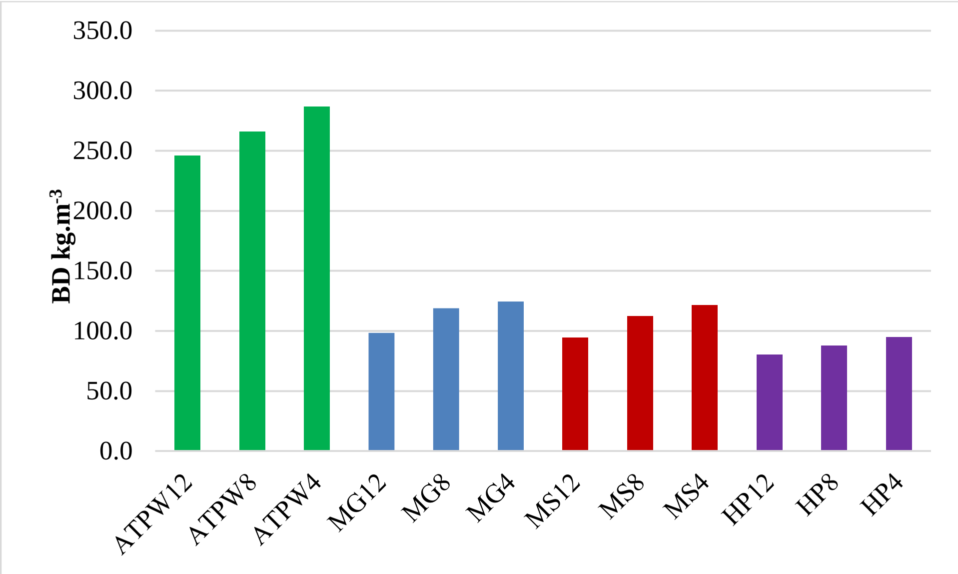


Figure 30. The bulk density of the initial raw material

In many cases, the use of raw material with a high *BD* contributes to the obtaining of the SB of high density (Döring 2013). The biomass of **ATPW has the highest *BD*** (especially ATPW4 **286.8 kg.m^{-3}**) (see **Figure 30**). The wood biomass is characterized by high *BD* according to (Döring 2013). The **BD of ATPW4 is higher by 14.33 %** in comparison with the ATPW12. The increasing of the *BD* is possible through the reduction of the particles size of biomass. The biomass crushed into a smaller fraction has higher *BD* (Tabil et al. 2011b). The feedstock from MG and MS does not have high *BD* (maximal value were in case of MG4 **124.6 kg.m^{-3}** and MS4 **121.2 kg.m^{-3}**). The **HP of fraction 12 mm** has the lowest *BD* comparing to other fractions (**HP12 79.9 kg.m^{-3}** and **HP4 94.7 kg.m^{-3}**) and within all tested materials. Use of raw material of a low *BD* and composed of big size particles has a negative influence on the briquetting process (Guo et al. 2016). The low *BD* of the hemp requires high energy consumption for the grinding (Kraszkiewicz et al. 2019).

The material with low density but at the same time with high volume has high amount of voids (high porosity) that affects negatively the productivity of briquetting equipment (Adapa et al. 2009). It is known that the material is added into the pressing chamber (working space) in portions (it is dosed) and it is pressed in the die, reducing the voids (pores) and making the structure more compact (Pietsch 2002, 2005). Based on this fact, it can be concluded that for filling of the working chamber of the die (channel) more material of low density is necessary, that needs more working cycles for its densification and more operational time. As a result, densification of the raw material with low density requires a higher consumption of energy. Also, the productivity of the equipment decreases. The opposite effect will be in the case of the use of raw material of high density.

5.2.6 Determination of particle density

The results of some studies indicates that the particle density (*DE*) or density of briquettes depends on the properties of initial raw materials like *MC*, particles size and shape, *BD*, etc.(Kaliyan & Morey 2010a).

The standard EN ISO 18847:2016 allow to determine particle density by the use of a buoyancy method or stereometric method. According to the research results of (Rabier et al. 2006), the stereometric method is simpler in measurements and in the same time give the possibility to receive measurements of high precision.

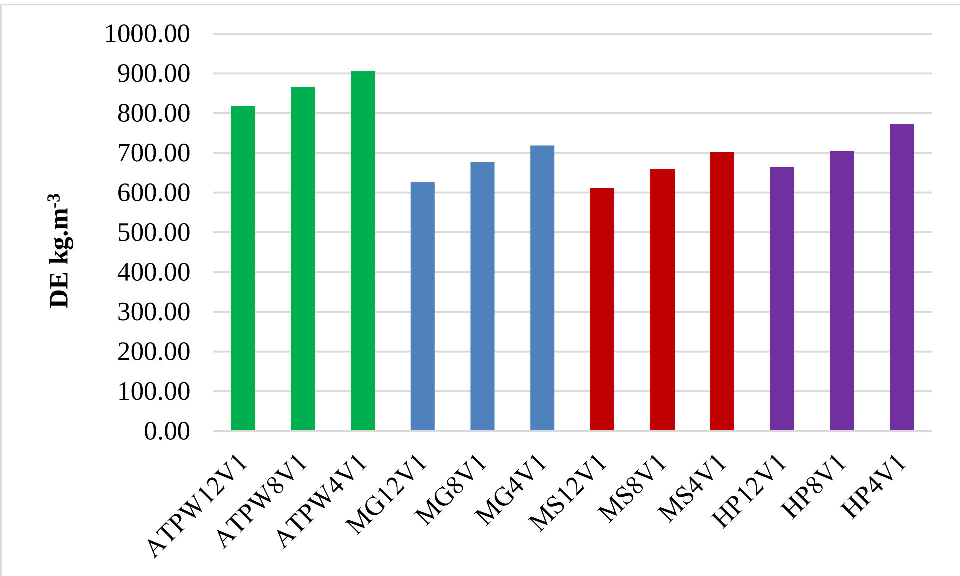


***Figure 31**. The DE of the briquettes obtained on SBP at the speed V1*

The particularity of briquettes produced on the SBP is their high density. Both types of briquettes obtained on the SBP at WS V1 and WS V3 have high density. The data related to the *DE* of briquettes obtained on the SBP at WS V1 (**Figure 31**) indicate that the biofuel obtained from wood biomass has high density (**ATPW4V1 - 905.74 kg.m^{-3}**). The briquettes obtained from the other samples of studied biomass as well have high *DE* (**MG4V1 718.24 kg.m^{-3}, MS4V1 703.15 kg.m^{-3}, HP4V1 772.14 kg.m^{-3}**). The highest values of the *DE* were observed at the briquettes made from the feedstock of the smallest fraction size and with the highest *BD*. The influence of the particles size and provenience of biomass on strength and density was mentioned in many studies (O'Dogherty & Gilbertson 1988; Hann & Strazisar 2007).

The briquettes obtained at WS V1 have lower *DE* in comparison with briquettes produced at WS V3.

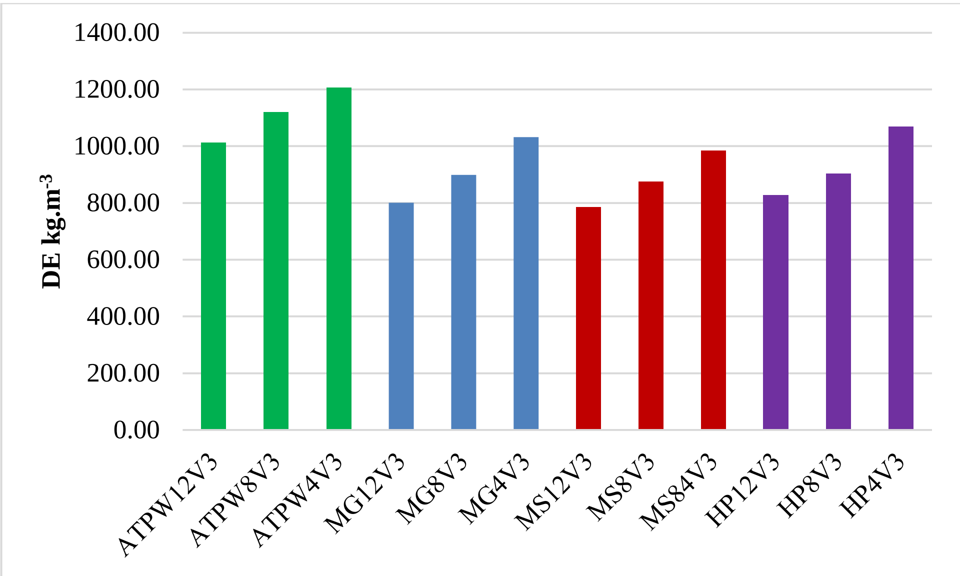


Figure 32. The density of the briquettes obtained on SBP at the speed V3

The ***DE* of the biofuel obtained on SBP at WS V3** is **higher approximately 19 - 28 %** (depending on the type of material and its fraction size) in comparison with briquettes obtained at WS V1 (**Figure 32**).

Like in case of previously analysed briquettes the highest result of *DE* belongs to briquettes obtained from wood biomass (**APTW4V3 – 1206.14 kg.m^{-3}**). Briquettes made from other types of biomass with particles of the smallest fraction have as well high *DE* (**MG4V1 1032.20 kg.m^{-3}, MS4V1 983.63 kg.m^{-3}, HP4V1 1067.94 kg.m^{-3}**).

Higher *DE* can be explained by the fact that the briquettes were exposed to the more intensive action of high temperature during densification on SBP.

The suitable temperature conditions during the densification process are an indispensable factor for the production of briquettes of high quality (Zhang & Guo 2014). The keeping of the high temperature during pressing can increase the efficiency of the pressing process of biomass (Demianiuk & Demianiuk 2016).

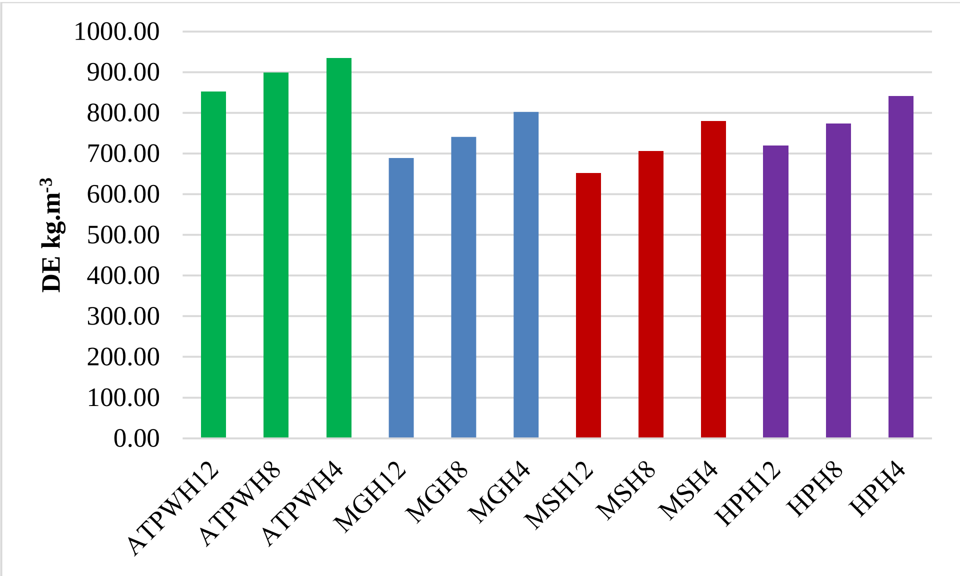


Figure 33. The density of the briquettes obtained on HBP

Comparing with briquettes obtained on SBP, the solid biofuel obtained on HBP was not exposed to the action of temperatures of high values. Even so, briquettes obtained on HBP have high *DE* (**Figure 33**).

The SB made from ATPW leads in the *DE* in comparison with other types of biomass (**934.21 kg.m^{-3} for ATPW4**). The same clear relationship can be observed between the particles size of feedstock and the *DE* of biofuel. Briquettes made from the material with particles of smaller size have higher *DE* (Pietsch 2002).

Briquettes made from HP biomass also **have high *DE*** (**HPH4 – 840.63 kg.m^{-3}**). Even though HP biomass has a low density, the structure of the fibres of particles can create strong bonds during compaction, and that is considered as an advantage of fibrous materials (Faborode & O'Callaghan 1989).

The low *DE* (lower than in other cases) was determined for the briquettes made from miscanthus – both MG (minimal **689.23 kg.m^{-3} for MGH12** and maximal **802.10 kg.m^{-3} for MGH4**) and MS (minimal **651.81 kg.m^{-3} for MSH12** and maximal **780.22 kg.m^{-3} for MSH4**). The applying of the high pressure for the densification process can facilitate obtaining of the briquettes of high density (O'Dogherty & Wheeler 1984; Demianiuk & Demianiuk 2016). Nevertheless, the application of the excessive pressure for the densification is the reason for high energy consumption for the briquetting (Rajaseenivasan et al. 2016).

5.2.7 Mechanical durability

Along with the particle density of the SB, mechanical durability (*DU*) is a significant parameter of quality. The Du characterize as capability of SB to keep the shape and structural integrity when transported, handled, stored (Temmerman et al. 2006).

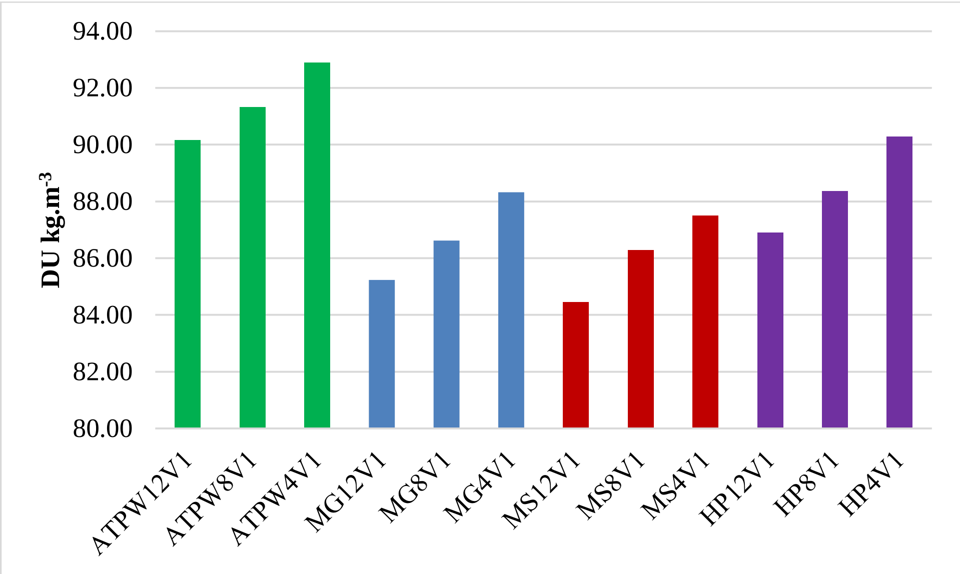


Figure 34. The mechanical durability of the briquettes obtained on SBP at the working speed V1

Even though the **briquettes obtained on SBP at WS V1 have a high density**, the ***DU* is low**. The results of the *DU* test for briquettes made at WS V1 are presented in **Figure 34**.

Only samples of **briquettes made from ATPW have *DU* higher than 90 %** (minimal **ATPW12V1 90.16 %** and maximal **ATPW4V1 92. 89 %**). Some briquettes made from HP also have *DU* 90 % (only HP4V1 90.28 %). Even these values are considered very low. It should be noted that the tested briquettes have high *DE*. The *DE* often is taken as a close to *DU* indicator of quality. But according to many research results, there is not always a direct relationship between the values of *DU* and *DE* of SB (Obernberger & Thek 2004; Temmerman et al. 2006).

The most probable reason for low *DU* of briquettes is insufficient heat treatment, which consists of only external exposing on briquettes of the high temperature. Some results demonstrated the direct relationship between the temperature and mechanical strength of briquettes (Okot et al. 2018).

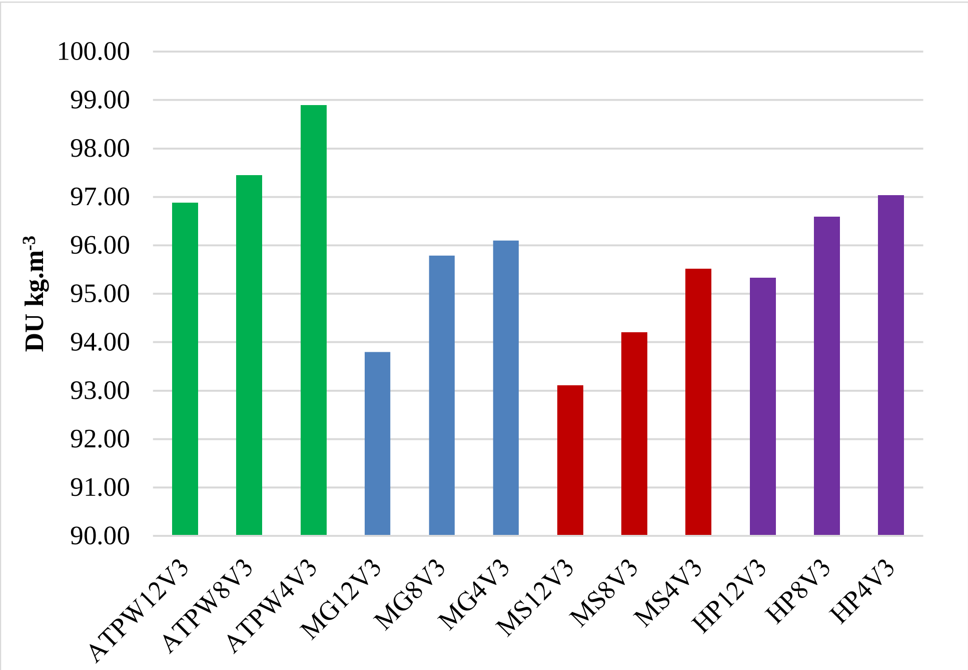


Figure 35. The mechanical durability of the briquettes obtained on SBP at the working speed V3

The **best result of *DU* belongs to the briquettes obtained on SBP at WS V3** (**Figure 35**). The tested samples of SB have high *DU* (**MG4V3 96.10 %**, **MS4V3 95.52 %**, **HP4V3 97.03 %**). The briquettes made from wood biomass have the highest values of *DU* (**ATPW4V3 98.89 %**).

Du is in closely connected with the external and internal action of the high heat on biomass during the briquetting that is decisive for efficient densification (Mikulandrić et al. 2016).

All samples of tested briquettes obtained from ATPW and HP (**Figure 36**) made on HBP as well has high mechanical durability **ATPWH4 96.14 %** and for **HPH4 96.86 %**). The high *DU* of briquettes obtained from the HP was mentioned by (Kraszkiewicz et al. 2019). The high strength of the briquettes made from HP is possible thanks to its specific fibrous structure of particles that creates strong bonds (Faborode & O'Callaghan 1989).

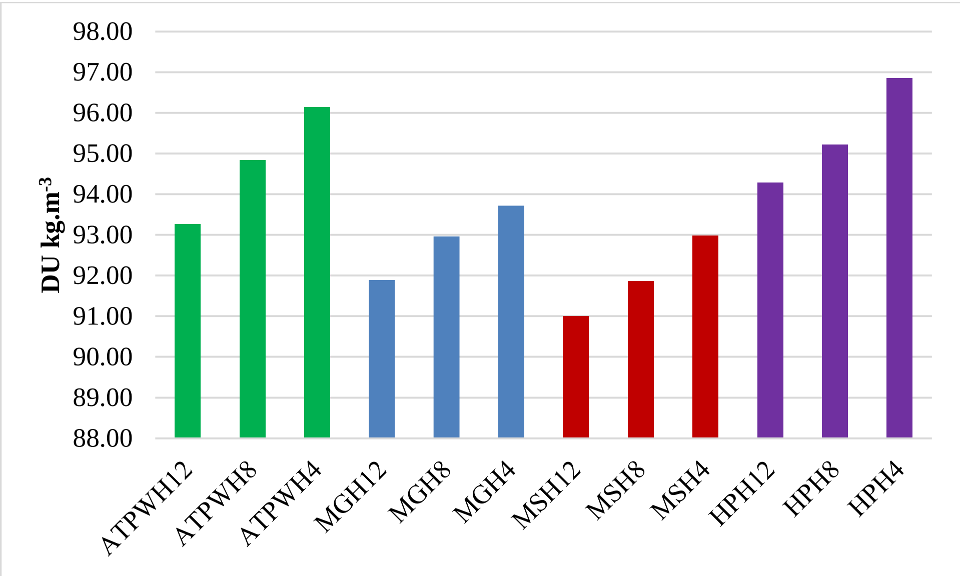


Figure 36. The mechanical durability of the briquettes obtained on HBP

The **lowest result on HBP belongs to briquettes obtained from MS** (**MGH4 93.72 %)** and **and MG (MSH4 92.98 %**). The studies performed by Urbanovicova et al (2017) also indicated the low *DU* of the briquettes made of MS. The reason for the low result is the characteristic tendency of the briquettes to the relaxation. The additional retention time of the briquettes in the cooling line (in the die) can prevent the densification or reduce their deformation caused by elastic deformation and relaxation (Faborode & O'Callaghan 1987; Lei et al. 2017). The relaxation is more characteristic for the raw materials of low density (herbaceous biomass, straw of cereals), particles of which are inclined to the elastic deformation during densification (Guo et al. 2016).

It was observed that the briquettes made from biomass with particles of bigger size have lower *DU*. The size of the biomass particles can influence considerably the density and strength of produced briquettes (Wang et al. 2018).

The mechanical durability of the briquettes can be also improved by the application of the organic or inorganic binders in the briquetting process (Zhang et al. 2018). But in this case, the price of the biofuel can increase and some other important properties of briquettes (calorific value, ash content, etc.) may worsen. Thus, the use of the raw material processed into a smaller size fraction is then more preferable.

5.2.8 Particle size distribution

Grinding of the raw material applied for the briquetting is an integral part of the production process, the processing quality of which affects the quality of biofuel. The evaluation of the quality of comminute biomass can be done by the determination of its fraction composition – particle size distribution (*PSD*) (Guo et al. 2012).

The particle size distribution has a major importance for the densification process of many kinds of solid biofuels and can have an interrelation with their mechanical properties (Harun & Afzal 2016; Wang et al. 2018).

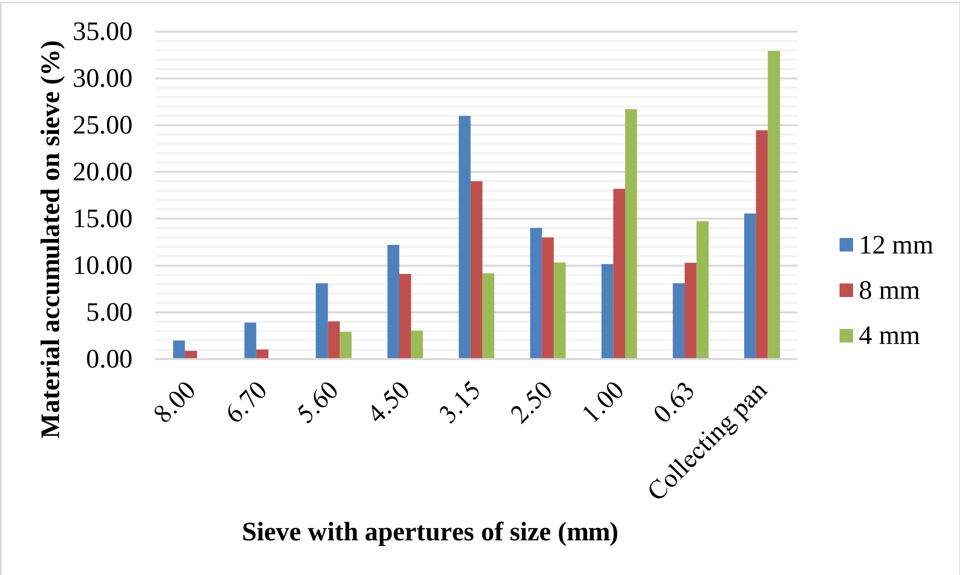


Figure 37. Particle size distribution for MS

The analysis of the **MS12** fractional composition allowed revealing that the highest part of the particles is retained on the sieve **3.15 mm** and composed **26% (Figure 37)**. The significant amount of the fraction of **MS8** was captured by the sieve

3.15 mm (**19.00 %**) and **1 mm** (**18.20 %**). The big part of the fraction **MS4** was retained on the sieve **1 mm** (**26.70 %**) and **0.63 mm** (**14.73 %**). But the biggest amount of the fractions of both **MS4** of **MS8** was captured mainly by the collecting pan (**32.93 %** and 24.46 %).

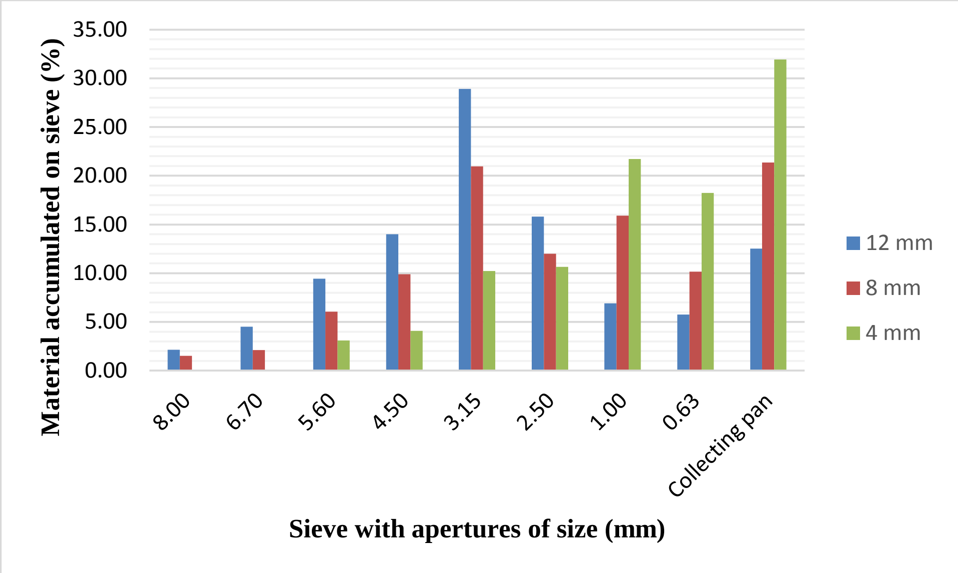


Figure 38. Particle size distribution for MG

The **same trend was observed during the research of the *PSD* of the MG** (**Figure 38**). Just with an exception that in comparison with MS4 more particles of **MG4** were retained on the sieve **0.630 mm** (**18.24 %**). The high percentage of the particles accumulated on the collecting pan indicates that there is a presence of small particles in a big amount that can have significant importance for the densification process. The particles of smaller size thanks to the higher area of contact facilitate the formation of strong bonds in the structure of briquettes (Tabil et al. 2011a). In the composition of fractions 12 mm and 8 mm, a wide range of particles with different size is present. This is characteristic for both MG and MS. The presence of the wide range of particles with different size in the fraction can cause the phenomenon segregation that can negatively impact on the quality of briquettes (Enstad 2001).

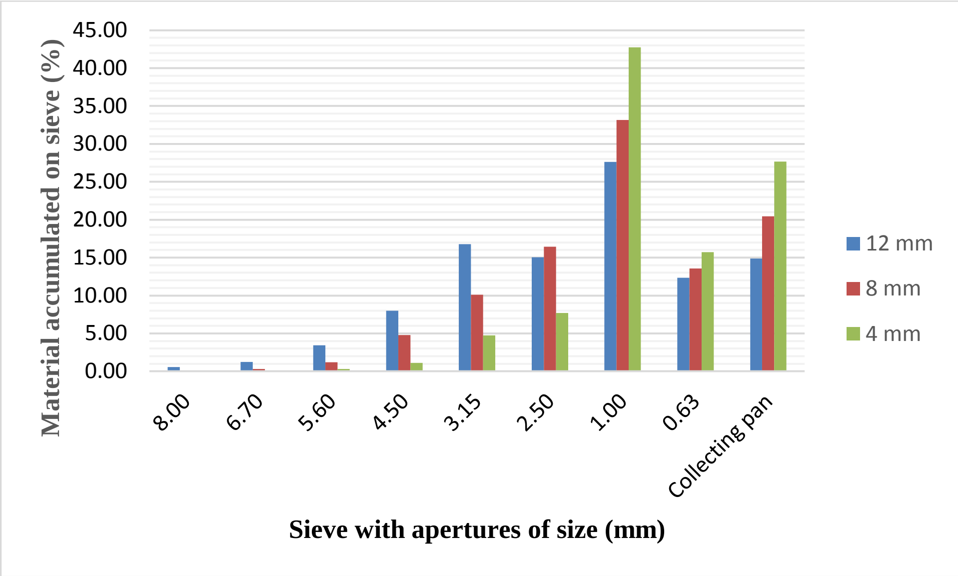


Figure 39. Particle size distribution for ATPW

The *PSD* of the ATPW and HP differ from results of both types of miscanthus. ATPW represent wood biomass with particles of high density. Particles of HP are of low density, soft and fibrous. The type of raw material and shape of the particles also can influence the *PSD* (Guo et al. 2012). The influence of the particles size and provenience of biomass on strength and density was mentioned in many studies (O'Dogherty & Gilbertson 1988; Hann & Strazisar 2007)

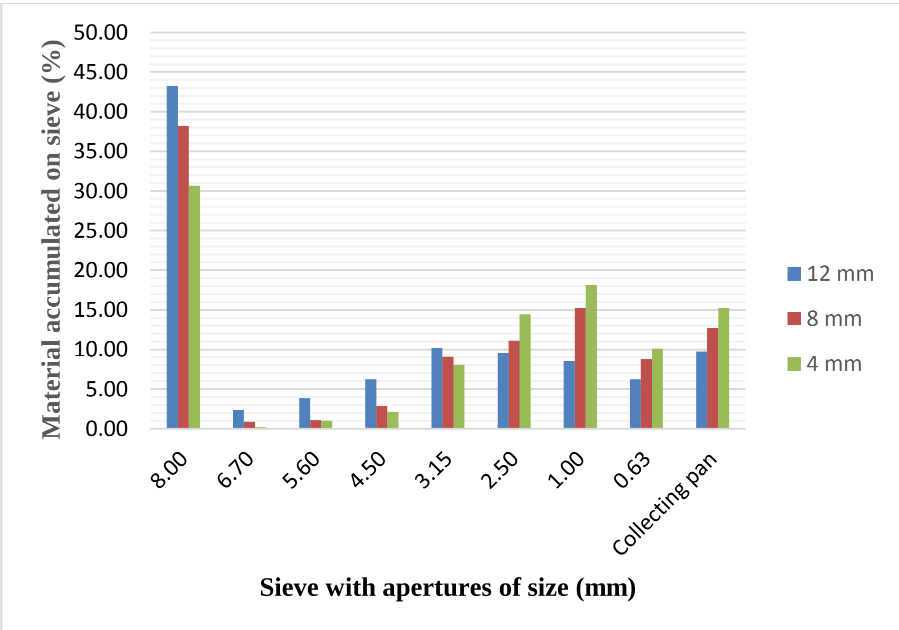


Figure 40. Particle size distribution for HP

In cases of **ATPW**, the greatest amount of **particles was retained by** the sieve with the size of openings **1 mm** (ATPW12 27.61 %, ATPW8 33.14 %, ATPW4 42.73 %) and **collecting pan** (ATPW12 14.89 %, ATPW8 20.46 %, ATPW12 27.66 %). The results are presented in the **Figure 39**.

The study of the *PSD* of HP was difficult and the results of measurements are approximate due to the fact that 30-43% of particles remained on the top sieve **8 mm** (**Figure 40**). The result is related to the specific fibrous structure of the HP (particles of material with long fibres), that creates intensive clogging on the surface of the sieve and retains the particles of smaller size. The bigger particles present in the fraction mainly composed of a small ones can be a reason for the apparition of cracks in the briquettes (Tabil et al. 2011b)

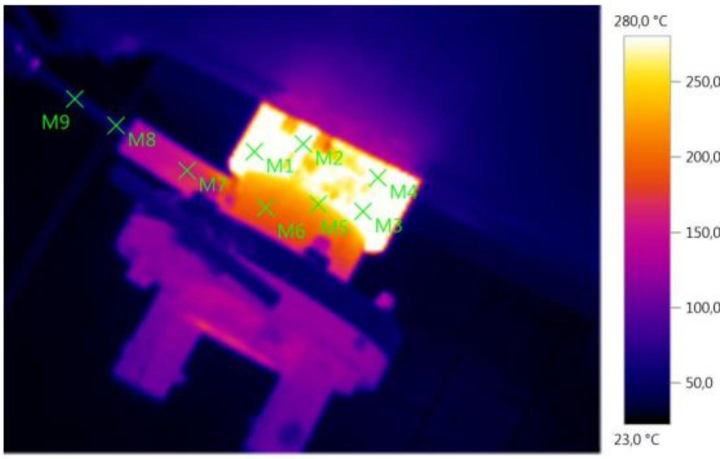
The problem of determination of particles size distribution for fibrous material was reported by (Chaloupkova et al. 2016). In the further studies it is mentioned that image analyse or photo-optical analysis can serve as a solution for determination of particles size distribution of fibrous material (that tends to form clogging) (Souza & Menegalli 2011; Hamzeloo et al. 2014; Chaloupkova et al. 2016).

5.3 Thermal analysis

The importance of high temperature for the densification process was confirmed by many studies (Mikulandrić et al. 2016; Okot et al. 2018). **The high temperature is an integral part of the briquetting on SBP**. For the efficient work of the equipment, it is necessary to identify the optimal working temperature.

The control of the temperature of the SBP is realised based on the data received from the transducer of the temperature, located on the heating die. In the framework of the research it was found that **the work of the transducer of the temperature is not reliable** (because of the slow time of the heater connection). The thermal analysis of the surface of the main pressing parts demonstrated the high difference between the data indicated by the thermal transducer of BP and the data of the thermal imager Testo 875.

For example, during the briquetting process, the unit for temperature setting and control with a display has shown the temperature 175 °C for the heated die, but in a fact, a thermal imager revealed the real **temperature of the heater higher than 320 °C**, **of the die 250 °C** and of **produced briquettes 110 °C**. The intensive use of high temperature for the densification process can be a reason for high energy consumption (Bhattacharya et al. 2002).

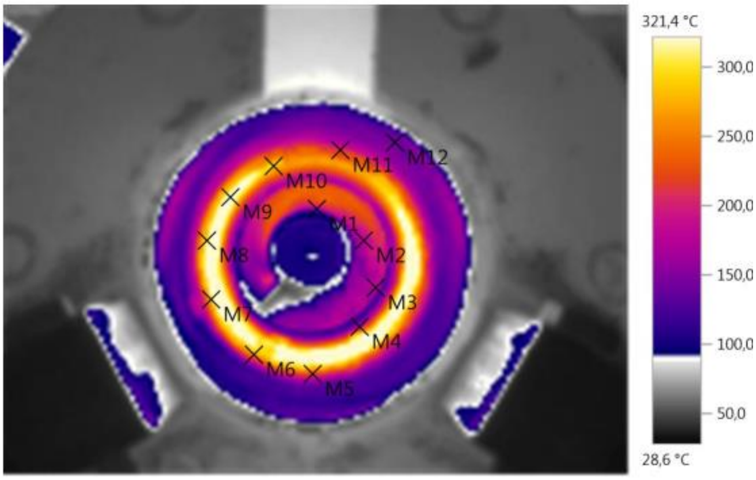


Number of hot spot	Value of temperature (°C)	Coefficient of emissivity	Reflection temperature (°C)
M1	+++	0.96	22.00
M2	318.00	0.96	22.00
M3	297.30	0.96	22.00
M4	280.60	0.96	22.00
M5	240.20	0.96	22.00
M6	198.30	0.96	22.00
M7	158.00	0.96	22.00
M8	56.90	0.96	22.00
M9	48.70	0.96	22.00

Figure 41. The thermal analysis of the heating die

On **Figure 41** are presented the hot spots (**M1, M2, M3, M4** – on the heater; **M5, M6** – on the die; **M7, M8, M9** – on the thermowell and transducer).

The **measurements inside the heating die showed** that the **temperature of die** (hot spots **M5…M12**) in the place of direct contact with the heater **can achieve values higher than 320 °C** (**Figure 42**). It has to be noted that the temperature of the screw (hot spots **M1…M4**), presented in the **Figure 42**, is lower than the temperature of the die. The temperature of the screw can be higher, in dependence on the working speed of the screw and the density of processed material, depending on the friction force (Mikulandrić et al. 2016).



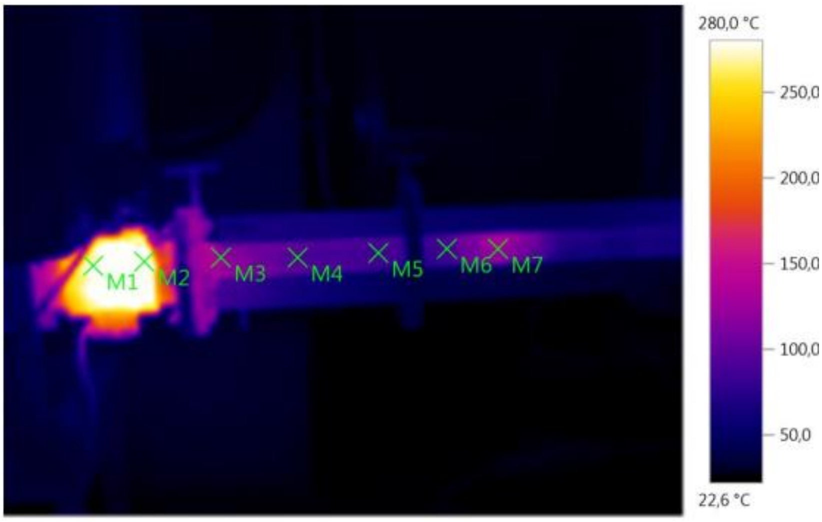
Number of hot spot	Value of temperature (°C)	Coefficient of emissivity	Reflection temperature (°C)
M1	167.40	0.96	22.00
M2	175.00	0.96	22.00
M3	176.30	0.96	22.00
M4	180.70	0.96	22.00
M5	216.70	0.96	22.00
M6	259.90	0.96	22.00
M7	278.40	0.96	22.00
M8	303.60	0.96	22.00
M9	+++	0.96	22.00
M10	288.20	0.96	22.00
M11	211.90	0.96	22.00
M12	139.90	0.96	22.00

Figure 42. The thermal analysis inside of the heating die (hot spots)

The problem related to the incorrect temperature measurement by the transducer of the temperature **can be in the incorrect location of the thermowell** of the transducer (contact between the rigid tip of the sensor and thermowell).

Another important use of the thermal analysis was within the research of the stress areas and detonation of briquettes. Visually it is very difficult to detect stress areas, without the use of special technical means.

Thus, thanks to the thermal analysis, the stress areas were found. These areas are characterized by a high temperature resulting from the accumulation of hot gases inside of briquettes that are precursors of detonation.



Number of hot spot	Value of temperature (°C)	Coefficient of emissivity	Reflection temperature (°C)
M1	280.20	0.95	22.00
M2	+++	0.95	22.00
M3	119.40	0.95	22.00
M4	95.20	0.95	22.00
M5	85.00	0.95	22.00
M6	88.40	0.95	22.00
M7	129.20	0.95	22.00

Figure 43. The thermal analysis of stress areas of briquettes.

In **Figure 43** is presented the thermal analysis of briquettes. The hot spot **M7** represent the stress area with a higher temperature in comparison with other parts of the briquette.

Additional data related to the temperature inside of the die are presented in the **Annex 3**.

If in the case of briquetting on SBP the high temperature is the necessary condition for efficient agglomeration of particles and the possibility of the extrusion process, then the **briquetting process on HBP does not require high temperatures**. However, even though the HBP is not equipped with the heater of the die (the same like SBP), it **was observed that the active working parts become hot during the work** (with different values of temperatures) the same as the produced briquettes.

High temperature has great value in the binding of particles during the densification process. Orth and Lowe 1977 found that the temperature value during densification on piston press influences the density of pressed material and power required. It has decisive importance in the softening and lower viscosity of lignin, which is considered as the main natural binding agent of biomass (Alaru et al. 2011). The lignin changes its state at the temperature higher than 70 °C (Lei et al. 2017). Cellulose and hemicellulose also contribute to the particle binding, however less. In some results of the studies, it is noted that the suitable temperature for the densification should be 80 °C (Okot et al. 2018). Nino et al. (2020) reported that production of the briquettes of high density and *DU* it is possible at the temperature of 110 °C.

Other important components (additional) like pectin, extractives, sugars, starches have the same high value in the particle binding process as lignin (Lestander 2012), but their importance in many research works is undervalued.

In the framework of the present study of the biomass densification on HBP, **the relationship between increasing of a temperature of the main pressing parts and raw material density was found**. Thanks to the friction that appears at the motion of the material under the load in the channel of die, the temperature of the main pressing parts increases (**Table 5**). As a result, the temperature of the raw material and briquettes also rises. The importance of the heat for the densification process, produced by the friction between particles of a material and walls of the die was mentioned by Mikulandric et al. 2016.

The temperature rises as well in the pressing chamber but not so essential like in the die (**Figure 44**). This can be explained by the fact that the material with a higher density of particles has a more tight contact with the surface of the die. During the measurements it **was observed that the same material but of different size of the particles affects the speed and the values of the achieved temperature**. **The reason** again is concluded **in the density**. In the raw material of smaller size fraction the arrangement of particles is more compact (enhance the density), which causes the higher friction with the surface of the pressing. Repsa et al2012 found that the material with particles of smaller size has higher friction coefficient. Higher friction force generates temperatures of higher values.

An example of the results of temperature increasing measurements in specific areas during the densification process is presented in the **Table 5**. The more data (for each type of biomass with specific fraction size), inclusive statistical processing using ANOVA single factor are presented in the **Annex 4, Annex 5, Annex 6**.

Table 5*. The results temperature measurements in specific areas during densification process for ATPW12*

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
ATPW12	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	24.60	25.40	25.90	**25.30**	35.80	37.00	39.20	**37.33**	30.20	28.00	27.70	26.80	**28.18**
	20	25.50	26.20	26.90	**26.20**	41.30	44.10	45.40	**43.60**	34.40	32.80	31.50	30.80	**32.38**
	30	26.90	27.20	28.30	**27.47**	43.90	47.50	48.70	**46.70**	37.70	34.50	33.60	32.70	**34.63**
	40	27.10	28.90	29.70	**28.57**	45.20	48.70	50.20	**48.03**	39.00	36.90	35.70	34.90	**36.63**
	50	28.40	29.60	30.10	**29.37**	48.10	51.00	52.90	**50.67**	40.40	37.30	36.70	35.00	**37.35**
	60	29.30	30.00	30.40	**29.90**	51.40	53.60	54.70	**53.23**	41.20	39.60	38.90	38.00	**39.43**

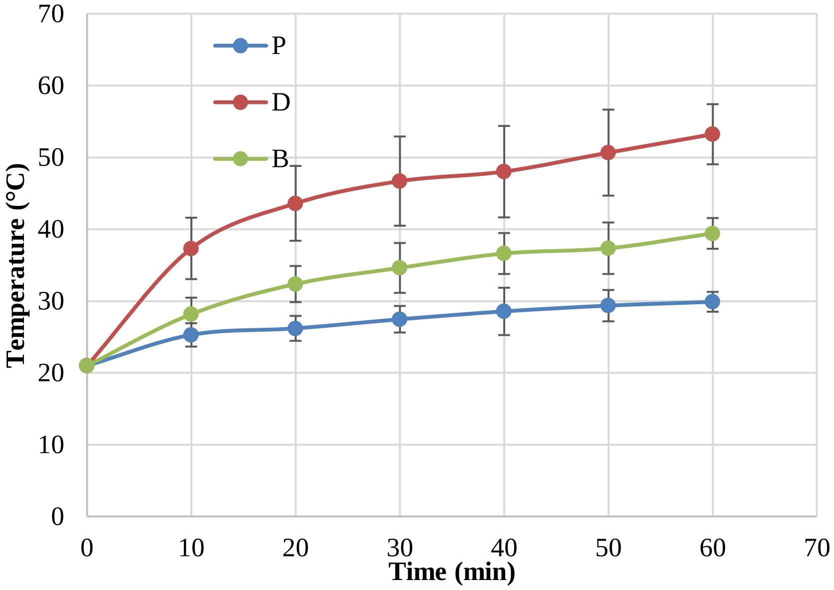


Figure 44. Temperature dependence on the BD of the material ATPW12

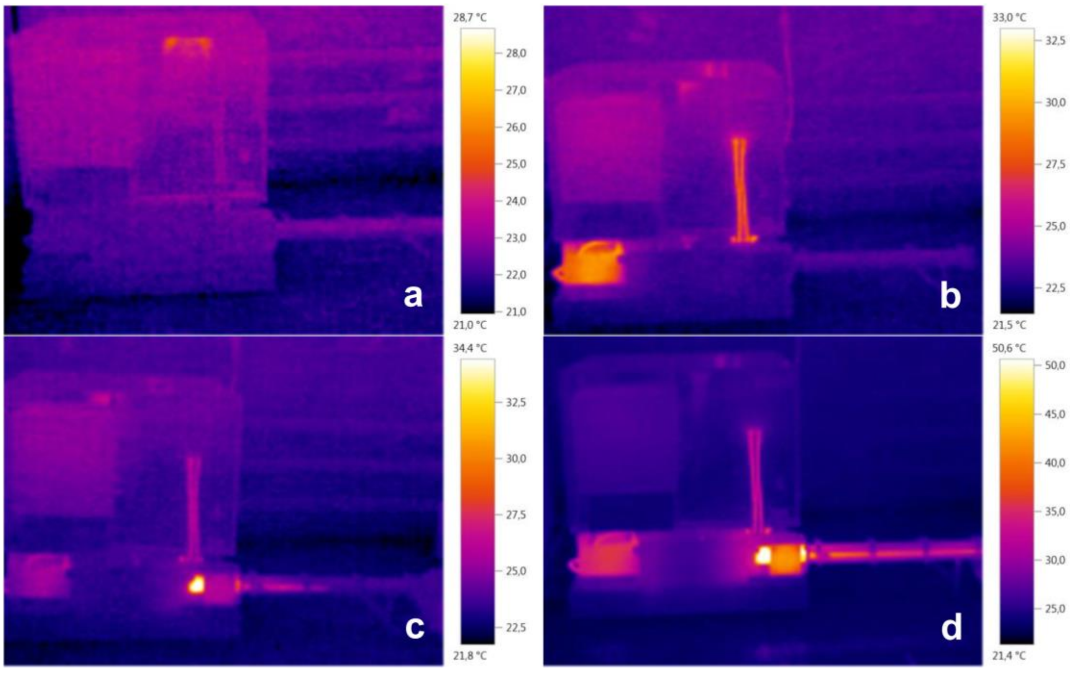


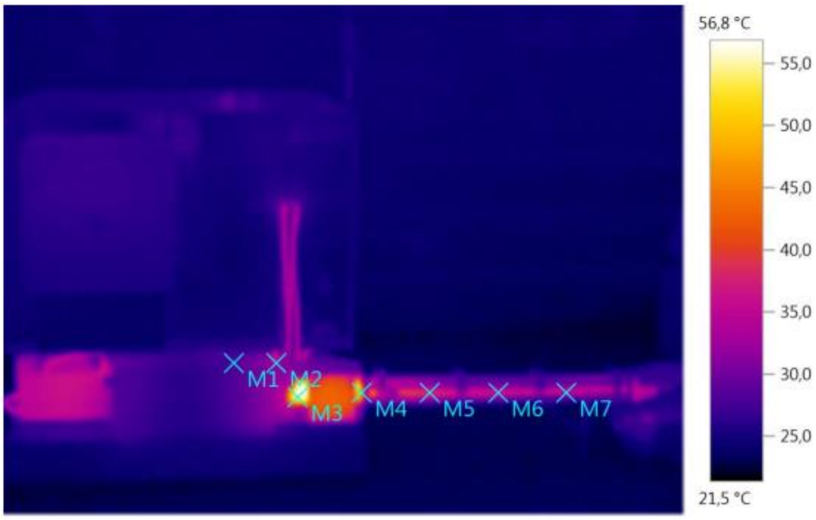
Figure 45. Thermography of working stages of the HBP: a-beginning of the work without material; b-after 60 minutes of the work without material; c-beginning of the work with the material; d-after 60 minutes of the work with the material.

In order to exclude the influence of external factors on the process measurement of temperature was performed the thermal analysis of BP before work, in the work without material during 60 minutes, beginning of the work with material and work with the material during 60 minutes.

At the beginning of work (**Figure 45 a**), are not distinguishing any specific hot parts of HBP that can characterize its active work. After the operational time of 60 minutes without material on HBP can be observed the parts that generate the heat (**Figure 45 b**). Those parts relate to the hydraulic drive system of the press (the main hydraulic cylinder and the flexible hose of the hydraulic system). During the thermal analysis was not observed any influence of the heat of these parts (heat-exchange) on the temperature of active pressing parts or pressed biomass.

The beginning of the work of HBP with the material is characterized by the active heat generation produced by the main pressing parts (**Figure 45 c**).

In the result of the briquetting process of equipment after 60 minutes of work (with the material) the temperature of the main pressing parts considerably increased, as well the temperature of the produced briquettes (**Figure 45 d**).



Number of hot spot	Value of temperature (°C)	Coefficient of emissivity	Reflection temperature (°C)
M1	28.40	0.95	22.00
M2	32.90	0.95	22.00
M3	50.00	0.95	22.00
M4	55.70	0.95	22.00
M5	39.00	0.95	22.00
M6	35.90	0.95	22.00
M7	34.40	0.95	22.00

Figure 46. The thermal analysis of HBP during briquetting

An example can serve the result of thermal analyses of wood biomass presented on **Figure 46** when during the measurement the maximal temperature of the die reached 55°C (hot spot M4) the value of and of briquettes 39 (hot spot M5).

Based on the fact that maximally developed temperature during briquetting on HBP did not exceed 60 °C (in case of the die and of briquettes it was 23 °C), it should be assumed that the lignin can change its state and act at a lower temperature in the briquetting process than it was considered before. The additional organic components (pectin, extractives, sugars, starches) also can influence the particles binding process at these temperatures. That needs additional research.

5.4 Research of the structural integrity of briquettes

During the research of the briquetting process of HBP, the inhomogeneity in the structure of briquettes was observed. The same problem is characteristic for production on many types of HBP that have the analogic principle of work, even for new ones produced by the Briklis company.

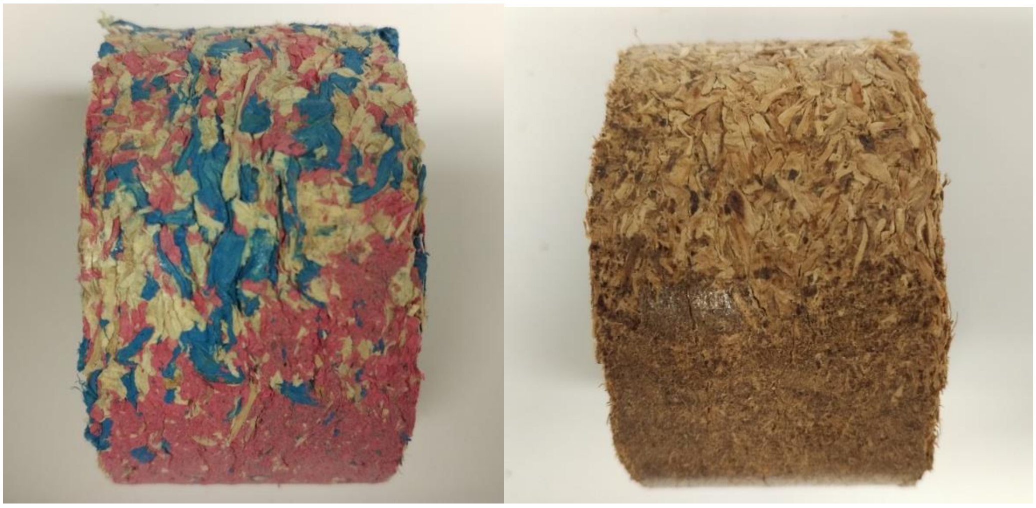


Figure 47. The result of the segregation of particles in the structure of briquettes

Phenomenon of the stratification (segregation) of the particle in the structure of briquettes takes place (**Figure 47**). Segregation is considered to be the opposite process of homogenisation (Gyenis 2001). The particles of bigger size are located on the top side and the smaller size particles are located on the bottom side of briquette

(**Figure 48**). The **structural disintegration of briquettes leads to** the **poor agglomeration** of the particles and **apparition of defects** (cracks, voids).

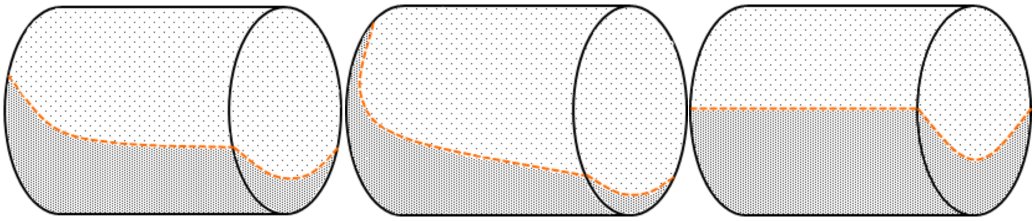


Figure 48. The prevalent ways of segregation of particles in the briquettes

It was observed that initial segregation of the particles starts in the hopper of HBP during the mixing of biomass by the agitator with vanes (**Figure 49**). The segregation of the particles during the mixing of biomass creates difficulties in its efficient use (Jacob et al. 2013).

Figure 49. The process of biomass agitating in the hopper of HBP

For better analysis and determination of the reason for particles segregation, in the briquetting process coloured wood biomass was used that consists of the particles of three different fractions – big (particles with size of 40 - 15 mm), medium (particles with size of 15 - 7 mm) and small (particles with size less than 7 mm).

By the agitating, **particles of smaller size migrate to the bottom side of the** hopper, creating the dense layer of the particles mostly of the same size.

***Figure 50**. The segregation of the particles in the hopper of HBP.*

The **particles of bigger size are displaced to the top** of the mixed material. Particles rearrangement takes place (**Figure 50**).The smaller size particles get first into the pressing chamber. The first obtained briquettes preponderantly consist of the particles of smaller size. In the Figure 51 is present the result of the image analysis of the briquettes' structure made from the material added from the hopper.

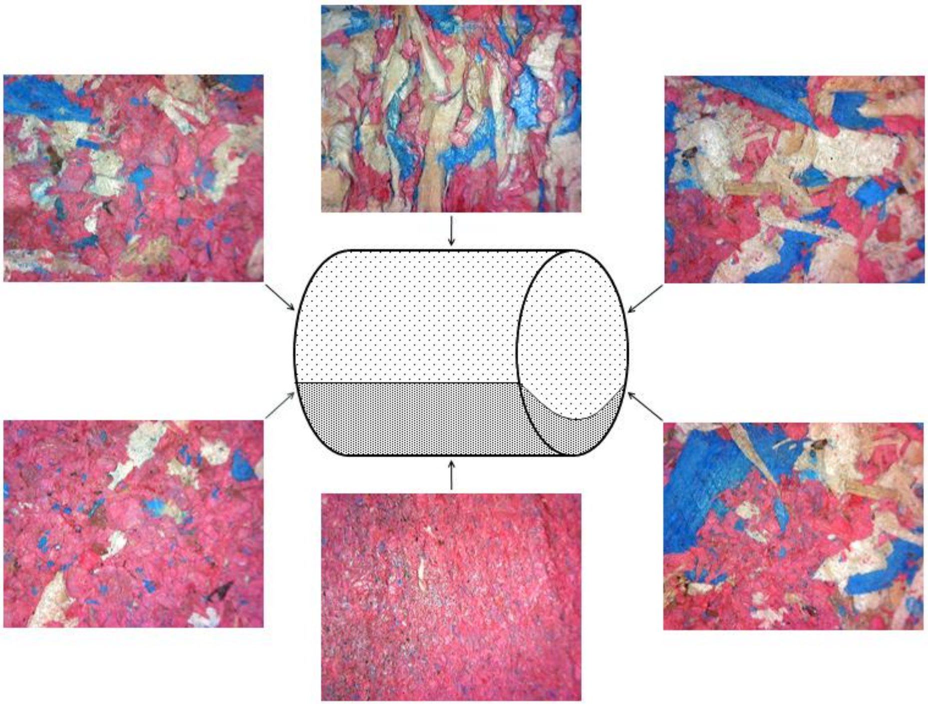


***Figure 51**. The structure of briquettes made from the material added from the hopper.*

But, as the research showed, the main segregation of the particles takes place in the pressing chamber of HBP and partially happens in the die. Heterogeneity of feedstock composition is caused by the size, shape and density of particles that displace under the action of the gravitational forces (Enstad 2001).

In the **Figure 51** is present the result of the image analysis of the structure of briquettes made from the material added directly into the pressing chamber, avoiding the mixing by the agitator of the hopper.

The directly added raw material into the pressing chamber was carefully mixed before use. Despite that the material before pressing had a homogeneous structure the obtained briquettes were with heterogeneous structure. In this case the segregation is more pronounced. More results of the macro analysis of the structure of briquettes are presented in the **Annex 7**.

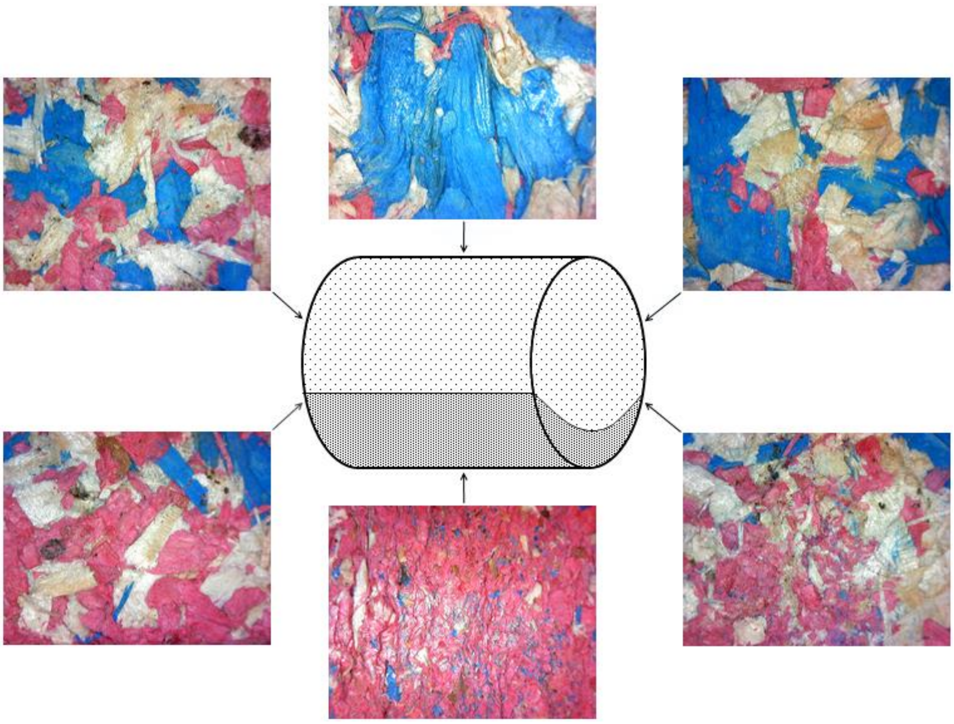


***Figure 52**. The structure of briquettes made from the material added directly into the pressing chamber*

The segregation of particles takes place in the SBP as well, but only in the hopper. During the densification in SBP, the phenomenon of clear segregation of particles was not observed (**Figure 52**).

Figure 53*. *The view of briquette made on SBP from the coloured material.

Usual **briquettes obtained on the SBP does not have such shortcoming**, their structure is homogeneous and dens, without stratification and cracks (Bhattacharya et al. 2002). The main **advantage of SBP is** the **production of briquettes of a homogeneous structure** due to the continuous mixing by screw (agitation) of feedstock during the densification process.

The use of feedstock composed of particles with a different size that differs significantly is the reason for inhomogeneous structure and as a result stratification of the mixture (Rumpf 1990).

It was observed that **briquettes made from biomass of smaller fraction**, **have more homogenous structure**. The densified biofuel made from the raw material with a homogeneous structure has better compressive strength and density (Wang et al. 2018). One of the ways to reduce the segregation of material and to achieve homogeneity of the mixture is to give uniform size to the particle (Bates 2001).

The improvement of the structure of briquettes can be done by the use of a few steps of grinding (of smaller size) for the production of the raw material (Hann & Strazisar 2007; Naimi et al. 2012). Grinding of the material into smaller size fraction, gives the possibility to obtain biomass with homogenous structure (Enstad 2001). The obtaining of the raw material of heterogeneous composition is also possible by its separating by screening (dividing) into a few fractions with, followed by their separately briquetting afterwards (Bates 2001).

6. CONCLUSION AND RECOMMENDATIONS

Renewable energy obtained from biomass represents a reliable type of energy, the interest of which will only increase with the growth of energy demand. Special interest has the solid densified biofuel that is the most accessible form of fuel obtained from biomass in the present and can assure with the cheap energy. Taking into consideration the importance of the solid biofuel for the production of the energy it is necessary to pay more attention to its quality and efficiency of production. The performed research work indicated that only correct use of pressing equipment and efficient use of raw material in the production can guaranty the obtaining of high-quality briquettes.

Both types of briquetting presses applied for the research are reliable equipment of high quality. However, the efficient work with them is possible only in case of using the most suitable raw material, initially optimally processed for each type of briquetting technology.

Materials of small particle size are more suitable for the production. Smaller particles permit to obtain briquettes with dense structure and high mechanical durability. This was partially confirmed by **Hypothesis 1.** The use of material with optimal fraction for each type of the studied briquetting technology can favourite the obtaining of briquettes with much more dense structure without additional grinding of raw materials. The research demonstrated that all three fractions of materials can be used successfully. But as optimal can be considered biomass of fraction 8 and 4 mm.

Also, crushed into smaller fraction biomass has a homogenous structure that prevents the segregation of the particles during densification and as a result, increases the quality of briquettes.

Even though the grinding of the raw material into the smaller fractions requires more consumption of energy, the use of the biomass of a smaller size is more preferable for the briquetting of biomass on HBP. The measurements demonstrated that the use of raw material of smaller fraction has a positive impact on the rise of the temperature during the briquetting process that favourably affects the quality of biofuel.

The study fully confirmed **Hypothesis 2**. After the selection of raw materials more suitable for densification on each type of briquetting press, it is expected to obtain high-quality briquettes with increased strength.

The performed research has indicated that for the production of high-quality solid biofuel on the hydraulic briquetting press, fibrous or wooden materials of high density are more suitable. The general evaluation demonstrated that from all tested types of biomass densified on SPB were received briquettes of high-quality. That's why SBP can be considered as more universal equipment for the briquetting of biomass.

Due to the fact that temperature has a decisive role in the briquetting technology of SBP, it was necessary to assure a special attention to the determination of the optimal operating temperature. During the research it was determined that the most suitable working temperature of the press is 160 – 180 °C for briquetting at the operating mode with the speed 1, and 180 -215 °C for the operation mode with the speed 3.

Besides this, it was observed that the rotation speed of the screw is important not only for the productivity of the equipment but also it influences the development of internal heat of the briquettes. The performed research of the properties of obtained briquettes confirmed that briquettes exposed to the higher heat influence have higher quality. These briquettes are possible to obtain at the operation mode with the speed 3.

The screw briquetting press represents an equipment that can produce high-quality solid biofuel, however, only in case of respecting the optimal operational modes and necessary working temperature. By respecting of optimal modes of work, suitable working temperature and elimination of shortcomings of the equipment it will be possible:

- To improve the densification process and as a result the quality of final product;
- To make the work of equipment reliable and efficient;
- To make the operation on equipment easier and to improve the working conditions of the operating personnel;
- To improve the working safety during the densification.

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8. ANNEX

Annex 1. The briquetting equipment applied for the densification study of biomass.

- **Figure 1.1** Hydraulic briquetting press HLS 50 Briklis
- **Figure 1.2.** Screw briquetting press BSL Briklis

Annex 2. Detailed determination of gross calorific value.

- **Table 2.1.** The detailed determination of gross calorific value for ATPW
- **Table 2.2.** The detailed determination of gross calorific value for MS
- **Table 2.3.** The detailed determination of gross calorific value for MG
- **Table 2.4.** The detailed determination of gross calorific value for HP

Annex 3. Thermal analysis of the densification process.

- **Figure 3.1.** The view of the die (HBP) in the various spectrum during thermal analysis
- **Figure 3.2.** Parts of the HBP with the highest temperature on a segment P1(during 60 minutes of work without material)
- **Figure 3.3.** Parts of the HBP with the highest temperature on a segment P1 (in process of briquetting)
- **Figure 3.4.** Distribution of high temperature the die and screw

Annex 4. The results of temperature measurements in specific areas of HBP during densification process

- **Table 4.1.** The results of temperature measurements in specific areas for ATPW12
- **Table 4.2.** The results of temperature measurements in specific areas for ATPW8
- **Table 4.3.** The results of temperature measurements in specific areas for ATPW4
- **Table 4.4.** The results of temperature measurements in specific areas for HP12
- **Table 4.5.** The results of temperature measurements in specific areas for HP8
- **Table 4.6.** The results of temperature measurements in specific areas for HP4

- **Table 4.7.** The results of temperature measurements in specific areas for MG12
- **Table 4.8.** The results of temperature measurements in specific areas for MG8
- **Table 4.9.** The results of temperature measurements in specific areas for M**G4**
- **Table 4.10.** The results of temperature measurements in specific areas for MS12
- **Table 4.11.** The results of temperature measurements in specific areas for MS8
- **Table 4.12.** The results of temperature measurements in specific areas for MS4

Annex 5. The results of ANOVA single factor analysis of temperature variance

- **Table 5.1.** The results of ANOVA single factor analysis of temperature variance for ATPW12
- **Table 5.2.** The results of ANOVA single factor analysis of temperature variance for ATPW8
- **Table 5.3.** The results of ANOVA single factor analysis of temperature variance for ATWP4
- **Table 5.4.** The results of ANOVA single factor analysis of temperature variance for HP12
- **Table 5.5.** The results of ANOVA single factor analysis of temperature variance for HP8
- **Table 5.6.** The results of ANOVA single factor analysis of temperature variance for HP4
- **Table 5.7.** The results of ANOVA single factor analysis of temperature variance for MG12
- **Table 5.8.** The results of ANOVA single factor analysis of temperature variance for MG8
- **Table 5.9.** The results of ANOVA single factor analysis of temperature variance for MG4
- **Table 5.10.** The results of ANOVA single factor analysis of temperature variance for MS12

Annex 1. The briquetting equipment applied for the densification study of biomass.

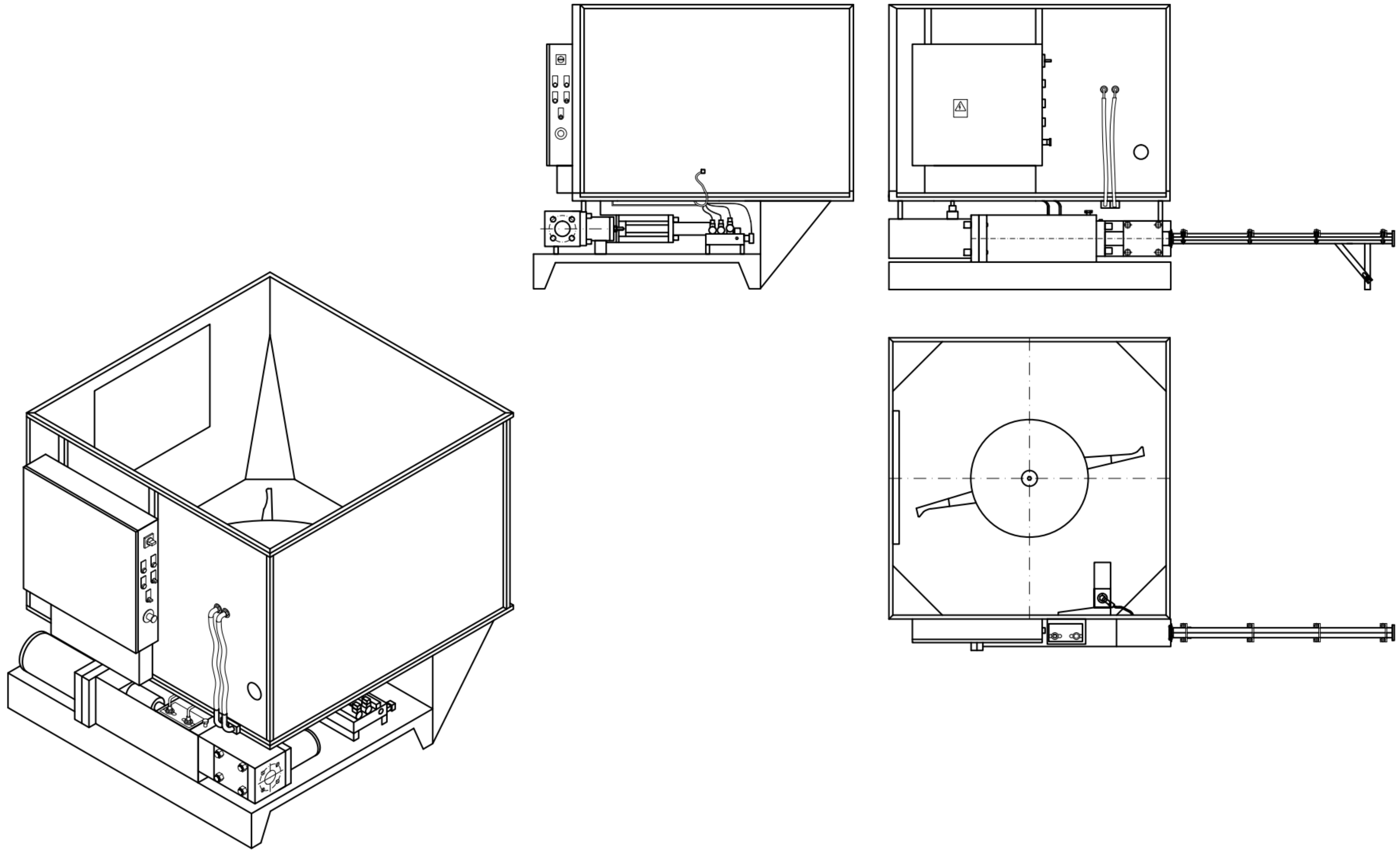

Figure 1.1 Hydraulic briquetting press HLS 50 Briklis

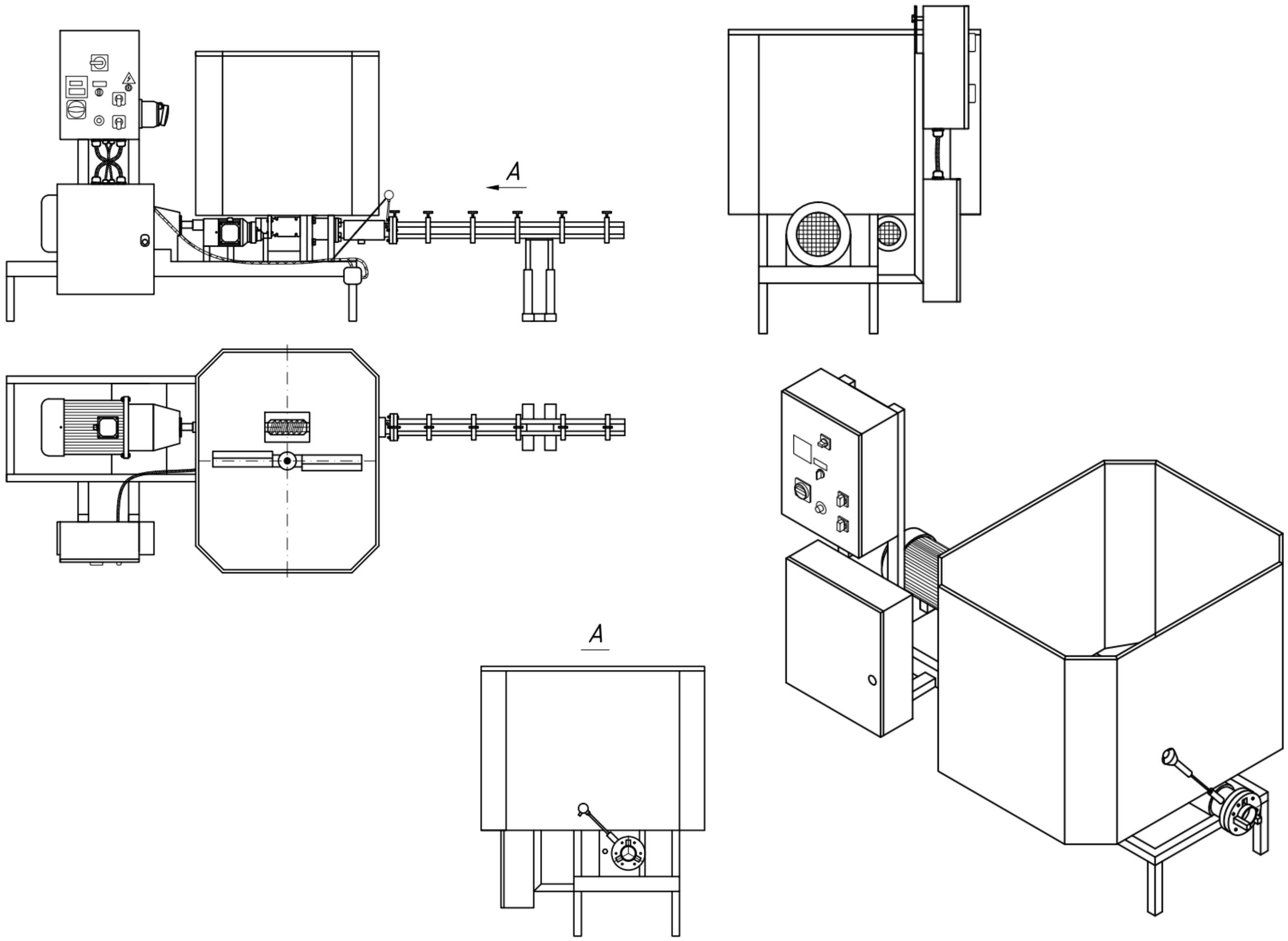

Figure 1.2. Screw briquetting press BSL Briklis

Annex 2. Detailed determination of gross calorific value.

Table 2.1. The detailed determination of gross calorific value for ATPW

Type of tested biomass or solid biofuel	Number of repetitions	The mass of ignition wire (g)	The mass of combustion bag (g)	The mass of sample (g)	Corrected temperature rise (°C)	Effective heat capacity of calorimeter ($J.°C^{-1}$)	Gross calorific value of ignition wire ($J.°C^{-1}$)	Gross calorific value of combustion bag ($J.°C^{-1}$)	Gross calorific value of the sample ($J.°C^{-1}$)	Average value of GCV of the sample ($J.°C^{-1}$)
ATPW	1	0.0085	0.0613	0.5547	1.30946	9099	51.0	997.9027	19588.74	19551.17
	2	0.0087	0.0620	0.5400	1.27703	9099	52.2	1009.298	19552.22	
	3	0.0089	0.0608	0.5627	1.32134	9099	53.4	989.7632	19512.55	
Standard deviation										38.1078
Quantity of samples										3
Confidence coefficient										1.96
Confidence interval										43.12304
Upper bound										19594.29
Lower bound										19508.04
Max										19588.74
Min										19512.55
Range										76.19388

Table 2.2. The detailed determination of gross calorific value for MS

Type of tested biomass or solid biofuel	Number of repetitions	The mass of ignition wire (g)	The mass of combustion bag (g)	The mass of sample (g)	Corrected temperature rise (°C)	Effective heat capacity of calorimeter ($J.°C^{-1}$)	Gross calorific value of ignition wire ($J.°C^{-1}$)	Gross calorific value of combustion bag ($J.°C^{-1}$)	Gross calorific value of the sample ($J.°C^{-1}$)	Average value of GCV of the sample ($J.°C^{-1}$)
MS	1	0.0092	0.0615	0.564	1.23470	9099	55.2	1001.159	18627.70	18607.2
	2	0.0085	0.0636	0.5335	1.20997	9099	51.0	1035.344	18600.14	
	3	0.0091	0.0605	0.5359	1.20935	9099	54.6	984.8795	18593.76	
Standard deviation										18.04006
Quantity of samples										3
Confidence coefficient										1.96
Confidence interval										20.41425
Upper bound										18627.61
Lower bound										18586.79
Max										18627.7
Min										18593.76
Range										33.94247

Table 2.3. The detailed determination of gross calorific value for MG

Type of tested biomass or solid biofuel	Number of repetitions	The mass of ignition wire (g)	The mass of combustion bag (g)	The mass of sample (g)	Corrected temperature rise (°C)	Effective heat capacity of calorimeter ($J.°C^{-1}$)	Gross calorific value of ignition wire ($J.°C^{-1}$)	Gross calorific value of combustion bag ($J.°C^{-1}$)	Gross calorific value of the sample ($J.°C^{-1}$)	Average value of GCV of the sample ($J.°C^{-1}$)
MG	1	0.0087	0.0604	0.5340	1.21645	9099	52.2	983.2516	18788.44	18739.44
	2	0.0088	0.0625	0.5536	1.25626	9099	52.8	1017.438	18714.73	
	3	0.0087	0.0612	0.5609	1.26891	9099	52.2	996.2748	18715.17	
Standard deviation										42.43203
Quantity of samples										3
Confidence coefficient										1.96
Confidence interval										48.01636
Upper bound										18787.46
Lower bound										18691.43
Max										18788.44
Min										18714.73
Range										73.71411

Table 2.4. The detailed determination of gross calorific value for HP

Type of tested biomass or solid biofuel	Number of repetitions	The mass of ignition wire (g)	The mass of combustion bag (g)	The mass of sample (g)	Corrected temperature rise (°C)	Effective heat capacity of calorimeter (J.°C^{-1})	Gross calorific value of ignition wire (J.°C^{-1})	Gross calorific value of combustion bag (J.°C^{-1})	Gross calorific value of the sample (J.°C^{-1})	Average value of GCV of the sample (J.°C^{-1})
HP	1	0.0087	0.0618	0.5246	1.16991	9099	52.2	1006.042	18274.44	18296.19
	2	0.0088	0.0596	0.5581	1.23623	9099	52.8	970.2284	18321.86	
	3	0.0093	0.0611	0.5302	1.18134	9099	55.8	994.6469	18292.28	
Standard deviation										23.95155
Quantity of samples										3
Confidence coefficient										1.96
Confidence interval										27.10373
Upper bound										18323.29
Lower bound										18269.09
Max										18321.86
Min										18274.44
Range										47.42141

Annex 3. Thermal analysis of the densification process.

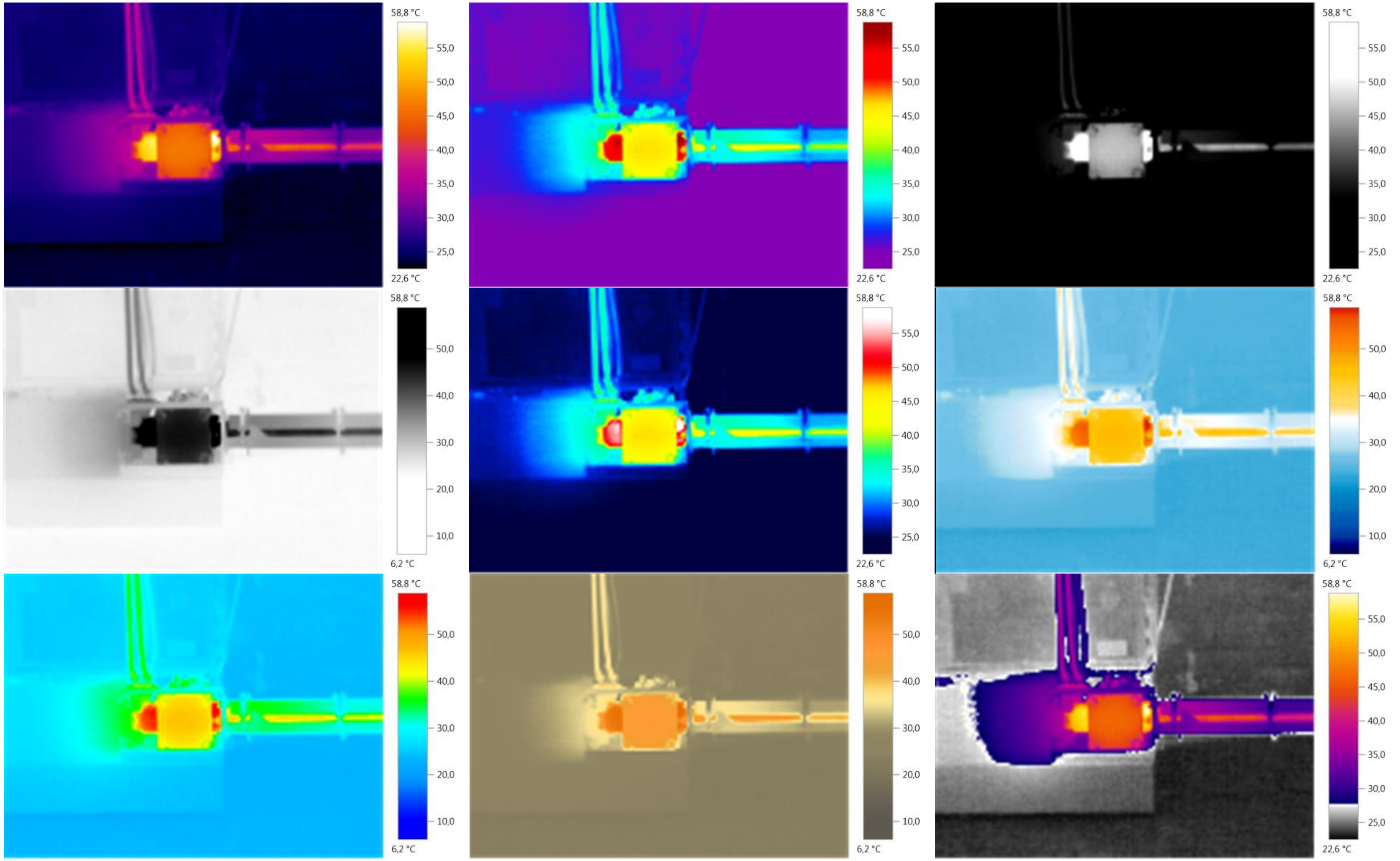

Figure 3.1. The view of the die (HBP) in the various spectrum during thermal analysis

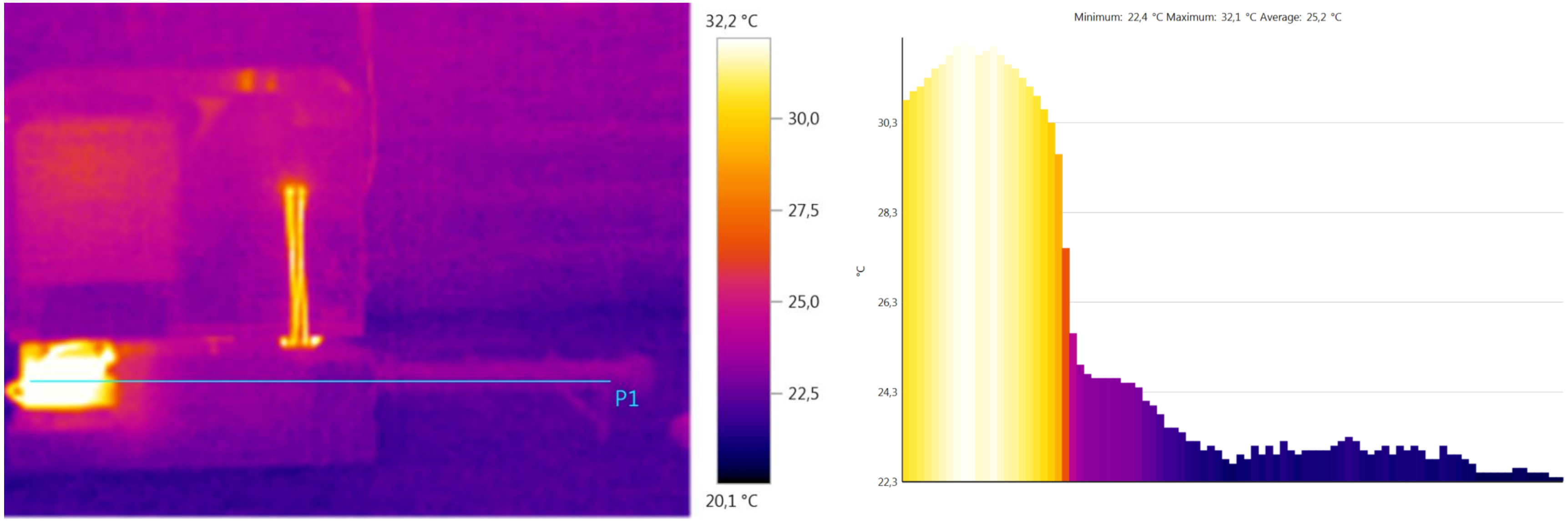

Figure 3.2. Parts of the HBP with the highest temperature on a segment P1(during 60 minutes of work without material)

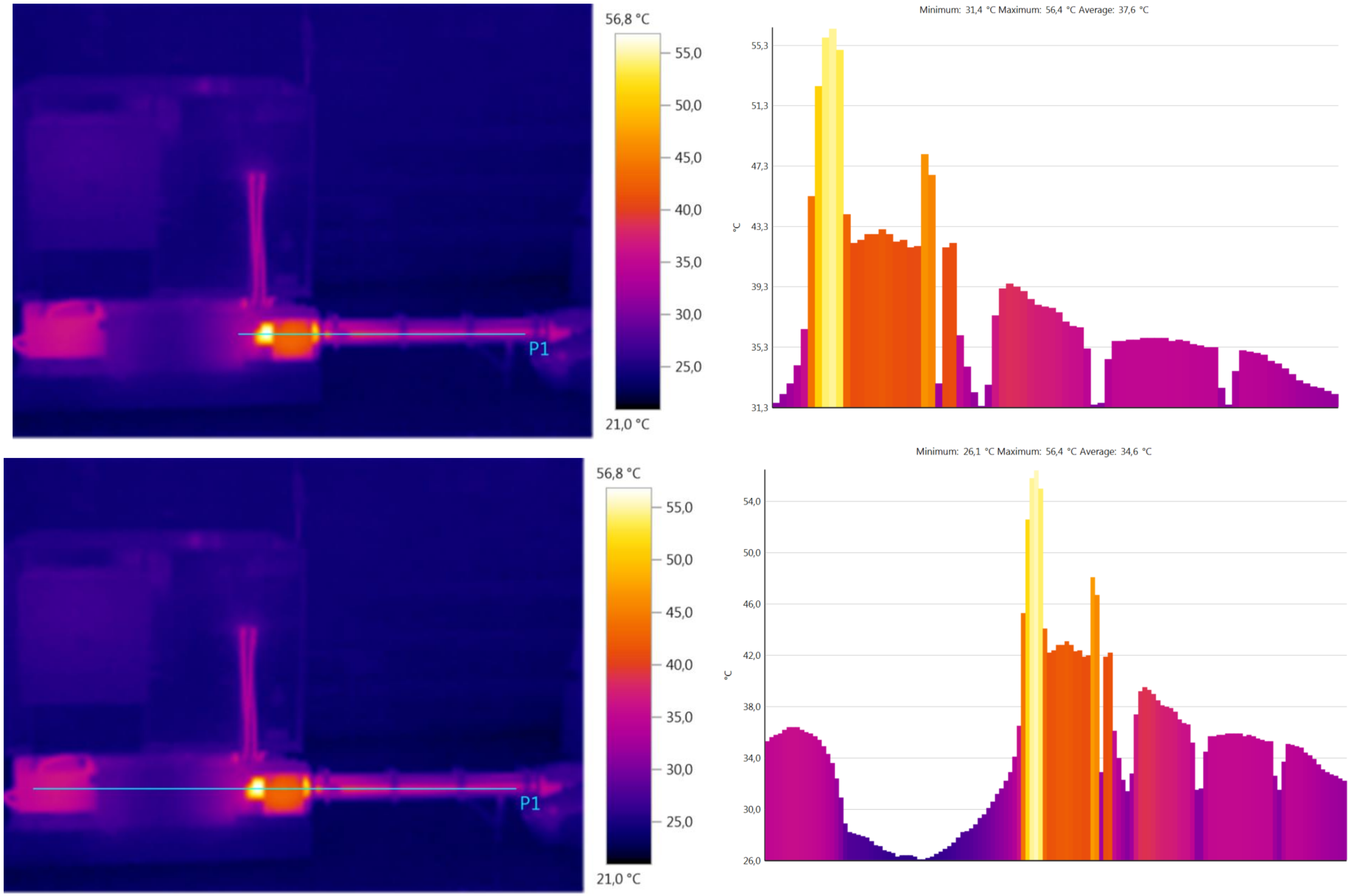

Figure 3.3. Parts of the HBP with the highest temperature on a segment P1 (in process of briquetting)

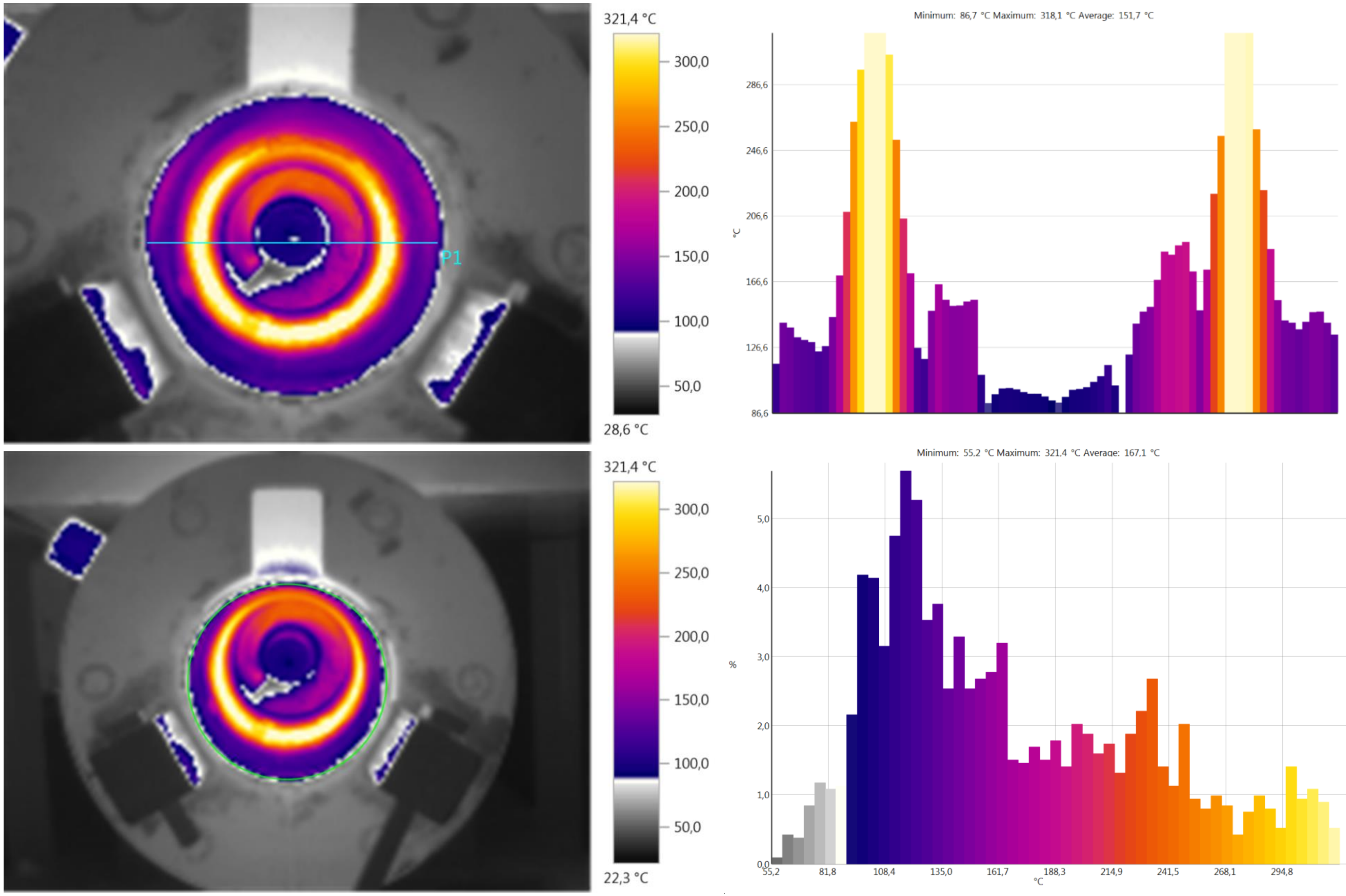

Figure 3.4. Distribution of high temperature the die and screw

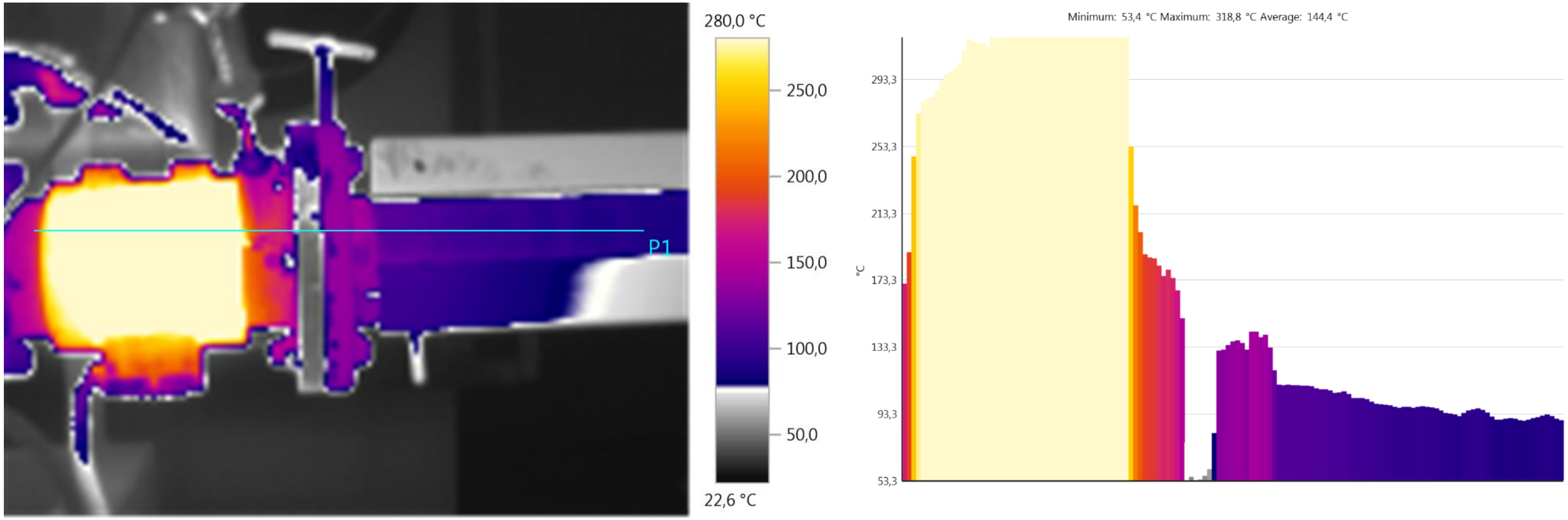

Figure 3.5. Parts of the SBP with the highest temperature on a segment P1 (in process of briquetting)

Annex 4. The results of temperature measurements in specific areas of HBP during densification process

Table 4.1. The results of temperature measurements in specific areas for ATPW12

Type of raw material	**Time (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes (°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
ATPW12	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	24.60	25.40	25.90	**25.30**	35.80	37.00	39.20	**37.33**	30.20	28.00	27.70	26.80	**28.18**
	20	25.50	26.20	26.90	**26.20**	41.30	44.10	45.40	**43.60**	34.40	32.80	31.50	30.80	**32.38**
	30	26.90	27.20	28.30	**27.47**	43.90	47.50	48.70	**46.70**	37.70	34.50	33.60	32.70	**34.63**
	40	27.10	28.90	29.70	**28.57**	45.20	48.70	50.20	**48.03**	39.00	36.90	35.70	34.90	**36.63**
	50	28.40	29.60	30.10	**29.37**	48.10	51.00	52.90	**50.67**	40.40	37.30	36.70	35.00	**37.35**
	60	29.30	30.00	30.40	**29.90**	51.40	53.60	54.70	**53.23**	41.20	39.60	38.90	38.00	**39.43**

Table 4.2. The results of temperature measurements in specific areas for ATPW8

Type of raw material	**Time (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes (°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
ATPW8	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	25.40	26.30	27.10	**26.27**	36.10	38.90	40.00	**38.33**	32.50	29.70	28.00	27.20	**29.35**
	20	26.20	27.00	28.40	**27.20**	43.30	45.10	46.50	**44.97**	37.40	34.80	32.30	31.80	**34.08**
	30	26.90	28.30	29.60	**28.27**	47.60	49.10	50.60	**49.10**	40.00	37.70	36.10	35.40	**37.30**
	40	28.50	29.40	30.20	**29.37**	50.40	52.70	54.00	**52.37**	42.20	39.30	37.40	35.80	**38.68**
	50	28.90	30.30	32.00	**30.40**	52.40	54.80	56.40	**54.53**	44.10	41.00	38.50	37.20	**40.20**
	60	29.70	31.90	33.70	**31.77**	53.90	56.50	57.70	**56.03**	46.20	42.50	40.60	39.70	**42.25**

Table 4.3. The results of temperature measurements in specific areas for ATPW4

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
ATPW4	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	27.60	29.00	30.30	**28.97**	39.90	41.80	43.90	**41.87**	35.40	32.10	31.50	30.30	**32.33**
	20	29.20	30.50	31.60	**30.43**	45.30	46.70	48.10	**46.70**	39.00	36.20	35.70	34.10	**36.25**
	30	30.90	32.70	33.70	**32.43**	48.80	50.90	52.20	**50.63**	42.20	38.70	37.40	36.80	**38.78**
	40	32.80	34.60	35.00	**34.13**	51.50	53.20	56.50	**53.73**	43.90	41.00	39.90	38.90	**40.93**
	50	33.90	36.10	36.90	**35.63**	53.00	54.70	57.10	**54.93**	45.40	43.70	42.20	40.00	**42.83**
	60	34.90	37.90	39.70	**37.50**	56.70	56.40	59.00	**57.37**	47.60	44.70	43.20	42.60	**44.53**

Table 4.4. The results of temperature measurements in specific areas for HP12

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
HP12	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	22.90	23.30	23.90	**23.37**	27.30	28.90	29.40	**28.53**	23.90	23.00	22.70	22.10	**22.93**
	20	23.40	24.10	24.80	**24.10**	31.60	33.00	35.30	**33.30**	26.00	25.10	24.30	23.70	**24.78**
	30	24.20	25.40	26.20	**25.27**	35.70	36.80	37.70	**36.73**	27.20	26.40	25.60	24.60	**25.95**
	40	25.60	26.30	27.30	**26.40**	38.30	40.20	41.80	**40.10**	29.40	27.00	26.40	25.50	**27.08**
	50	26.40	26.90	28.20	**27.17**	39.90	41.80	43.00	**41.57**	30.50	27.90	26.70	25.80	**27.73**
	60	27.10	27.50	29.30	**27.97**	41.40	42.60	44.10	**42.70**	31.10	29.20	27.50	26.40	**28.55**

Table 4.5. The results of temperature measurements in specific areas for HP8

Type of raw material	**Time (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes(°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
HP8	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	23.70	24.30	25.30	**24.43**	28.60	30.00	31.20	**29.93**	24.70	24.10	23.60	23.30	**23.93**
	20	24.50	25.60	26.70	**25.60**	35.50	37.10	38.40	**37.00**	28.40	26.80	25.50	24.40	**26.28**
	30	26.00	26.70	27.50	**26.73**	39.00	40.60	41.70	**40.43**	29.60	27.30	26.20	25.30	**27.10**
	40	27.10	28.30	29.50	**28.30**	41.80	42.90	44.60	**43.10**	31.30	28.70	27.10	26.60	**28.43**
	50	28.20	29.40	30.50	**29.37**	43.70	44.90	45.30	**44.63**	33.20	29.70	28.40	27.50	**29.70**
	60	29.40	30.00	31.90	**30.43**	44.70	45.30	46.60	**45.53**	36.50	31.20	29.80	28.80	**31.58**

Table 4.6. The results of temperature measurements in specific areas for HP4

Type of raw material	**Time. (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes (°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
HP4	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21	**21.00**
	10	24.90	26.30	27.70	**26.30**	29.20	31.50	32.40	**31.03**	25.50	24.60	23.90	23.60	**24.40**
	20	25.70	27.40	29.50	**27.53**	36.70	38.10	40.30	**38.37**	28.90	26.70	25.70	24.00	**26.33**
	30	27.10	28.20	30.00	**28.43**	39.90	41.60	43.40	**41.63**	30.70	28.30	27.20	26.50	**28.18**
	40	28.50	29.40	31.70	**29.87**	43.70	44.80	46.20	**44.90**	34.80	31.20	30.50	29.40	**31.48**
	50	29.70	30.90	32.60	**31.07**	45.40	46.90	48.00	**46.77**	37.80	33.30	32.40	31.80	**33.83**
	60	31.90	32.40	34.50	**32.93**	47.00	47.90	49.00	**47.97**	40.00	35.60	33.20	32.50	**35.33**

Table 4.7. The results of temperature measurements in specific areas for MG12

Type of raw material	**Time (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes (°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MG12	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	23.00	23.60	23.90	**23.50**	29.50	30.70	32.10	**30.77**	24.90	24.10	23.70	23.20	**23.98**
	20	23.60	24.40	25.00	**24.33**	35.40	38.20	39.80	**37.80**	28.80	26.70	25.50	24.50	**26.38**
	30	24.50	25.90	26.50	**25.63**	38.80	41.80	42.30	**40.97**	31.50	28.10	27.30	26.60	**28.38**
	40	25.60	26.70	27.80	**26.70**	41.30	44.10	44.90	**43.43**	35.10	31.70	30.20	29.20	**31.55**
	50	26.90	27.40	29.00	**27.77**	44.00	45.20	47.00	**45.40**	37.00	33.90	31.90	30.70	**33.38**
	60	27.50	29.10	30.30	**28.97**	46.60	47.60	48.40	**47.53**	38.00	34.50	33.40	32.50	**34.60**

Table 4.8. The results of temperature measurements in specific areas for MG8

Type of raw material	**Time. (minutes)**	**The temperature of the pressing chamber (°C)**				**The temperature of the die (°C)**				**The temperature of briquettes (°C)**				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MG8	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	24.50	25.30	26.10	**25.30**	30.40	32.30	33.70	**32.13**	26.90	26.10	25.10	24.30	**25.60**
	20	25.70	26.80	27.40	**26.63**	35.80	36.40	37.10	**36.43**	30.40	28.30	27.60	26.50	**28.20**
	30	26.30	27.80	29.00	**27.70**	39.10	41.60	41.90	**40.87**	32.60	29.90	30.20	29.70	**30.60**
	40	27.80	28.90	30.10	**28.93**	42.70	44.10	46.40	**44.40**	36.00	34.10	33.10	31.70	**33.73**
	50	28.60	29.70	31.90	**30.07**	46.20	45.00	48.20	**46.47**	37.90	35.10	33.40	32.40	**34.70**
	60	29.60	31.20	32.40	**31.07**	47.80	49.30	50.00	**49.03**	39.60	36.20	35.90	34.80	**36.63**

Table 4.9. The results of temperature measurements in specific areas for M**G4**

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MG4	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	25.90	26.60	27.60	**26.70**	33.00	34.20	34.90	**34.03**	27.90	26.00	25.30	24.80	**26.00**
	20	26.70	27.40	28.50	**27.53**	39.50	41.10	42.40	**41.00**	32.90	31.20	30.30	29.70	**31.03**
	30	27.50	28.90	29.80	**28.73**	42.60	44.20	47.00	**44.60**	36.00	34.10	33.60	32.60	**34.08**
	40	28.40	29.70	30.40	**29.50**	44.50	45.10	48.90	**46.17**	37.80	35.20	34.50	33.00	**35.13**
	50	29.60	31.20	33.00	**31.27**	46.10	47.50	49.90	**47.83**	40.80	37.50	35.80	34.30	**37.10**
	60	31.10	32.30	33.80	**32.40**	49.10	49.90	51.90	**50.30**	42.70	38.50	36.50	35.30	**38.25**

Table 4.10. The results of temperature measurements in specific areas for MS12

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MS12	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	23.10	23.90	24.00	**23.67**	30.60	32.10	33.60	**32.10**	25.40	24.90	24.00	23.60	**24.48**
	20	23.90	24.70	25.10	**24.57**	36.10	37.70	40.80	**38.20**	30.90	27.60	26.40	25.70	**27.65**
	30	24.10	25.40	26.10	**25.20**	40.80	42.70	44.90	**42.80**	34.50	29.30	28.30	25.90	**29.50**
	40	25.70	26.60	28.20	**26.83**	43.30	44.20	46.80	**44.77**	36.60	33.80	30.50	28.60	**32.38**
	50	27.70	28.20	29.70	**28.53**	45.10	45.60	49.30	**46.67**	37.90	34.80	32.00	31.30	**34.00**
	60	28.90	29.50	31.00	**29.80**	47.00	48.20	50.20	**48.47**	39.10	35.80	34.90	33.30	**35.78**

Table 4.11. The results of temperature measurements in specific areas for MS8

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MS8	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	25.20	26.30	27.50	**26.33**	32.30	33.30	33.90	**33.17**	27.90	26.60	25.80	24.00	**26.08**
	20	26.90	27.80	28.30	**27.67**	38.90	40.00	42.10	**40.33**	32.40	30.10	29.30	28.70	**30.13**
	30	27.70	28.10	29.40	**28.40**	41.60	43.40	44.20	**43.07**	35.40	33.50	31.00	30.20	**32.53**
	40	28.50	29.50	30.80	**29.60**	43.80	45.30	46.00	**45.03**	37.00	35.10	34.60	33.70	**35.10**
	50	29.90	30.70	32.90	**31.17**	46.50	47.10	48.90	**47.50**	38.80	36.30	35.50	34.00	**36.15**
	60	31.20	32.00	33.60	**32.27**	47.70	49.60	51.90	**49.73**	41.20	38.80	36.20	35.30	**37.88**

Table 4.12. The results of temperature measurements in specific areas for MS4

Type of raw material	Time (minutes)	The temperature of the pressing chamber (°C)				The temperature of the die (°C)				The temperature of briquettes (°C)				
		P1	P2	P3	Pav	D1	D2	D3	Dav	B1	B2	B3	B4	Bav
MS4	0	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	**21.00**	21.00	21.00	21.00	21.00	**21.00**
	10	26.50	27.40	28.20	**27.37**	33.80	34.00	35.50	**34.43**	28.00	26.90	26.10	25.70	**26.68**
	20	27.10	27.90	29.00	**28.00**	40.40	42.10	43.70	**42.07**	33.40	31.10	29.50	28.90	**30.73**
	30	28.20	29.60	30.70	**29.50**	42.60	44.30	46.20	**44.37**	36.70	33.90	32.70	31.50	**33.70**
	40	29.50	30.30	33.00	**30.93**	43.60	45.80	47.90	**45.77**	38.00	36.20	34.80	33.60	**35.65**
	50	30.30	31.40	33.90	**31.87**	46.60	47.90	49.80	**48.10**	39.60	37.20	36.10	35.30	**37.05**
	60	31.70	32.20	34.90	**32.93**	48.50	49.70	52.00	**50.07**	41.80	38.80	36.90	36.00	**38.38**

Annex 5. The results of ANOVA single factor analysis of temperature variance

Table 5.1. The results of ANOVA single factor analysis of temperature variance for ATPW12

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	75.90	25.30	0.43
Row 3	3	78.60	26.20	0.49
Row 4	3	82.40	27.47	0.54
Row 5	3	85.70	28.57	1.77
Row 6	3	88.10	29.37	0.76
Row 7	3	89.70	29.90	0.31

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	536	6	89.33635	41.83906	3.76E-08	2.847726
Within Groups	29.89	14	2.135238			
Total	565.9	20				

Area of the die D
Summary

Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	125.60	41.86	4.00
Row 3	3	140.10	46.70	1.96
Row 4	3	151.90	50.63	2.94
Row 5	3	161.20	53.73	6.46
Row 6	3	164.80	54.93	4.24
Row 7	3	172.10	57.36	2.02

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2790.876	6	465.146	150.4863	6.78E-12	2.847726
Within Groups	43.27333	14	3.090952			
Total	2834.15	20				

Area of briquettes B
Summary

Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	129.30	32.32	4.76
Row 3	4	145.00	36.25	4.16
Row 4	4	155.10	38.77	5.84
Row 5	4	163.70	40.92	4.66
Row 6	4	171.30	42.82	5.25
Row 7	4	178.10	44.52	4.98

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1546.899	6	257.8165	60.81433	3.45E-12	2.572712
Within Groups	89.0275	21	4.239405			
Total	1635.927	27				

Table 5.2. The results of ANOVA single factor analysis of temperature variance for ATPW8

Area of pressing chamber P
Summary

Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	78.8	26.26	0.72
Row 3	3	81.6	27.20	1.24
Row 4	3	84.8	28.26	1.82
Row 5	3	88.1	29.36	0.72
Row 6	3	91.2	30.40	2.41
Row 7	3	95.3	31.76	4.01

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	222.3	6	37.05095	23.72165	1.41E-06	2.847726
Within Groups	21.87	14	1.561905			
Total	244.2	20				

Area of the die D
Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	115.00	38.33	4.04
Row 3	3	134.90	44.97	2.57
Row 4	3	147.30	49.10	2.25
Row 5	3	157.10	52.37	3.32
Row 6	3	163.60	54.53	4.05
Row 7	3	168.10	56.03	3.77

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2711.66	6.00	451.9441	158.0487	4.84E-12	2.847726
Within Groups	40.03	14.00	2.859524			
Total	2751.69	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	117.40	29.35	5.50
Row 3	4	136.30	34.08	6.64
Row 4	4	149.20	37.30	4.17
Row 5	4	154.70	38.68	7.57
Row 6	4	160.80	40.20	9.25
Row 7	4	169.00	42.25	8.30

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1306.06	6.00	217.6773	36.79497	4.39E-10	2.572712
Within Groups	124.23	21.00	5.915952			
Total	1430.299	27				

Table 5.3. The results of ANOVA single factor analysis of temperature variance for ATWP4

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	86.90	28.97	1.82
Row 3	3	91.30	30.43	1.44
Row 4	3	97.30	32.43	2.01
Row 5	3	102.40	34.13	1.37
Row 6	3	106.90	35.63	2.41
Row 7	3	112.50	37.50	5.88

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	536.00	6.00	89.33635	41.83906	3.76E-08	2.847726
Within Groups	29.89	14.00	2.135238			
Total	565.90	20.00				

Area of the die D
Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	86.90	28.97	1.82
Row 3	3	91.30	30.43	1.44
Row 4	3	97.30	32.43	2.01
Row 5	3	102.40	34.13	1.37
Row 6	3	106.90	35.63	2.41
Row 7	3	112.50	37.50	5.88

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2790.87	6.00	465.146	150.4863	6.78E-12	2.847726
Within Groups	43.27	14.00	3.090952			
Total	2834.15	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	63.00	21.00	0.00
Row 2	4	125.60	41.87	4.00
Row 3	4	140.10	46.70	1.96
Row 4	4	151.90	50.63	2.94
Row 5	4	161.20	53.73	6.46
Row 6	4	164.80	54.93	4.24
Row 7	4	172.10	57.37	2.02

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1546.89	6.00	257.8165	60.81433	3.45E-12	2.572712
Within Groups	89.02	21.00	4.239405			
Total	1635.92	27.00				

Table 5.4. The results of ANOVA single factor analysis of temperature variance for HP12

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	70.10	23.37	0.25
Row 3	3	72.30	24.10	0.49
Row 4	3	75.80	25.27	1.01
Row 5	3	79.20	26.40	0.73
Row 6	3	81.50	27.17	0.86
Row 7	3	83.90	27.97	1.37

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	105.00	6.00	17.49714	25.93084	8.1E-07	2.847726
Within Groups	9.44	14.00	0.674762			
Total	114.40	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	85.60	28.53	1.20
Row 3	3	99.90	33.30	3.49
Row 4	3	110.20	36.73	1.00
Row 5	3	120.30	40.10	3.07
Row 6	3	124.70	41.57	2.44
Row 7	3	128.10	42.70	1.83

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1115.91	6.00	185.9854	99.83879	1.12E-10	2.847726
Within Groups	26.08	14.00	1.862857			
Total	1141.99	20.00				

Area of briquettes B

Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	91.70	22.93	0.56
Row 3	4	99.10	24.78	1.00
Row 4	4	103.80	25.95	1.24
Row 5	4	108.30	27.08	2.78
Row 6	4	110.90	27.73	4.16
Row 7	4	114.20	28.55	4.22

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	177.22	6.00	29.53786	14.81478	1.39E-06	2.572712
Within Groups	41.87	21.00	1.99381			
Total	219.09	27.00				

Table 5.5. The results of ANOVA single factor analysis of temperature variance for HP8

Area of pressing chamber P

Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	73.30	24.43	0.65
Row 3	3	76.80	25.60	1.21
Row 4	3	80.20	26.73	0.56
Row 5	3	84.90	28.30	1.44
Row 6	3	88.10	29.37	1.32
Row 7	3	91.30	30.43	1.70

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	186.89	6.00	31.14762	31.62959	2.3E-07	2.847726
Within Groups	13.79	14.00	0.984762			
Total	200.67	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	89.80	29.93	1.69
Row 3	3	111.00	37.00	2.11
Row 4	3	121.30	40.43	1.84
Row 5	3	129.30	43.10	1.99
Row 6	3	133.90	44.63	0.69
Row 7	3	136.60	45.53	0.94

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1455.09	6.00	242.5152	183.0633	1.76E-12	2.847726
Within Groups	18.54	14.00	1.324762			
Total	1473.63	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.0
Row 2	4	95.70	23.93	0.38
Row 3	4	105.10	26.28	2.97
Row 4	4	108.40	27.10	3.45
Row 5	4	113.70	28.43	4.48
Row 6	4	118.80	29.70	6.26
Row 7	4	126.30	31.58	11.75

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	304.39	6.00	50.7331	12.13019	6.83E-06	2.572712
Within Groups	87.83	21.00	4.182381			
Total	392.22	27.00.				

Table 5.6. The results of ANOVA single factor analysis of temperature variance for HP4

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	78.90	26.30	1.96
Row 3	3	82.60	27.53	3.62
Row 4	3	85.30	28.43	2.14
Row 5	3	89.60	29.87	2.72
Row 6	3	93.20	31.07	2.12
Row 7	3	98.80	32.93	1.90

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	268.00	6.00	44,66937	21,59928	2,52E-06	2,847726
Within Groups	28,95	14.00	2,068095			
Total	297.00	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	93.10	31.03	2.72
Row 3	3	115.10	38.37	3.29
Row 4	3	124.90	41.63	3.06
Row 5	3	134.70	44.90	1.57
Row 6	3	140.30	46.77	1.70
Row 7	3	143.90	47.97	1.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1710.24	6.00	285.0408	149.385	7.13E-12	2.847726
Within Groups	26.713	14.00	1.908095			
Total	1736.95	20.00				

Area of briquettes B

Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	97.60	24.40	0.71
Row 3	4	105.30	26.33	4.19
Row 4	4	112.70	28.18	3.38
Row 5	4	125.90	31.48	5.46
Row 6	4	135.30	33.83	7.40
Row 7	4	141.30	35.33	11.48

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	646.13	6.00	107.6887	23.10503	3.13E-08	2.572712
Within Groups	97.87	21.00	4.660833			
Total	744.00	27.00				

Table 5.7. The results of ANOVA single factor analysis of temperature variance for MG12

Area of pressing chamber P

Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	70.50	23.50	0.21
Row 3	3	73.00	24.33	0.49
Row 4	3	76.90	25.63	1.05
Row 5	3	80.10	26.70	1.21
Row 6	3	83.30	27.77	1.20
Row 7	3	86.90	28.97	1.97

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	132.52	6.00	22.08651	25.1664	9.77E-07	2.847726
Within Groups	12.29	14.00	0.877619			
Total	144.81	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	92.30	30.77	1.69
Row 3	3	113.40	37.80	4.96
Row 4	3	122.90	40.97	3.58
Row 5	3	130.30	43.43	3.57
Row 6	3	136.20	45.40	2.28
Row 7	3	142.60	47.53	0.81

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1575.64	6.00	262.606	108.7503	6.26E-11	2.847726
Within Groups	33.81	14.00	2.414762			
Total	1609.43	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	95.90	23.98	0.52
Row 3	4	105.50	26.38	3.42
Row 4	4	113.50	28.38	4.72
Row 5	4	126.20	31.55	6.66
Row 6	4	133.50	33.38	7.58
Row 7	4	138.40	34.60	5.81

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	606.10	6.00	101.0174	24.63839	1.77E-08	2.572712
Within Groups	86.10	21.00	4.1			
Total	692.20	27.00				

Table 5.8. The results of ANOVA single factor analysis of temperature variance for MG8

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	75.90	25.30	0.64
Row 3	3	79.90	26.63	0.74
Row 4	3	83.10	27.70	1.83
Row 5	3	86.80	28.93	1.32
Row 6	3	90.20	30.07	2.82
Row 7	3	93.20	31.07	1.97

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	206.34	6.00	34.39079	25.7931	8.37E-07	2.847726
Within Groups	18.67	14.00	1.333333			
Total	225.01	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	96.40	32.13	2.74
Row 3	3	109.30	36.43	0.42
Row 4	3	122.60	40.87	2.36
Row 5	3	133.20	44.40	3.49
Row 6	3	139.40	46.47	2.61
Row 7	3	147.10	49.03	1.26

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1697.36	6.00	282.8932	153.5476	5.9E-12	2.847726
Within Groups	25.79	14.00	1.842381			
Total	1723.15	20.00				

Area of briquettes B

Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	102.40	25.60	1.29
Row 3	4	112.80	28.20	2.70
Row 4	4	122.40	30.60	1.82
Row 5	4	134.90	33.73	3.27
Row 6	4	138.80	34.70	5.79
Row 7	4	146.50	36.63	4.30

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	735.15	6.00	122.5249	44.73655	6.83E-11	2.572712
Within Groups	57.51	21.00	2.73881			
Total	792.66	27.00				

Table 5.9. The results of ANOVA single factor analysis of temperature variance for MG4

Area of pressing chamber P

Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	80.10	26.70	0.73
Row 3	3	82.60	27.53	0.82
Row 4	3	86.20	28.73	1.34
Row 5	3	88.50	29.50	1.03
Row 6	3	93.80	31.27	2.89
Row 7	3	97.20	32.4	1.83

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	250.63	6.00	41.77159	33.8036	1.5E-07	2.847726
Within Groups	17.30	14.00	1.235714			
Total	267.93	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	102.10	34.03	0.92
Row 3	3	123.00	41.00	2.11
Row 4	3	133.80	44.60	4.96
Row 5	3	138.50	46.17	5.69
Row 6	3	143.50	47.83	3.69
Row 7	3	150.90	50.30	2.08

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1862.29	6.00	310.3816	111.6481	5.23E-11	2.847726
Within Groups	38.92	14.00	2.78			
Total	1901.21	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	104.00	26.00	1.85
Row 3	4	124.10	31.03	1.94
Row 4	4	136.30	34.08	2.04
Row 5	4	140.50	35.13	4.02
Row 6	4	148.40	37.10	7.79
Row 7	4	153.00	38.25	10.54

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	947.22	6.00	157.8695	39.20949	2.41E-10	2.572712
Within Groups	84.55	21.00	4.02631			
Total	1031.77	27.00				

Table 5.10. The results of ANOVA single factor analysis of temperature variance for MS12

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	71.00	23.67	0.24
Row 3	3	73.70	24.57	0.37
Row 4	3	75.60	25.20	1.03
Row 5	3	80.50	26.83	1.60
Row 6	3	85.60	28.53	1.08
Row 7	3	89.40	29.80	1.17

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	161.60	6.00	26.93413	34.25903	1.38E-07	2.847726
Within Groups	11.01	14.00	0.78619			
Total	172.61	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	96.30	32.10	2.25
Row 3	3	114.60	38.20	5.71
Row 4	3	128.40	42.80	4.21
Row 5	3	134.30	44.77	3.30
Row 6	3	140.00	46.67	5.26
Row 7	3	145.40	48.47	2.61

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1704.59	6.00	284.0986	85.16874	3.29E-10	2.847726
Within Groups	46.70	14.00	3.335714			
Total	1751.29	20.00				

Area of briquettes B

Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	97.90	24.48	0.68
Row 3	4	110.60	27.65	5.31
Row 4	4	118.00	29.50	13.15
Row 5	4	129.50	32.38	12.55
Row 6	4	136.00	34.00	9.05
Row 7	4	143.10	35.78	5.98

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	673.56	6.00	112.2595	16.82301	4.86E-07	2.572712
Within Groups	140.13	21.00	6.672976			
Total	813.69	27.00				

Table 5.11. The results of ANOVA single factor analysis of temperature variance for MS8

Area of pressing chamber P

Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	79.00	26.33	1.32
Row 3	3	83.00	27.67	0.50
Row 4	3	85.20	28.40	0.79
Row 5	3	88.80	29.60	1.33
Row 6	3	93.50	31.17	2.41
Row 7	3	96.80	32.27	1.49

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	248.40	6.00	41.40714	36.90789	8.5E-08	2.847726
Within Groups	15.710	14.00	1.121905			
Total	264.10	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	99.50	33.17	0.65
Row 3	3	121.00	40.33	2.64
Row 4	3	129.20	43.07	1.77
Row 5	3	135.10	45.03	1.26
Row 6	3	142.50	47.50	1.56
Row 7	3	149.20	49.73	4.42

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1780.58	6.00	296.7641	168.6616	3.1E-12	2.847726
Within Groups	24.63	14.00	1.759524			
Total	1805.21	20.00				

Area of briquettes B
Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	104.30	26.08	2.66
Row 3	4	120.50	30.13	2.63
Row 4	4	130.10	32.53	5.65
Row 5	4	140.40	35.10	1.94
Row 6	4	144.60	36.15	4.03
Row 7	4	151.50	37.88	7.12

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	869.82	6.00	144.9707	42.2362	1.18E-10	2.572712
Within Groups	72.08	21.00	3.432381			
Total	941.90	27.00				

Table 5.12. The results of ANOVA single factor analysis of temperature variance for MS4

Area of pressing chamber P
Summary

P Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	82.10	27.37	0.72
Row 3	3	84.00	28.00	0.91
Row 4	3	88.50	29.50	1.57
Row 5	3	92.80	30.93	3.36
Row 6	3	95.60	31.87	3.40
Row 7	3	98.80	32.93	2.96

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	285.20	6.00	47.53222	25.7262	8.51E-07	2.847726
Within Groups	25.87	14.00	1.847619			
Total	311.10	20.00				

Area of the die D

Summary

D Groups	Count	Sum	Average	Variance
Row 1	3	63.00	21.00	0.00
Row 2	3	103.30	34.43	0.86
Row 3	3	126.20	42.07	2.72
Row 4	3	133.10	44.37	3.24
Row 5	3	137.30	45.77	4.62
Row 6	3	144.30	48.10	2.59
Row 7	3	150.20	50.07	3.16

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1832.17	6.00	305.3616	124.2269	2.52E-11	2.847726
Within Groups	34.41	14.00	2.458095			
Total	1866.58	20.00				

Area of briquettes B

Summary

B Groups	Count	Sum	Average	Variance
Row 1	4	84.00	21.00	0.00
Row 2	4	106.70	26.68	1.03
Row 3	4	122.90	30.73	4.04
Row 4	4	134.80	33.70	4.96
Row 5	4	142.60	35.65	3.58
Row 6	4	148.20	37.05	3.50
Row 7	4	153.50	38.38	6.58

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	932.95	6.00	155.4931	45.95047	5.28E-11	2.572712
Within Groups	71.06	21.00	3.383929			
Total	1004.02	27.00				

Annex 6. The graphical representation of temperature increasing in pressing areas of HBP.

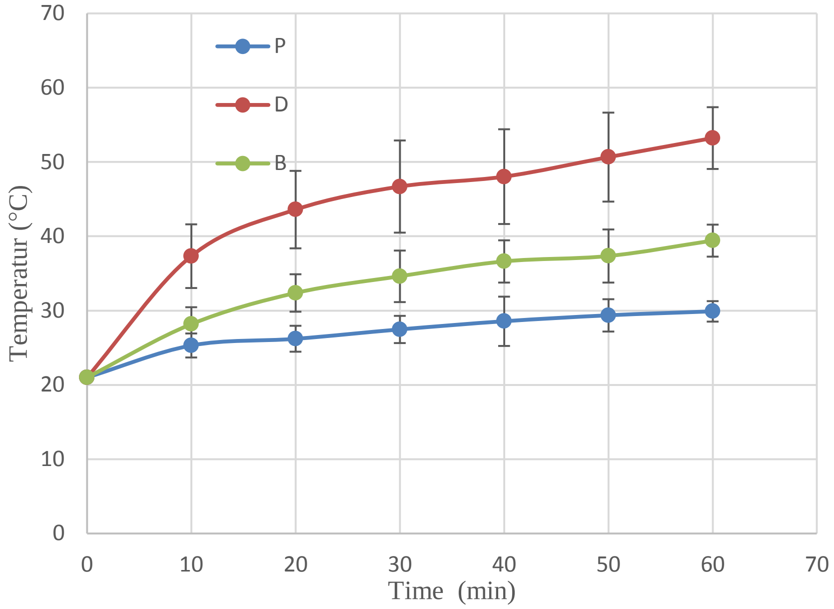

Figure 6.1. Temperature dependence on the BD of the material ATPW12

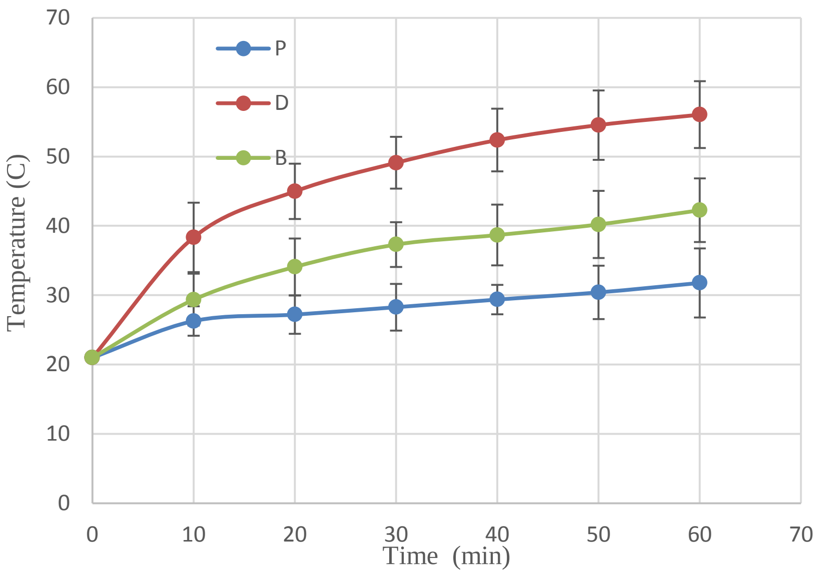

Figure 6.2. Temperature dependence on the BD of the material ATPW 8

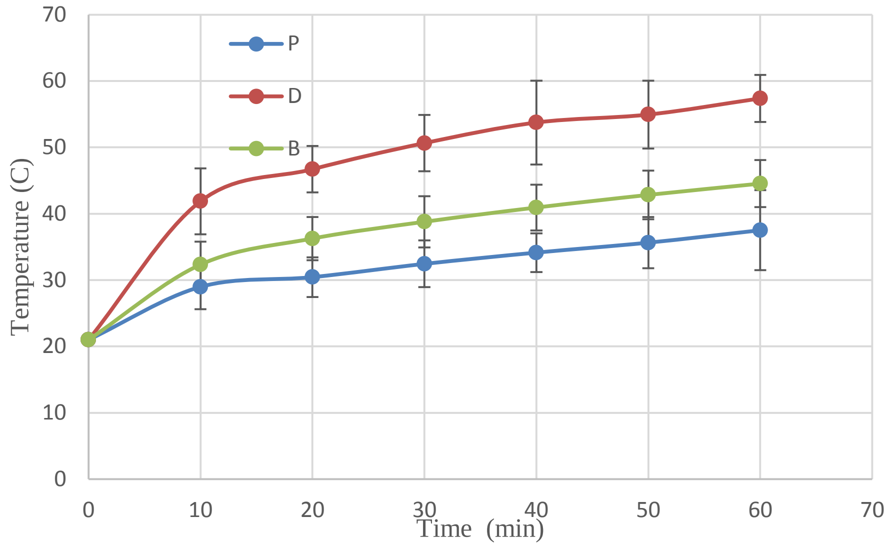

Figure 6.3. Temperature dependence on the BD of the material ATPW 4

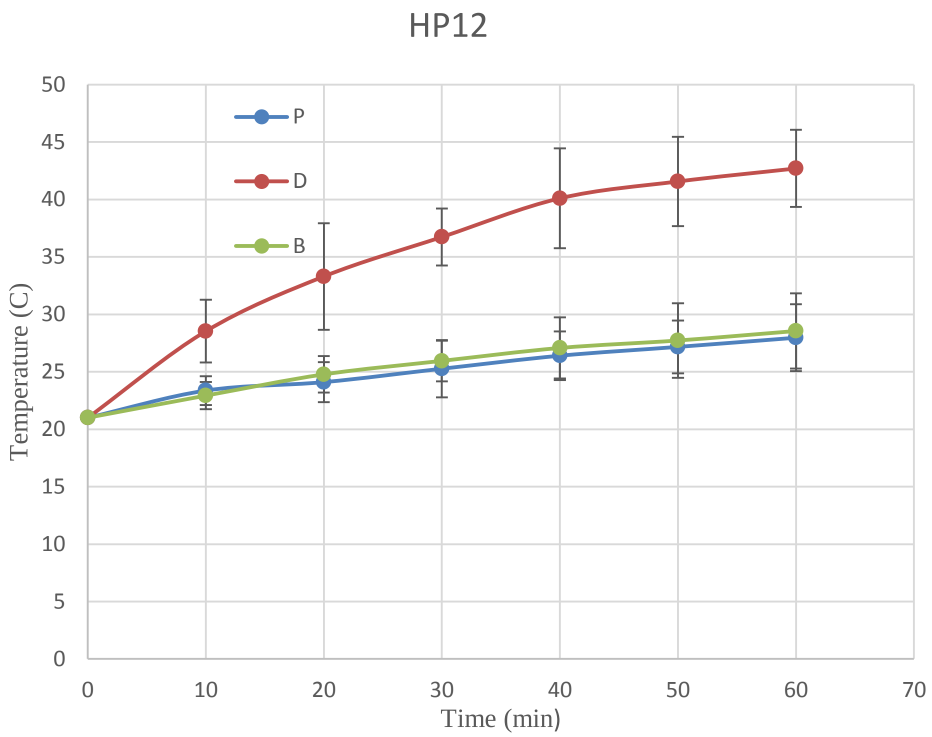

Figure 6.4. Temperature dependence on the BD of the material HP12

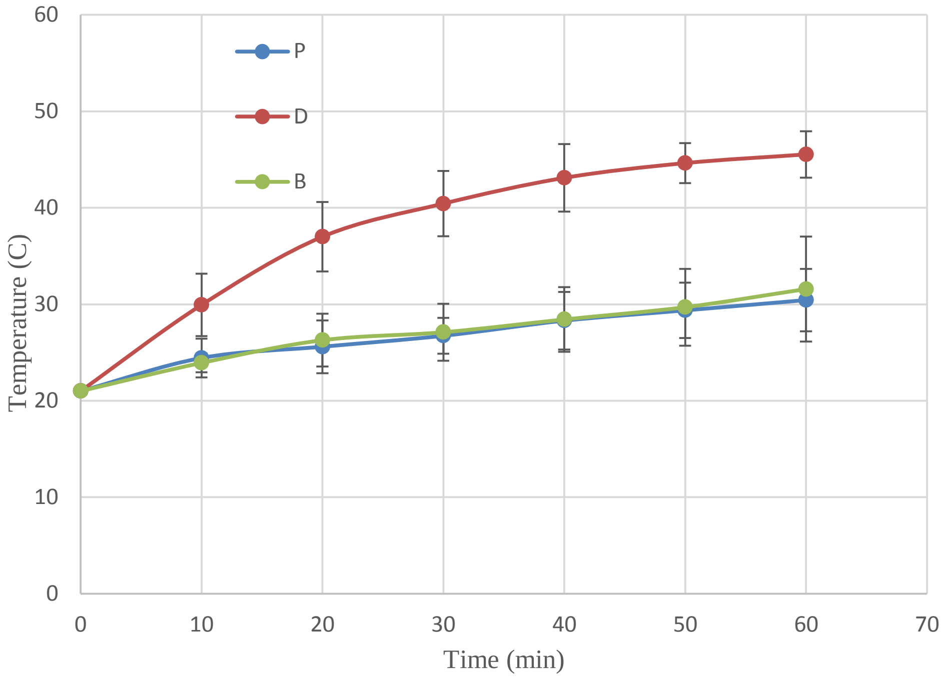

Figure 6.5. Temperature dependence on the BD of the material HP8

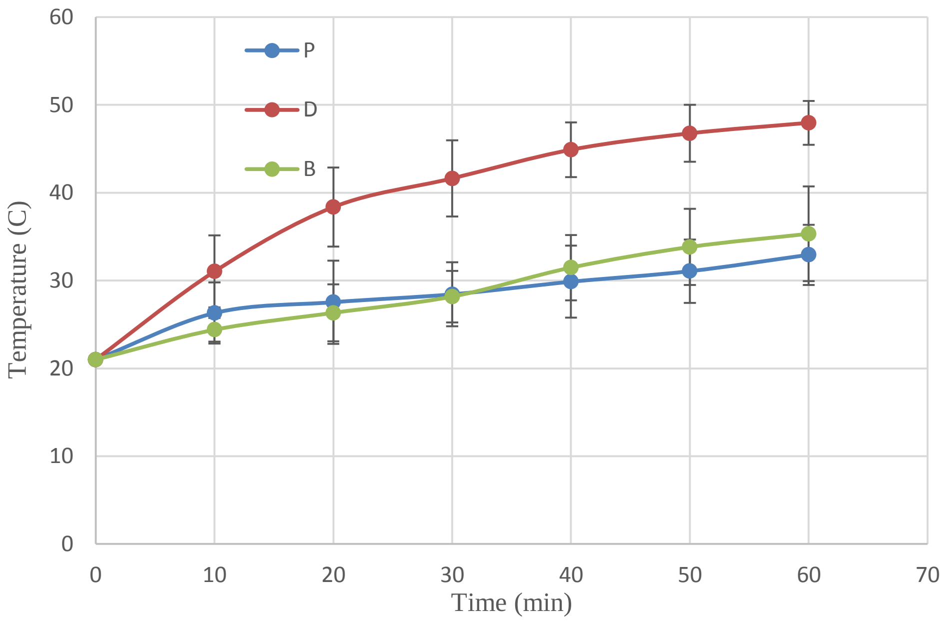

Figure 6.6. Temperature dependence on the BD of the material HP4

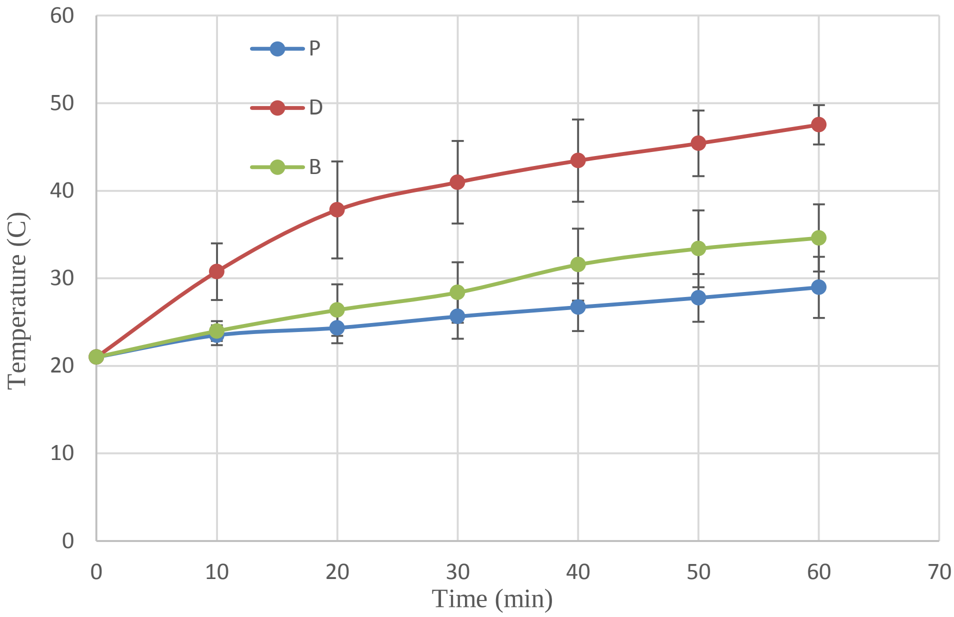

Figure 6.7. Temperature dependence on the BD of the material MG12

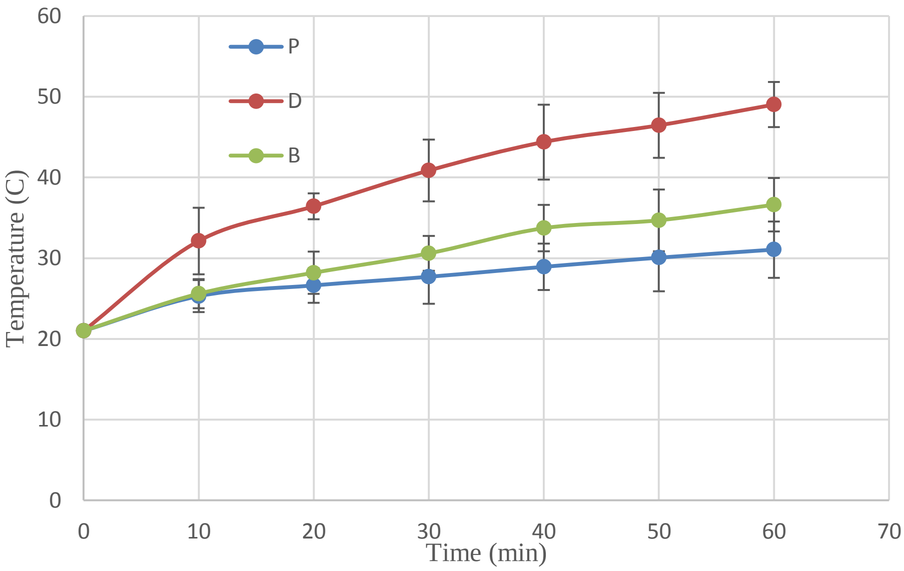

Figure 6.8. Temperature dependence on the BD of the material MG8

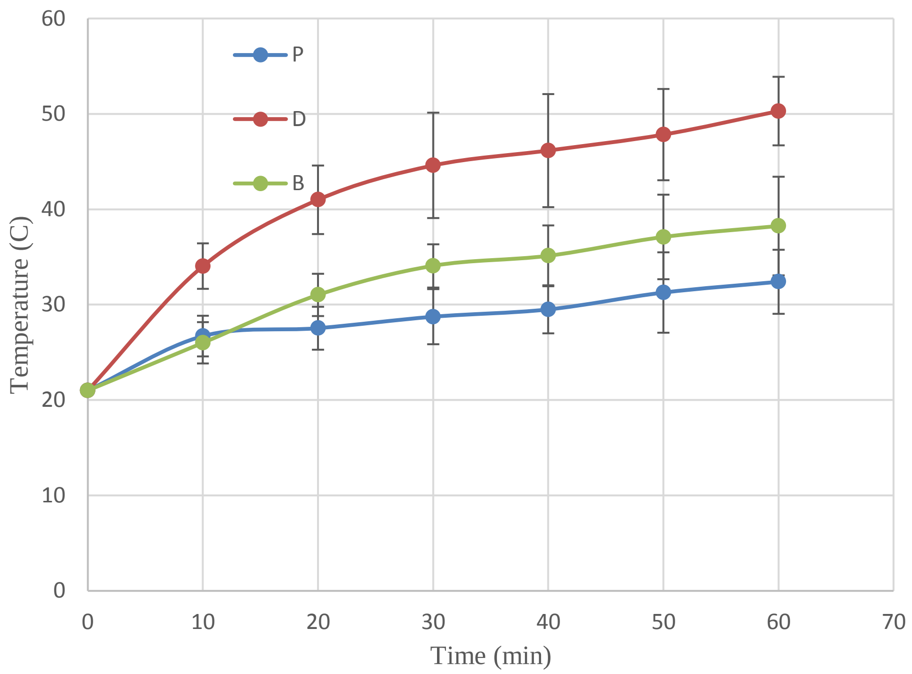

Figure 6.9. Temperature dependence on the BD of the material MG4

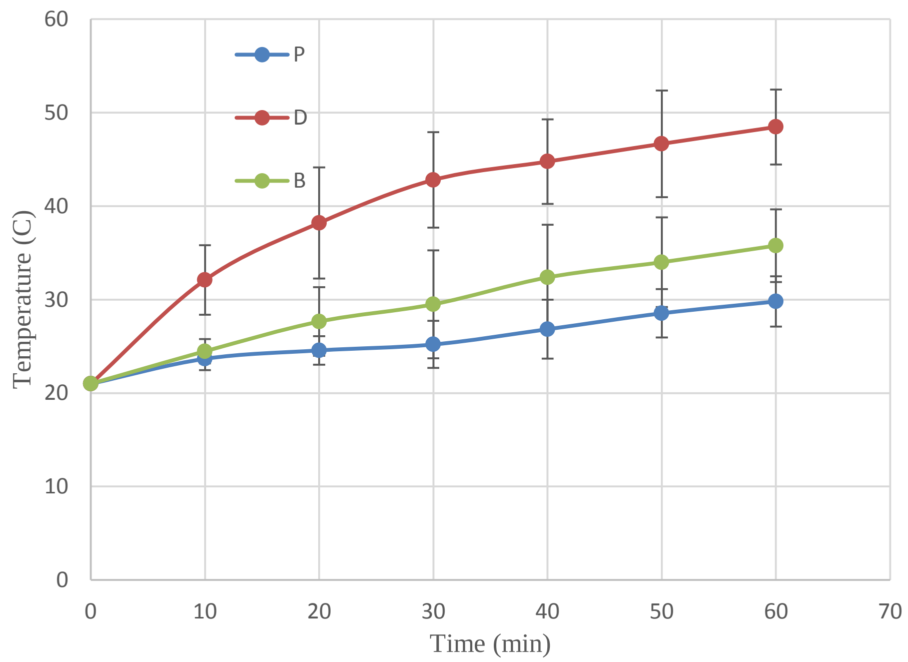

Figure 6.10. Temperature dependence on the BD of the material MS12

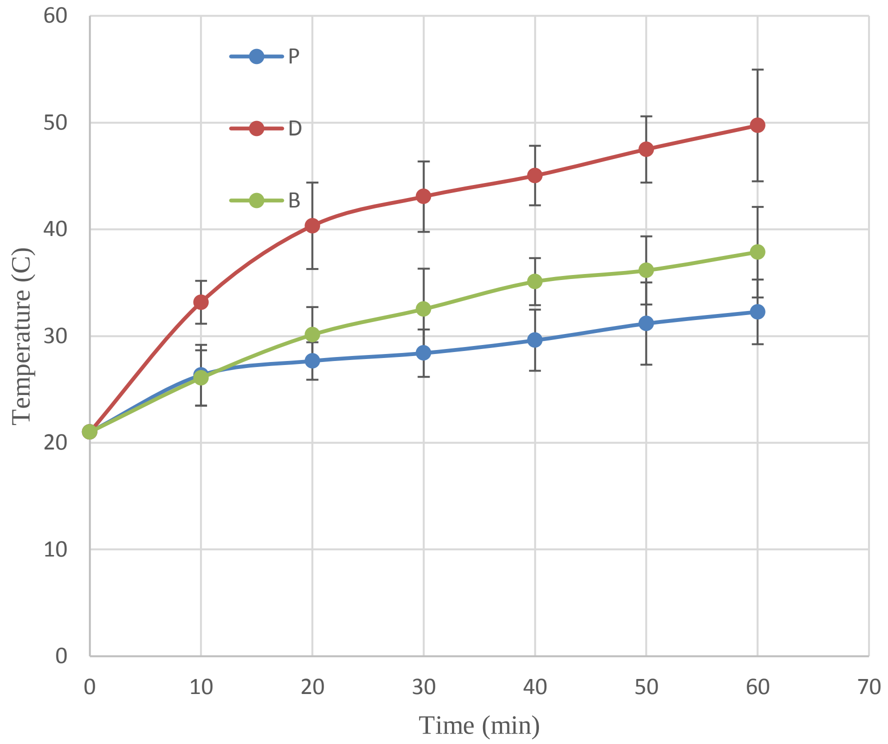

Figure 6.11. Temperature dependence on the BD of the material MS8

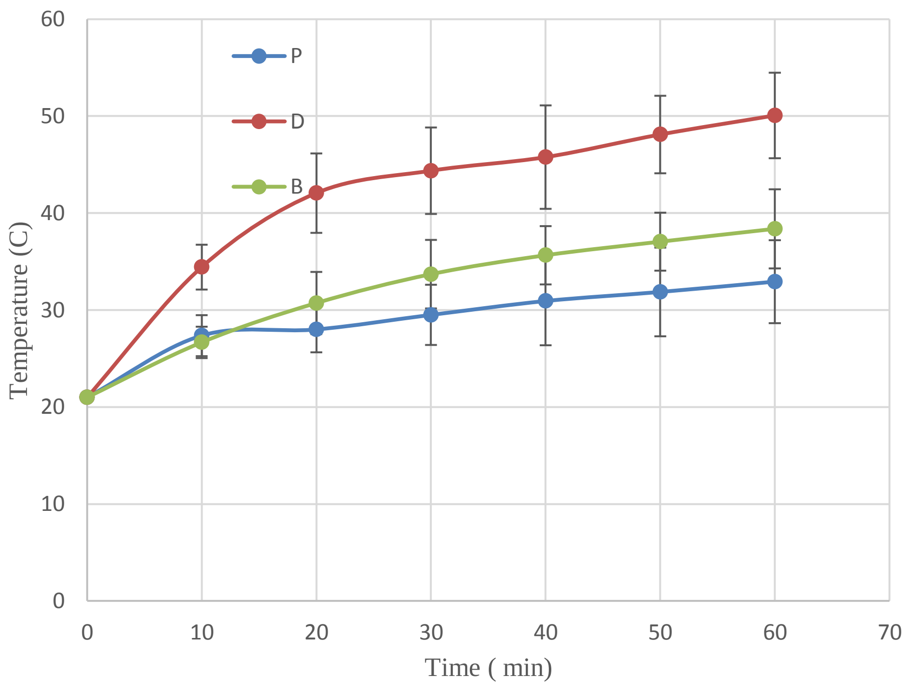

Figure 6.12. Temperature dependence on the BD of the material MS4

Annex 7. The results of the macroanalysis of briquettes produced on HBP

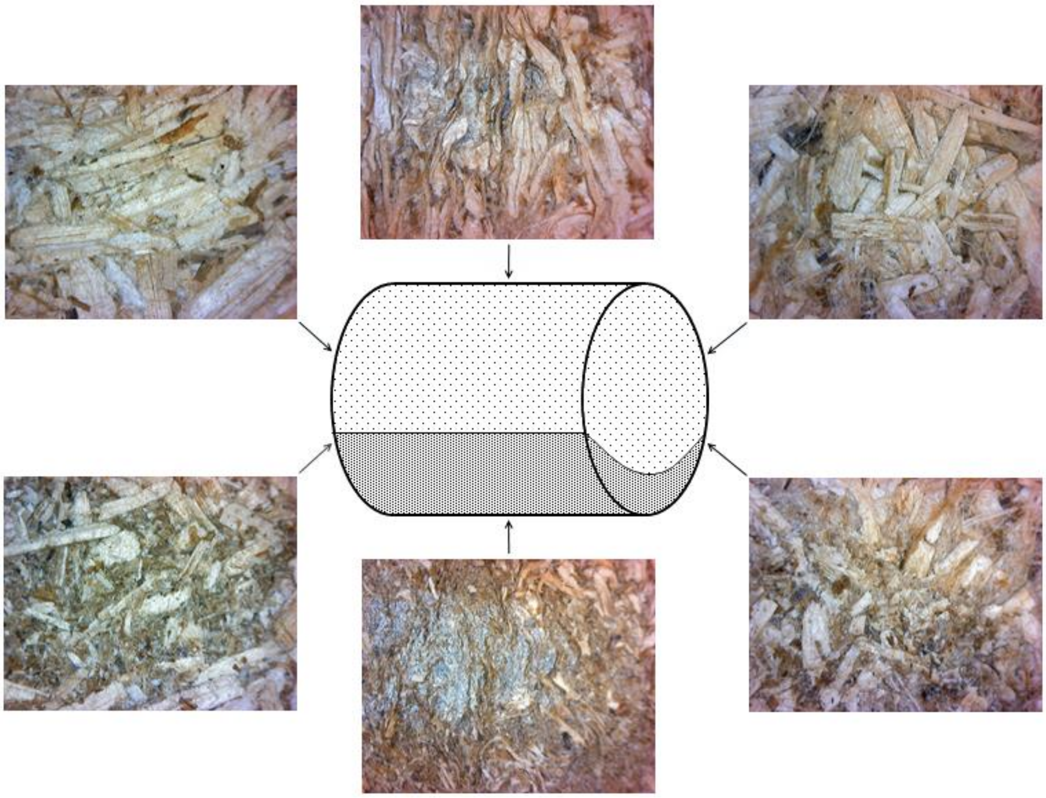

Figure 7.1. The macroanalysis of the structure of briquettes HPH12

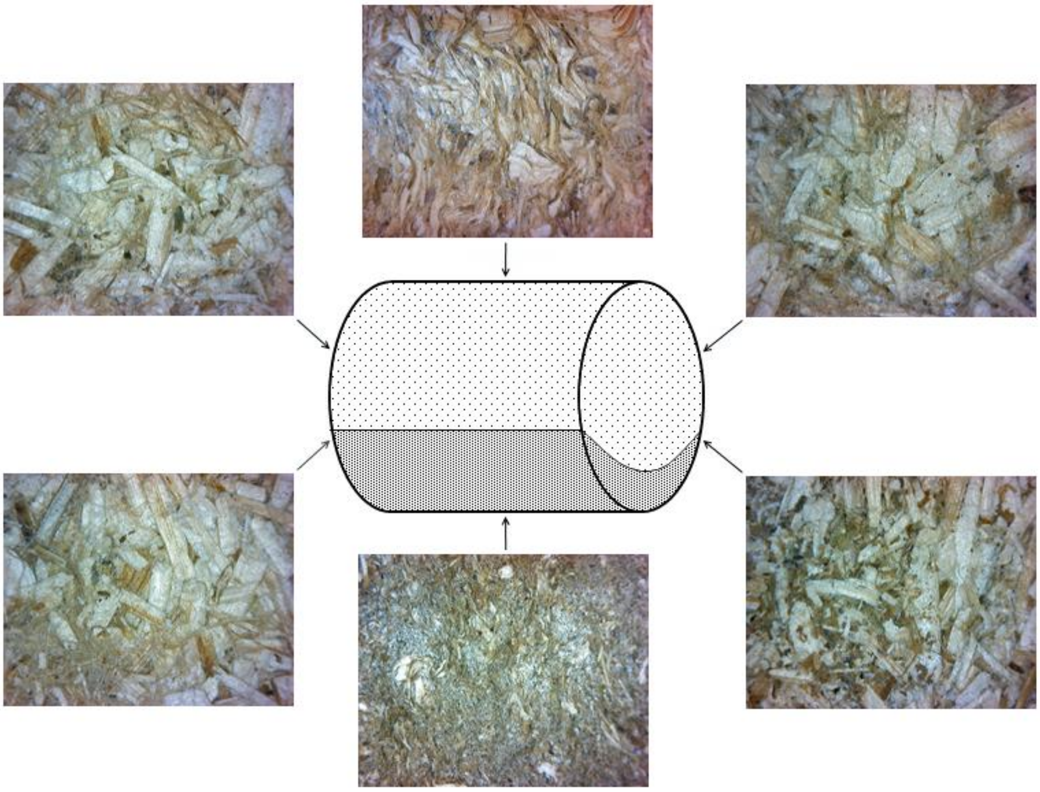

Figure 7.2. The macroanalysis of the structure of briquettes HPH8

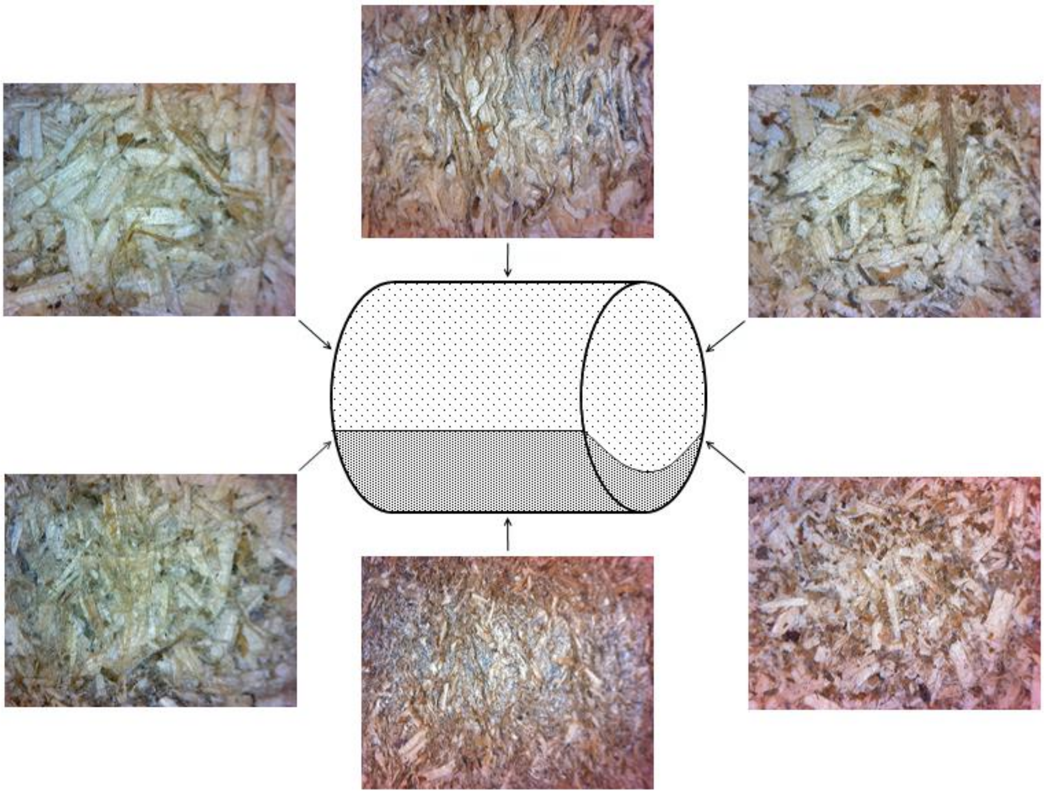

Figure 7.3. The macroanalysis of the structure of briquettes HPH4

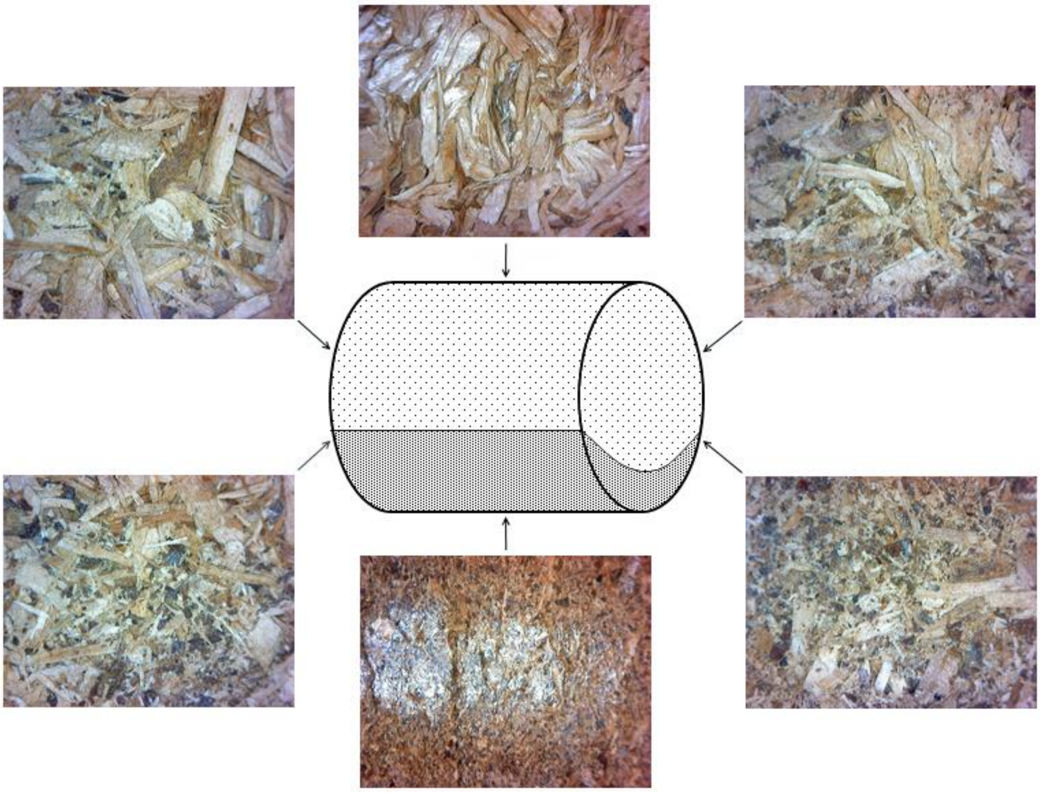

Figure 7.4. The macroanalysis of the structure of briquettes ATPWH12

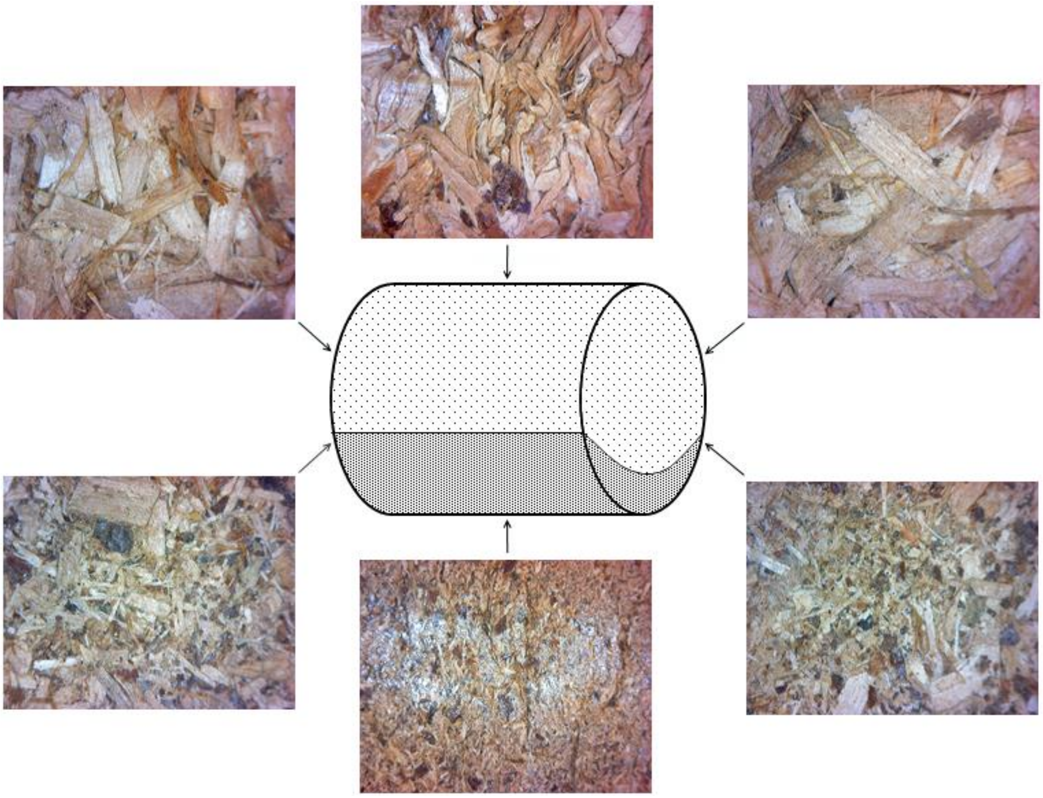

Figure 7.5. The macroanalysis of the structure of briquettes ATPWH8

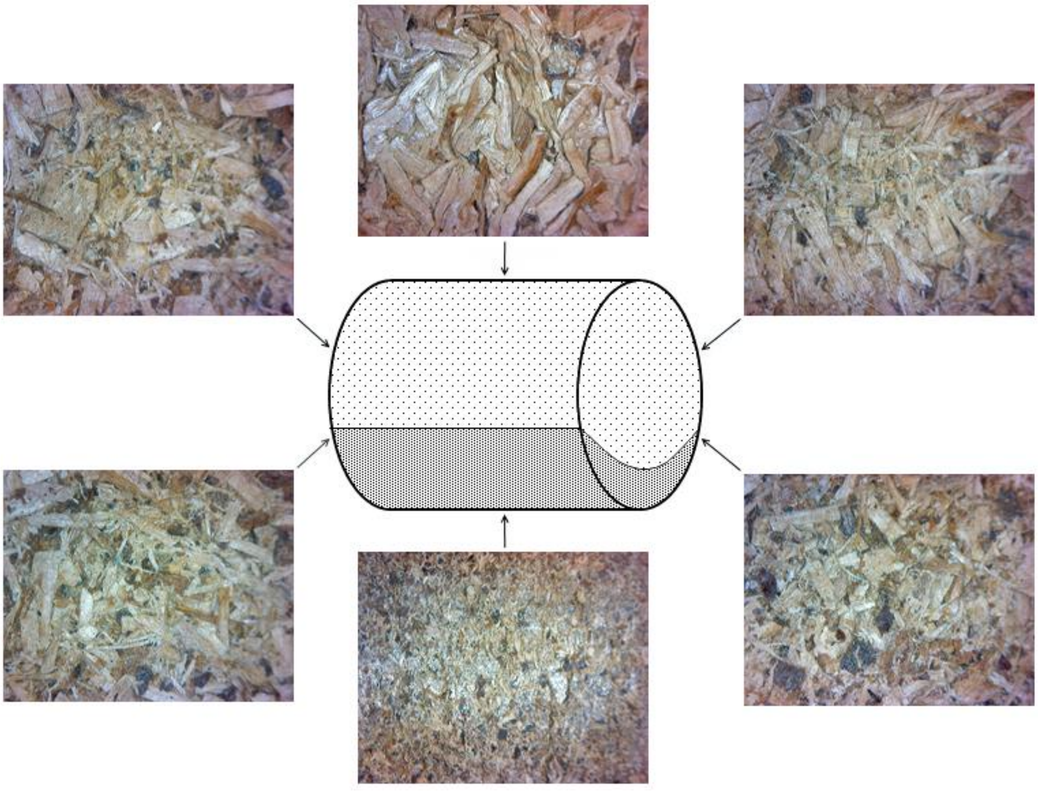

Figure 7.6. The macroanalysis of the structure of briquettes ATPWH4

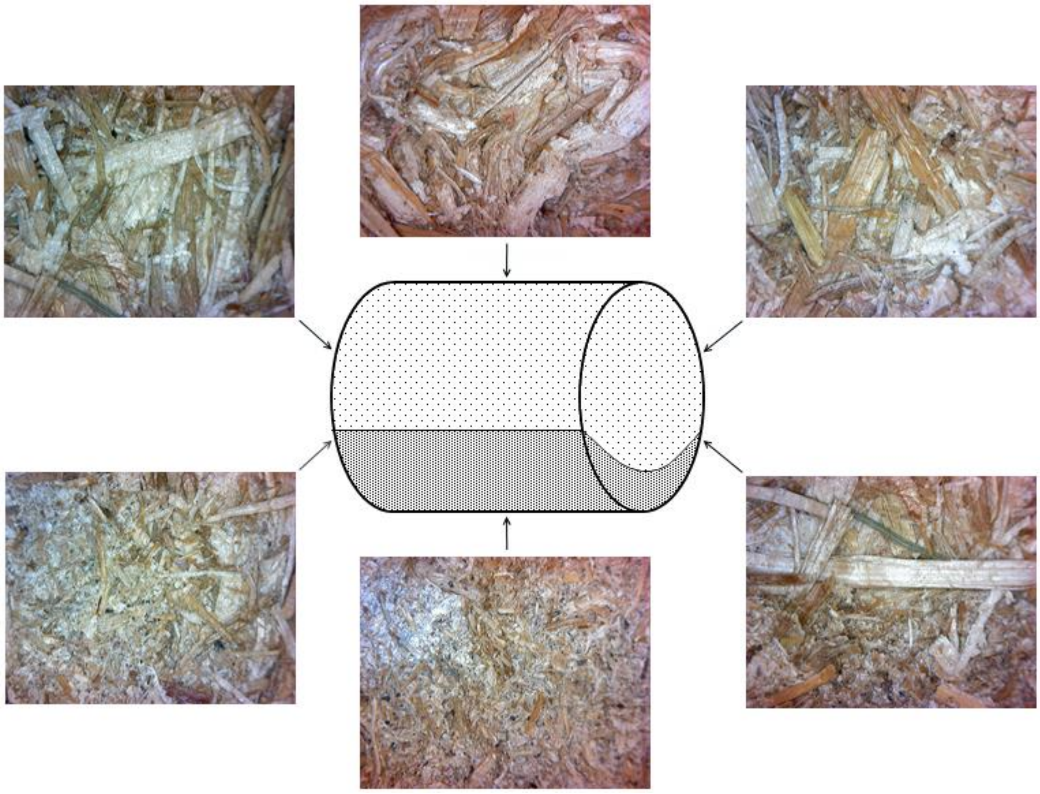

Figure 7.7. The macroanalysis of the structure of briquettes MGH12

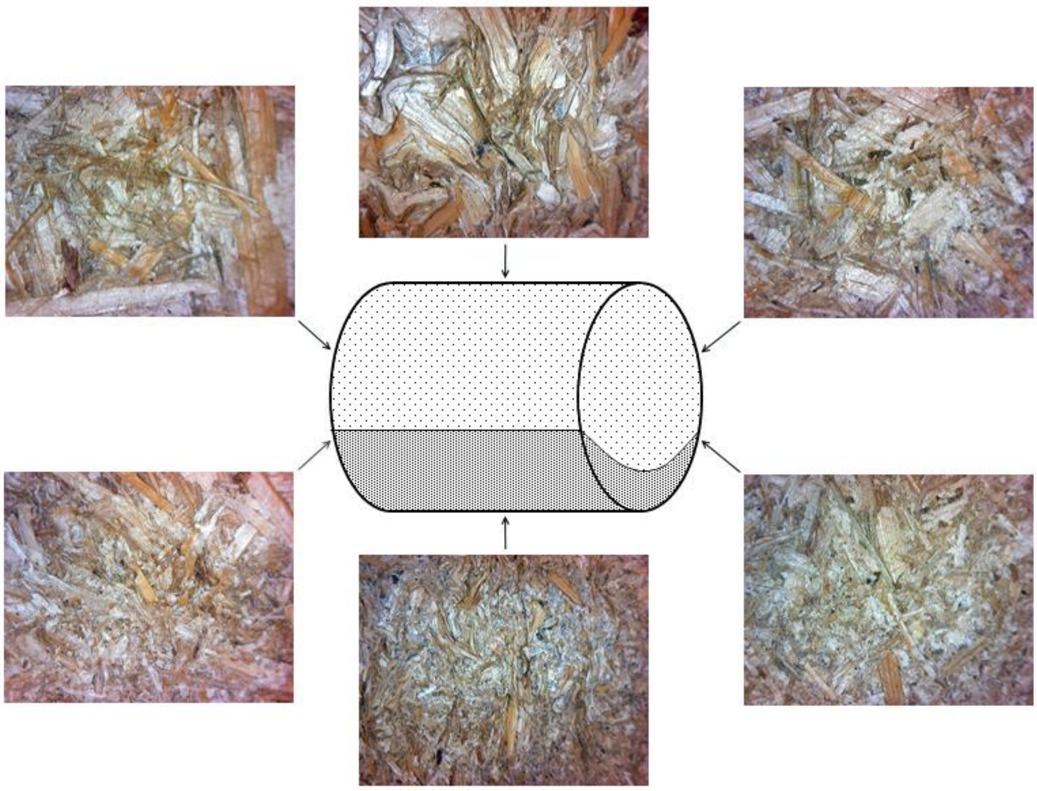

Figure 7.8. The macroanalysis of the structure of briquettes MGH8

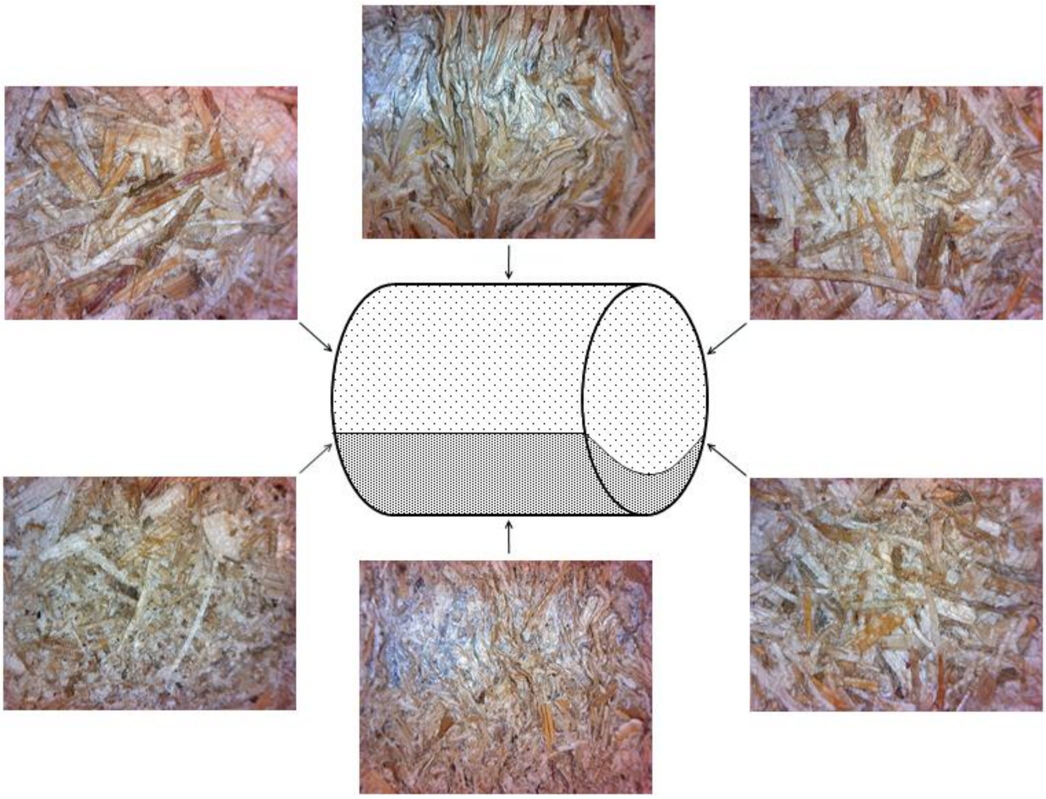

Figure 7.9. The macroanalysis of the structure of briquettes MGH4

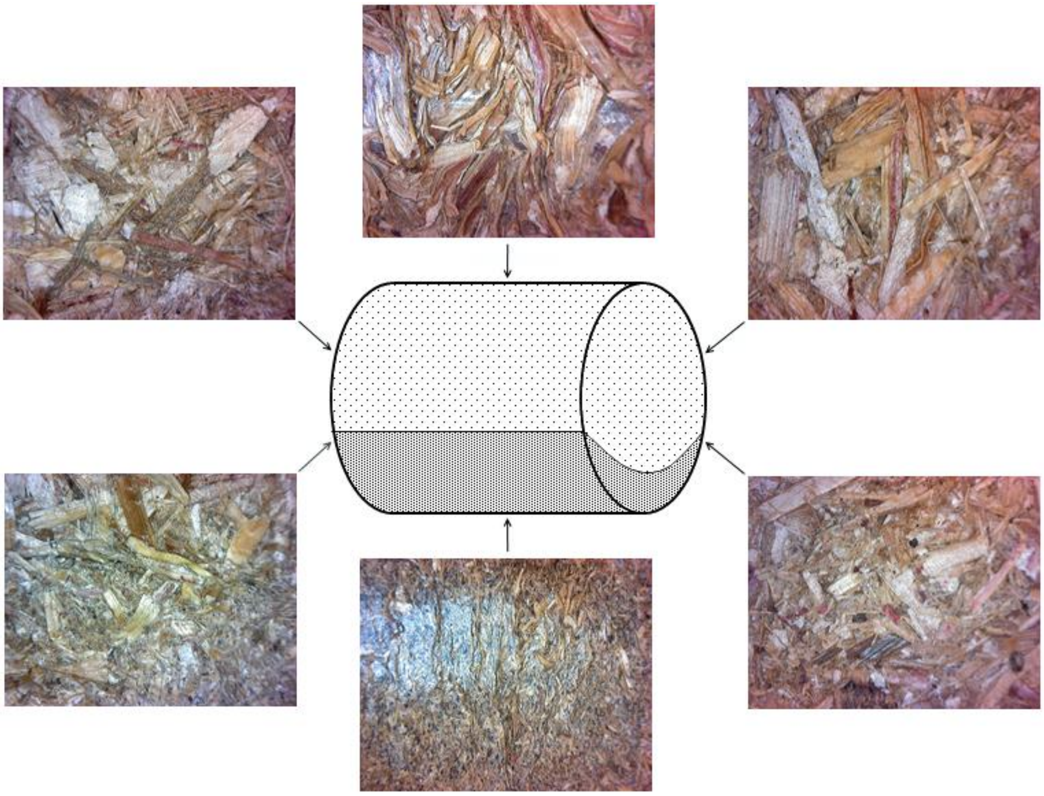

Figure 7.10. The macroanalysis of the structure of briquettes MS12

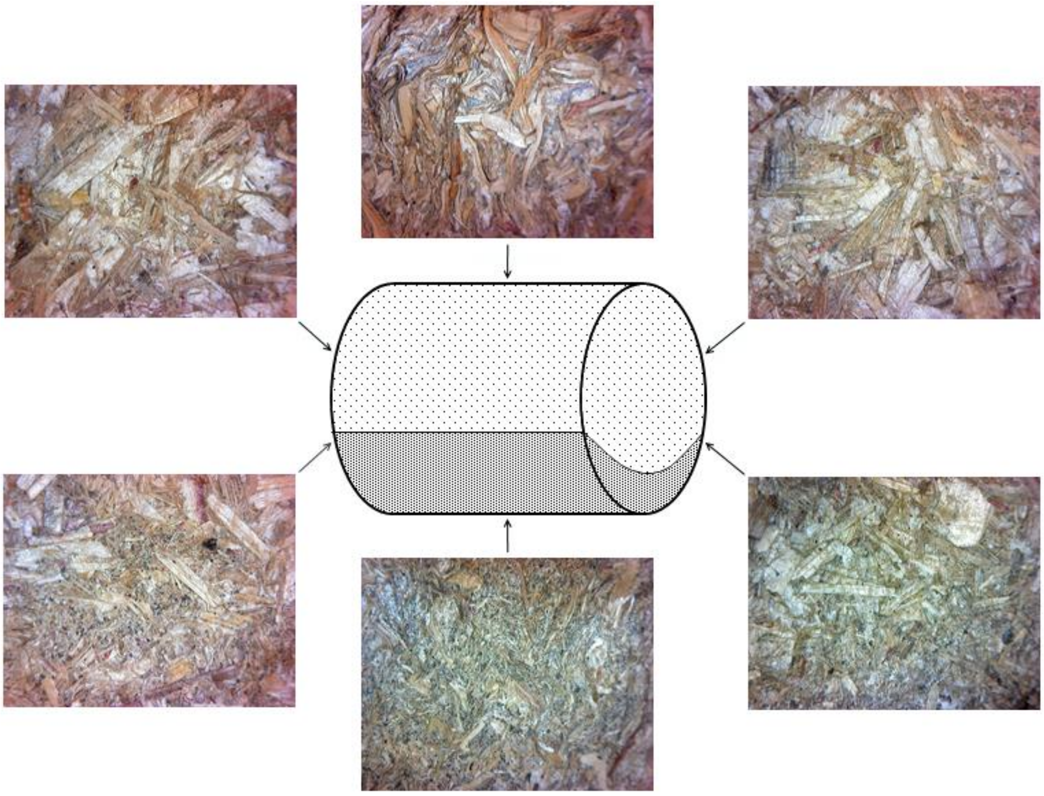

Figure 7.11. The macroanalysis of the structure of briquettes MSH8

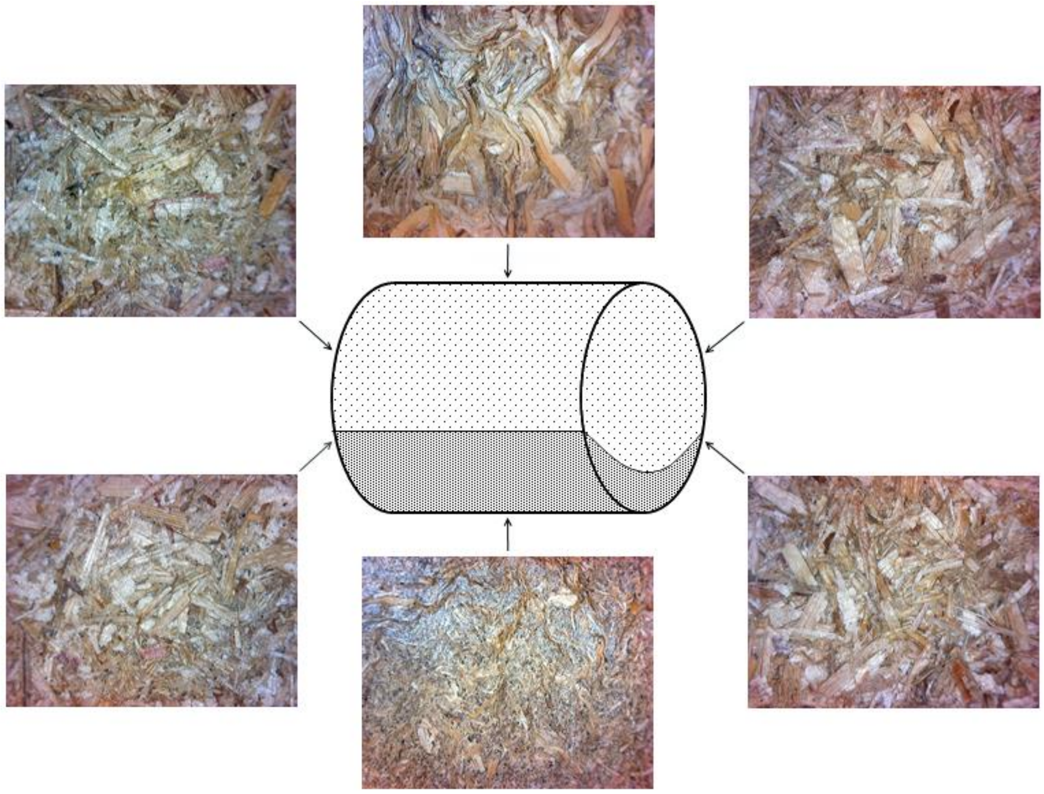

Figure 7.12. The macroanalysis of the structure of briquettes MSH4

Annex 8. List of Author's publications

Articles in the Journals with IF

1. AKHMEDOV, S., IVANOVA, T., SURAYYO, A., **MUNTEAN, A.**, KREPL, V. 2019. Contribution to the energy situation in Tajikistan by using residual apricot branches after pruning as an alternative fuel. *Energies,* 12(16):1–11.

2. PROCHÁZKOVÁ, K., IVANOVA, T., **MUNTEAN, A.** 2019. An analysis of waste management in the Republic of Moldova: a comparison of rural and urban area. *Polish Journal of Environmental Studies,* 28(3):1869–1875.

Articles with SJR index (Scopus)

1. CHALOUPKOVÁ, V., IVANOVA, T., **MUNTEAN, A**. 2018. Particle size distribution analysis of pine sawdust: comparison of traditional oscillating screen method and photo-optical analysis. *Agronomy Research,* 16(5): 1966–1975.

2. **MUNTEAN, A.**, IVANOVA, T., HUTLA, P., HAVRLAND, B. 2017. Influence of raw material properties on the quality of solid biofuel and energy consumption in briquetting process. *Agronomy Research,* 15(4): 1708–1715.

3. AKHMEDOV, S., IVANOVA, T., KREPL, V., **MUNTEAN, A.** 2017. Research on solid biofuels from cotton waste biomass – alternative for Tajikistan's energy sector development. *Agronomy Research,* 15(5): 1846–1855.

4. IVANOVA, T., **MUNTEAN, A.**, TITEI, V., HAVRLAND, B., KOLAŘÍKOVÁ, M. 2015. Energy crops utilization as an alternative agricultural production. *Agronomy Research,* 13(2): 311–317.

5. IVANOVA, T., **MUNTEAN, A.**, HAVRLAND, B., POBEDINSKY, V. 2013. Theoretical modelling of the briquetting process at different pressing equipment. *Agronomy Research,* 11(1): 47–52.

6. IVANOVA, T., HAVRLAND, B., HUTLA, P., **MUNTEAN, A**. 2012. Drying of cherry tree chips in the experimental biomass dryer with solar collector. *Research in Agricultural Engineering,* 58(1):16–23.

Articles in conference proceedings (WoS)

1. IVANOVA, T., **MUNTEAN, A.**, HAVRLAND, B., HUTLA P. 2018. Quality assessment of solid biofuel made of sweet sorghum biomass. In *BIO Web of Conferences 10,* Contemporary Research Trends in Agricultural Engineering 2018, Krakow. Poland, pp. 1–5.

2. IVANOVA, T., HAVRLAND, B., NOVOTNY, R., **MUNTEAN, A.**, HUTLA P. 2018. Influence of raw material properties on energy consumption during briquetting process. In

BIO Web of Conferences 10, Contemporary Research Trends in Agricultural Engineering 2018, Krakow. Poland, pp. 1–6.

3. **MUNTEAN, A.**, IVANOVA, T., HAVRLAND, B., POBEDINSKY, V., VRANCEAN, V. 2013. Particularities of bio-raw material particle agglomeration during solid fuel pressing process. In *Engineering for Rural Development*, Jelgava, Latvia, pp. 505–509.
4. **MUNTEAN, A.**, IVANOVA, T., HAVRLAND, B., POBEDINSKY, V. 2012. Comparative analysis of methods for fuel briquettes production. In *Engineering for Rural Development*, Jelgava, Latvia. pp. 496–499.
5. **MUNTEAN, A.**, HAVRLAND, B., POBEDINSCHI, V., IVANOVA, T., MARIAN, G. 2010. Features of bio-briquettes pressing with the piston briquetting press. In *Engineering for Rural development*, Jelgava, Latvia, pp. 246–251.

Scientific book (Monograph)

1. HAVRLAND, B., POBEDINSCHI, V., VRANCEAN, V., PECEN, J., IVANOVA, T., **MUNTEAN, A.**, KANDAKOV, A. 2011. *Biomass Processing to Biofuel.* Powerprint, Prague, 86 pp. ISBN 978-80-87415-20-7 (in English).

University textbook

1. POBEDINSCHI, V., HAVRLAND, B., **MUNTEAN, A.**, VRANCEAN, V., KANDAKOV A., IVANOVA, T. 2009. *Analiz i issledovanie processov proizvodstva granul i briketov iz fitomassy (Research and analysis of the processes of pellets and briquettes production from phytomass).* Powerprint, Prague, 162 pp. ISBN 978-80-213-2029-1 (in Russian).