CZECH UNIVERSITY OF LIFE SCIENCES

FACULTY OF TROPICAL AGRISCIENCES

The hemp biomass processing for solid biofuels in form of briquettes

Diploma thesis

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DECLARATION

I hereby declare that this diploma thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been acknowledged.

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Prague, April 23rd 2013 ……………………………

Ondřej Špur

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ABSTRACT

Development of new technologies causes still increasing energy consumption. Today's society is predominantly dependent on non-renewable sources of energy, e.g. oil, coal etc. These non-renewable sources, however, have two significant disadvantages – they are **exhaustible** and environment **unfriendly**. Hence, it is necessary to find new appropriate (alternative) renewable energy sources, which could be friendly to the environment as well. One of the possible renewable sources of energy could be use of the plant biomass.

This thesis investigates suitability of industrial hemp's (*Cannabis sativa*) biomass as an alternative solid fuel in form of briquettes. This evaluation includes several significant mechanical and physical characteristics and properties, generally measured, in the solid fuels. Specifically, there are ash content, moisture content, mechanical durability, gross and net calorific values and flue gas emissions during combustion. For purposes of examination of these characteristics, five mixtures of hemp's (variety *Bialobrzeskie*) stem's and press cake's biomass were prepared.

Currently, there were sown two varieties of industrial hemp – Polish variety of *Cannabis sativa Bialobrzeskie* and French variety *Ferimon*, on the experimental field belonging to the CULS campus. To compare them the two important characteristics were examined – yield per hectare and moisture content of biomass.

Key words: hemp, biofuel, briquettes, moisture content, mechanical durability, ash content, calorific value, emissions, yield per hectare

ABSTRAKT

S rozvojem nových technologií přichází stále se zvyšující spotřeba energie. Současná společnost je převážně závislá na neobnovitelných zdrojích energie, např. ropa, uhlí apod. Tyto neobnovitené zdroje energie mají však dvě, zcela zásadní nevýhody – jsou **vyčerpatelné** a **negativně působí na životní prostředí**. Z toho důvodu je zapotřebí najít jiné vhodné (alternativní) obnovitelné zdroje, které by zároveň byly ohleduplné vůči životnímu prostředí. Jedním z nabízejících se směrů výzkumu by mohlo být využití rostlinné biomasy.

Tato práce zkoumá vhodnost využití technického konopí (*Cannabis sativa*), jakožto alternativního tuhého paliva ve formě briket. Tento výzkum zahrnuje několik významných mechanických a fyzikálních vlastností a charakteristik, které jsou obecně zkoumány u tuhých paliv. Jmenovitě to jsou obsah popela, obsah vlhkosti, mechanická odolnost, spalné teplo, výhřevnost a emise plynů při spalování. Pro účely tohoto výzkumu, bylo připraveno pět směsí konopné biomasy (*Bialobrzeskie*) ze stonků a pokrutin.

Současně s tím, byl založen pokusný pozmek, patřící k areálu ČZU, na němž byly vysazeny dvě odrůdy technického konopí – polská odrůda *Bialobrzeskie* a francouzská odrůda *Ferimon*. V rámci tohoto pokusu byly sledovány dvě důležité charakteristiky – hektarový výnos a obsah vlhkosti v biomase.

Klíčová slova: konopí, biopalivo, brikety, vlhkost, mechanická odolnost, obsah popela, výhřevnost, emise, hektarový výnos

List of abbreviations:

AC	Ash Content
CULS	Czech University of Life Sciences
DU	Mechanical Durability
EU	European Union
FE	Faculty of Engineering
FTA	Faculty of Tropical AgriSciences
GCV	Gross Calorific Value
MC	Moisture Content
NCV	Net Calorific Value
RIAE	Research Institute of Agricultural Engineering
THC	Tetrahydrocannabinol
UEA	University of East Anglia

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1. Introduction

In connection with distortion of the ozone layer and other negative impacts of greenhouse gases on the environment, the seeking new environment-friendly (renewable) sources of energy has been a trend of recent years. Generally, we can divide these renewable sources of energy into several groups:

- Solar radiation
- Hydropower
- Wave and tidal energy
- Wind energy
- Geothermal energy
- Biomass

All these resources are renewable, which means they can be restored. This is their significant advantage, because they practically cannot be exhausted unlike coal or oil sources. The last item - plant biomass is actually intended as a replacement of coal and other solid fuels, being considerate to the environment. The plant's biomass is usually pressed into forms of briquettes or pellets (solid biofuels) for combustion purposes.

The biomass, in a broader sense, refers to any biological material. Basically, according to its origins, the biomass can be divided into two groups: animal biomass (zoomass) and plant's biomass (fytomass). BENDA et al. (2012) divide the biomass originated in the Plant Kingdom furthermore into a dendromass (woody biomass). As a renewable energy source, there is especially significant the plant's biomass, which can be used either directly as a solid biofuel or as a raw material for liquid or gaseous biofuels (ŠNOBL, 2004). Among the most significant liquid biofuels belongs ethanol (used especially for power of vehicles). Among well-known gaseous biofuels made from biomass, there can be categorized a biogas (used mainly for heat and electricity generation and power of vehicles). However, this thesis is rather focused on its utilization as solid biofuel in form of briquettes and its properties.

2. Literature review and References analysis

2.1 Hemp (*Cannabis sativa*)

2.1.1 Botanical characteristics

The hemp (also known as *Cannabis sativa*) is a tall, annual and vigorous plant. Its surface is covered with top or glandular hairs (BAXTER and SCHEIFLE, 2000). Industrial hemp may grow up to a height 2-4 m (BOSCA and KARUS, 1998; HONZÍK, 2007). Some references even mention 6 m of height (ŠIROKÁ, 2011). Male plants are higher than female ones. They have pale leaves and grayish-green top and are slimmer. Unlike the male plant, the female plant is darker and has more leaves (MOUDRÝ, 2004). The hemp's roots usually reach 0.4 m to deep, in very deep soils up 2 m (MOUDRÝ, 2004; REHMAN et al., 2012). Stem is initially soft and fleshy, but later becomes woody. Stem contains about 13.5-19.5 % of fibers. Leaves are alternate with short stalks. The fruit is monospermous ovoidal achaene with average weight of thousand seeds about 20 g. (MOUDRÝ, 2004). Hemp usually flourishes for three months since June. The hemp family includes following three species (MOUDRÝ, 2004; SLADKÝ et al., 2004; ŠIROKÁ, 2011):

- *Cannabis indica* – this is the main source of marijuana, due to its high content of delta-9 tetrahydrocannabinol (THC) (above 10 %) in all green parts of the plant

- *Cannabis ruderalis* – is an annual weed, without any psychotropic effects

- *Cannabis sativa* – is the most widespread kind of hemp, belonging to *Cannabaceae* family (as well as hops, for instance), utilized as a renewable source of energy among others. It is warm, water, soil and agronomical technology demanding plant. It is usually being divided into three categories: northern, southern and transient. This species is well known for its weed suppressing features among others and that's why it almost doesn't require any herbicide or pesticide applications.

Fig. 1 – Cannabis plant (MOUDRÝ, 2004)

Fig. 2 – Hemp seeds (MOUDRÝ, 2004)

2.1.2 Growth phases of Cannabis sativa

The growth phases of *Cannabis sativa* may be divided as follows (SLADKÝ et al., 2004):

- Germination

Germination usually takes 3-15 days. Growth of stalk is slower than growth of roots. The plant is sensitive to lack or excess of water and lower temperatures.

- Phase of fast growth

This phase begins after creation of third pair of true leaves and goes up to beginning of buds sprout.

- Development of the buds

This stage is characterized by higher growth of the stem.

- Flowering

The highest amount of the fiber is created during this period. The male flowers start to develop anthers, meanwhile the female plants develop stigmas.

- Ripening of the seeds

The seeds ripen approximately 30-40 days after the stigmas were fertilized.

2.1.3 Utilization

Generally, the industrial hemp is considered as an important agricultural plant, cultivated in all continents, excepting Antarctica. Its origins can be found in Asia (REHMAN et al., 2012). Main way of industrial hemp's utilization is a fiber production. The hemp's seeds may also be used for pharmaceutical purposes (according to MOUDRÝ et al. (2004) the Cannabidiolic acid has a strong bactericidal effect, and thus, can be used as an antibiotic) or as a source of food oil etc., due to its high content of oil. Since the oil contains unique mixture of omega 6 and omega 3 fatty acids, it seems suitable to be used in a food industry. However, *Cannabis* oil has also some disadvantages - for instance the expensiveness, due to relative low hectare yields and rigorous extraction processes. The low stability of oil is often considered as the one of disadvantages as well (BOSCA and KARUS, 1998).

Being called an energy crop, the plant starts to be considered as a suitable fytomaterial for energetic purposes, due to its beneficial combustion properties especially (ŠIROKÁ, 2011). However, these properties may be influenced by a number of factors like moisture, size of the briquettes, oil content etc. Therefore this way of use is still a subject of many researches, including this one.

2.1.4 Legislative regulations and restrictions

The cultivation of hemp for private purposes is forbidden or at least restricted in majority of countries for its psychotropic effects. The plant is notorious for its utilization as a drug, called marijuana, because of various contents (depends on cultivars and kinds) of psychotropic substance THC. Nevertheless, the industrial hemp often contains to 0.3% of THC that is a relatively small amount. Anyway, the main source of marijuana is in *Cannabis indica* with more than 10 % of THC, not usually used for energetic purposes (MOUDRÝ, 2004).

In many countries, the free cultivation is prohibited or at least more often restricted by regulations ordered by legislative. For instance, in the United States of America, private cultivation had been prohibited in 1930's and subsequently banned at the international level in 1961 under the United Nations' Single Convention on Narcotics (BOSCA and KARUS, 1998). MOUDRÝ et al. (2004) mention the hemp cultivation is still strictly prohibited in the US, regardless of its use intention.

In the Czech Republic, there is permitted the cultivation of hemp with less than 0.3 % THC (in restricted amount as well) or breed that has been approved by EU. Some of the approved breeds for 2007/2008 were following: *Bialobrzeskie*, *Fasamo*, *Lovrin 110*, *Cannakomp* and few others. Breeds *Diana* and *Zenit* were approved by European Commitee for cultivation in Romania only. Nonetheless, if total cultivating area exceeds over 100 m^2 (no matter on breed), the reporting obligation arises in any way (HONZÍK, 2007). In the Czech Republic, there was possible the free cultivation of any species of the hemp until 1996 without any reporting obligation (MOUDRÝ, 2004 and ŠIROKÁ, 2011).

Canada, for instance, created Industrial Hemp Regulations under the Controlled Drugs and Substances Act as late as in 1998, saving controlled production, sale, movement, processing, import and export rules. According to these regulations, the products made of hemp must not contain more than 10 μg of THC per one gram, withdrawing stems, leaves and seeds of industrial hemp (BOSCA and KARUS, 1998). Industrial cultivation must be licensed for agricultural or scientific research. Decision of license granting submits current police criminal records (BAXTER and SCHEIFLE, 2000).

2.1.5 Cultivated varieties and cultivars

There exist some differences among used and cultivated varieties of the industrial hemp in various countries. These differences are predominantly given by different legislative orders and interdictions. The particular varieties and cultivars differ from each other in many ways like an average yield per one hectare, strength and properties of the fiber, cultivation conditions etc.

Among the most popular varieties of the industrial hemp, spread in Europe especially, belong *Bialobrzeskie* and *Beniko*. Please, see the **Table 1** below, where some individual (the main) cultivars of industrial Cannabis, that have been approved to be cultivated for energetic purposes in the EU, are mentioned.[1]

[1] The list is not exhaustive.

Table 1 - List of selected cultivars of the industrial hemp, approved for cultivation in the EU (EU, 2011)

Cultivar	Country
Asso, Carma, Carmagnola, CS	Italy
Beniko	Netherlands, Austria
Bialobrzeskie	Czech rep., Austria, Poland
Cannacomp	Hungary
Chameleon	Netherlands
Denise, Diana, Lovrin 110, Zenit	Romania
Dioica 88, Epsilon 68, Fedora 17	France
Ferimon	France, Denmark
Finola	Finland
Monoica	Czech rep., Hungary
Wielkopolskie, Wojko	Poland

2.1.6 Hemp cultivation

The suitable conditions for Cannabis cultivation depend on many factors. The first decisive influence is definitely a selection of a cultivar. The hemp is generally a thermophilic plant, but some cultivars, suitable for cooler climate, have been bred as well. MOUDRÝ et al. (2011) refer the hemp is relatively easy to cultivate plant, that doesn’t requires any special conditions and that can be cultivated in various areas of different latitudes. Generally, the hemp is a fast growing and low input adaptive crop.

2.1.6.1 Soil

The most suitable types of soils for hemp cultivation are deep, well-processable loam or sandy-loam soils with neutral or slightly alcalic pH (7.0-7.5) (BOSCA and KARUS, 1998; BAXTER and SCHIEFLE, 2000; HONZÍK, 2007 and MOUDRÝ et al., 2011) Plants usually poorly tolerate higher acidity. In first weeks after the plants sprout, it is important to pay increased attention to correct irrigation, as the young plants are sensitive to excessive flooding (BAXTER and SCHIEFLE, 2000). However, the lack water in the initial phase severely impacts the growth as well (ŠNOBL et al., 2004).

The next important factor, significantly influencing growth, is fertilization. In the beginning of the growth phase the hemp requires manure with high content of nitrogen. Lack of nitrogen may lead in deterioration of the fiber quality (BOSCA and KARUS, 1998). Noticeable symptom of lack of nitrogen is yellow coloring of leaves. If the lack of nitrogen is observed, it is suggested that some (optimally) organic fertilizer (e.g. manure or slurry) be applied. (MOUDRÝ et al., 2011)

2.1.6.2 Crop rotation

The suitable forecrops for the hemp would be crops leaving the soil well stocked with nutrients, especially with nitrogen. Some tuber crops, corn, legumes or alfalfa may be used for this purpose (SLADKÝ et al., 2004 and MOUDRÝ et al., 2011).

2.1.6.3 Harvest

Selection of appropriate harvest method must always be chosen with regard to its intended use. If long stem fibers intended for textile industry are demanded, the harvest method is different from the one used for seeds that oil is subsequently extracted from. Alternatively, there exists combined use for both fiber and seed gaining. The monoescious (modern plants) and dioecious plants (historical plants) are also harvested in different ways (HONZÍK, 2007).

Since the hemp stems could be reeled during the reaping process, the standard rotating reaping machines, usually used for harvest of fodders, are excluded (SLADKÝ et al., 2004 and MOUDRÝ et al., 2011). SLADKÝ et al. (2004) consider the harvesters with reciprocating cutting bars as the most effective and suitable for the hemp’s cutting, because there are no problems with fibers reeling. In Netherlands and Germany some experiments with specially modified corn cutting machine have been carried out. The stems are currently shortened to length of about 60 cm and left on the field to dry. Every three days during the next 14 days the mowed biomass is turned out to ensure even drying

(MOUDRÝ et al., 2011).

At the University of East Anglia (UEA) in Norwich, UK, there was recently developed a new type of special hemp harvester by local engineer Stephen Eyles. It is a multi-blade harvester equipped with three reciprocating cutting bars (UEA, 2010). The bars are consecutively positioned in a trailer in adjustable heights from the ground level. The trailer is attached to a tractor. The mown crops rest on the field and later are dried by repeated turning out. The main advantage of this method is undoubtedly its speed. The developer states this method helps to avoid the losses of biomass as well.

The time of harvest is scheduled with regard either to maturity of the seeds or level of defoliation (BENHAIM, 2011 and MOUDRÝ et al., 2011). According to SLADKÝ et al. (2004), the optimal time of harvest is in August. If the seeds are needed, the harvest can be even put over by September, though. REHMAN et al. (2012) contrary think the optimal time for the hemp harvest is usually in late September and in October, but from lower moisture content point of view, they concede as more suitable date of harvest to be in spring (March and April). In 2012 PRADE et al. published a research focused on influence of the harvest date on the combustion properties of hemp biomass. In this study, they mention, and thus confirm, the lower moisture content in biomass harvested in spring.

2.2 Mechanical and physical characteristics of briquettes

The suitability of use to individual plant's materials for energetic purposes is given by set of characteristics and indicators. For the Czech Republic, the characteristics are specified by European Standard for Specification and Classification of Solid Biofuels (Evropská norma pro specifikace a klasifikace tuhých biopaliv "**ČSN EN 14961-1 Tuhá biopaliva – Specifikace a třídy paliv**"). The main characteristics examined according to this standard, are mentioned in **Tab. 2.** below.

Table 2 - The mechanical and physical characteristics and indicators of solid biofuels and their units (according to the above mentioned standard)

Parameter	Abbreviation	Unit
Diameter	D	*mm*
Length	L	*mm*
Moisture	M	*%*
Ash	A	*%*
Particle density	DE	*g/cm*^{3}
Net calorific value	Q	*kcal/kg (J/kg)*
Mechanical durability	DU	*%*
Bulk density	BD	*g/cm*^{3}
Amount of fines	F	
Deformation temperature (Ash fusion temperature)	DT	*°C*

> "*In order to understand the suitability of biomass for briquetting, it is essential to know the physical and chemical properties of biomass which also influence its behaviour as a fuel*" (NALLADURAI et al., 2008)

Every biomass material has different values of the characteristics above, thus not every plant or variety of the plant, are suitable for energy gaining by combustion. Some crops are intentionally cultivated for heat or another way of energy gaining. These crops are called energy crops (sometimes power plants). Apart from the hemp, among the next significant energy crops belong especially Corn (*Zea mays*), Sudan grass (*Sorghum bicolor*), Willow tree (*Salix herbacea*), Switchgrass (*Panicum virgatum*), Sugar cane (*Saccharum sp.*) etc.

The utilization of plant biomass for energy generation by combustion offers several advantages (ŠNOBL, 2004):

- Possibility of fast and easy renewal
- Regional availability
- Considerateness to the environment (the plant biomass combustion doesn´t increase a CO_2 level in the atmosphere)

2.2.1 Briquettes

The term briquette refers to a block of flammable material pressed often into a cylindrical shape. As mentioned above, in case of plant biomass briquettes, the material must be disintegrated by a grinding mill prior to pressing (PLÍŠTIL et al., 2005). The aim of this disintegration is a reduction of the particles size. The material also becomes softer.

2.2.2 Mechanical durability

The most significant mechanical property examined in solid fuels (briquettes and pellets) is the mechanical durability and the particle density. Mechanical durability is a qualitative indicator, describing an ability of the material to cling together during manipulation. As the material is disintegrated and must hold together, the solid biofuels are liable to the crumbling during transit and storage. The crumbling processes have few negative effects. Besides the loss of material occurrence, there are produced dust emissions during the scrambling process, which may cause few inconveniences including a health hazard and undesirable inhomogeneous combustion processes inside combustion unit (TEMMERMANN et al., 2006).

„*Particle density is calculated as the ratio of the mass to the sample volume including pore volume*“ (RABIER et al., 2006)

RABIER et al. 2006 distinguish methods of estimation of the particle density for briquettes and pellets into three basic groups namely *Liquid displacement methods, Stereometric methods* and *Solid displacement methods*. Each of them includes several methods based on different principles. The liquid displacement methods contain *Hydrostatic method, Buoyancy method* and *Paraffin coating*. All these methods are based on Archimedes principle. When the sample is submerged into liquid, it displaces certain amount of the liquid. The particle density can be estimated with the aid of the displaced amount of liquid.

The stereometric methods use so called length-measuring instruments to measure the dimensions (length, width, height…) of a single regularly shaped particle. Subsequently the volume of the nearest geometrical shape is calculated and thereby the total volume of the sample can be determined (RABIER et al., 2006).

Using powder pycnometer the solid displacement method is carried out. The sample volume is estimated by amount of displaced volume of the powder (RABIER et al., 2006).

2.2.3 Moisture content

Most of plant biomass materials are naturally hygroscopic. It means they may absorb moisture present in form of humidity in the air (SINGH, 2003). The absorbed moisture in biomass may deteriorate some of its mechanical and physical properties and characteristics. According to JENSEN et al. (2006), the price of the fuel as well as its main properties such as combustion optimization, storage management and handling properties are given by moisture content.

SINGH (2003) mentions that if the biomass is intended to be used for gasification, the limited amount of moisture in the biomass may positively influence a quality of the gas. However, the main disadvantage of high moisture content in briquettes is deterioration of its strength and durability (SINGH, 2003 and NALLADURAI et al., 2008). Next significant disadvantage is a prevention of its utilization for thermo-chemical conversion processes (SINGH, 2003 and CHEN et al., 2009). High moisture content has a negative impact on the efficiency of the combustion (GIL et al., 2010). Energy yield is usually lower, while there is higher moisture content (REHMAN et al., 2012). Contrary, the lower moisture content improves especially combustion properties and may help to decrease losses due to microbial degradation during storage (PRADE et al., 2012).

The excess of moisture can be removed from the material by using special dryers. Determination of the moisture content works on the same principle. The sample is weighed prior to the examination and then put into dryer. After a set time, the sample is removed from the dryer and weighed again. The moisture content is calculated with a difference of the two weights.

As mentioned above, the moisture content present in biomass may be influenced, to a certain extent, by appropriate harvest time choice. REHMAN et al. (2012) recommend that the energetic crops be harvested in March and April, if the biomass is designated as a solid fuel.

Optimal moisture content in plant biomass intended for combustion should get into the range of 10-15 % (CHEN et al., 2009).

2.2.4 Ash content

Combustion of any solid material produces a solid residue, called ash. In case of ash content remaining after plant biomass combustion, two basic characteristics are examined – the amount of ash and its (chemical) composition with related physical properties. One of the most important physical properties measured in the biomass ash, is the ash melting point that may result in ash sintering. The slag produced by sintering of ash may severely damage the combustion device from inside, and besides that, it adhere to the inside wall of the boiler and causes difficulties with its removal and cleaning (KOTLÁNOVÁ, 2010). The ash melting temperature depends on many factors, mainly on chemical composition of the biomass material. PRADE et al. (2011) report the chemical elements Si, K, Na, Al, Mg, Ca, Cl, S and P to negatively influence the ash melting behavior, and also fouling corrosion of the boiler.

The ash produced by combustion of a plant biomass usually contains trace amount of some heavy metals, therefore the ash seems suitable as a fertilizer or as a source of minerals (HANUŠ, 2010).

The ash content of the wooden briquettes is normalized on 1.50 %. The value may change in correlation with kind of biomass used for briquette preparation, though. The ash content of non-wooden briquettes may even excess 10 % (KOTLÁNOVÁ, 2010).

2.2.5 Calorfic values

2.2.5.1 Gross calorific value

Gross calorific value (GCV) is the total amount of energy released when the fuel is completely and perfectly burned in an oxygen atmosphere, including the latent heat contained in water vapors (NÚÑEZ-REGUEIRA et al., 2000 and MCKENDRY, 2001). GCV belongs among the major investigated energetic properties of both solid and nonsolid biofuels. The GCV is expressed on a per mole basis or as a mass or a volume of the fuel (GUIBET, 1997). Amount of heat energy during combustion is measured by a device called calorimeter. Procedure of the heat measurement is called calorimetry. There exist several types of calorimeters used in calorimetry, e.g. flame calorimeter, solution calorimeter, bomb calorimeter etc.

2.2.5.2 Net calorific value

Net calorific value (NCV) is gained, not by measurement, but calculation. The NCV does not include the latent heat contained in water vapors, unlike the GCV. LLORENTE et al. (2007) report the NCV is the most important criterion for determining of price of biofuel for final consumers.

The NCV is affected by several factors. LLORENTE et al. (2007) and EVERARD et al. (2012) state the GCV and NCV relate to the carbon and the ash contents. According to LESTANDER et al. (2005) and EVERARD et al. (2012), the NCV is also influenced by the moisture content in biomass.

2.2.6 Flue gas emissions

The climatic conditions on the Earth have been changing very rapidly in recent years. Number of various natural disasters and related damages of property and human lives still increases every year. There are increased occurrences of tornadoes, iceberg melting etc. These negative phenomena are caused by combustion of fossil fuels in particular (VÁŇA, 2003). Fossil fuels have another significant disadvantage. They are exhaustible and non-renewable. Hence, the tendencies of recent years and decades have been the seeking renewable and environment friendly sources of energy. The utilization of biomass as an alternative is generally considered as one of the possibilities.

One of the significant characteristic of solid biofuels in considerateness to the environment is undoubtedly monitoring of concentrations of gases emitted during the fuel combustion. KOLONIČNÝ (2010) claims that the amount of harmful emissions is primarily influenced by correct way of combustion. ROY and CORSCADDEN (2012) mention that selection of biomass is conductive to mitigate to green house gas emissions before all. MANKOWSKI and KOLODZIEJ mention combustion of the hemp's biomass, as an alternative to fossil fuels, leads to reduction of CO_2 emitted to atmosphere. They also claim that one hectare of hemp vegetation absorbs about 2.5 tons of CO_2, which significantly contributes to reduction of greenhouse effect.

Since the fossil fuels negatively impact the atmosphere mainly with greenhouse gases, the greatest attention is paid to levels of carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxides (SO_x) and nitrogen oxides (NO_x). The perfect combustion is characterized by production of two major products – CO_2 and H_2O (NÚÑEZ-REGUEIRA et al., 2000 and OBERNBERGER et al., 2006). Both these combustion's products and moreover SO_2, N_2 and O_2 can be found in the form of flue gas (VILLENEUVE et al., 2011).

The composition of flue gas emissions is not only influenced just by chemical composition of biomass, though. Rates of individual gases, emitted during combustion, are influenced by physical properties (e.g. moisture content) of the biofuel and combustion equipment as well. All these factors interact together and produce unique levels of gases concentrations and substances (VILLENEUVE et al., 2011).

3. Objectives

This thesis aims to evaluate the appropriatness and applicability of hemp's biomass utilization for energetic purposes in form of solid biofuels (briquettes), based on results of literature analysis and practical characteristics measurements.

Specific objectives:

1) Production of briquettes from hemp stem biomass and hempseeds cake mixed in various ratios.
2) Measurement of the main mechanical and physical characteristics such as moisture content, mechanical durability, gross and net calorific value as well as ash content and emissions during combustion.
3) Evaluation of briquettes quality based on measurements.
4) Establishment of experimental field and comparison of yield and moisture content of hemp's varieties *Bialoobrzeskie* and *Ferimon*

4. Materials and methods

The experiment was divided into two parts. First part was focused on determination of two significant characteristics of two examined varieties of industrial hemp - *Bialobrzeskie* and *Ferimon*. The measured characteristics were the yield per hectare and the moisture content. The biomass of the two varieties was not used for the briquettes preparation.

Second part of the experiment was mainly focused on briquettes made from variety *Bialobrzeskie* and determination of their moisture content, mechanical durability, gross and net calorific values, ash content and gases’ emissions.

4.1 The experimental field establishment

The experimental field was established on the experimental and demonstrative fields belonging to the CULS campus located in the north of Prague, the Czech Republic (Geographical coordinates: 50° 7' 37.8114"N 14° 22' 30.108"W), on 14th May 2012. Total area was set up to 25 m^2 of *Bialobrzeskie* variety and equal size of the field was sown by *Ferimon* variety. One meter wide pathway was kept between these two fields. Total seeding rates ensuring normal density and maximum yield were calculated of 70 kg/ha for *Bialobrzeskie* variety and 63.6 kg/ha for *Ferimon* variety. Recalculated on total sown area, the seeding rates equal to 0.175 kg of *Bialobrzeskie* and 0.159 kg of *Ferimon*. The sowing was implemented by manually powered seeding machine, pictured in **Fig. 3** below.

Fig. 3 – Manually powered sowing machine

The machine is equipped with a front wheel, which rolls the soil surface and currently works as a sliding wheel. The soil rolling is implemented for better soil compaction, reduction of lumpiness and improvement of the soil capillarity. There is a seeding mechanism, behind the wheel. This mechanism consists of seed coulter, seed line and batcher, which is connected to a lever on wood handle. When pressing the lever, the dose of seeds is released into a shaft below. The shaft is rotating as the whole machine is moving and thus the seeds are moved to the seed line and finally falling down to the seed coulter. This mechanism serves for equal distribution of the seeds into a row. The doses of the seeds that are released after each lever pressing have to be calculated and divided, prior to sowing. Once the dose is released, it is necessary to refill the batcher manually with next dose and the whole process is then repeated. After the seeds are placed, the row is covered with soil by seed's coulter and the soil surface is rolled again by the smaller wheel in the rear.

4.2 Biomass preparation for briquetting

Before the fytomass is pressed into form of briquettes or pellets, it is necessary to grind it in a special biomass grinder. The grinder has a system of rotating knives, which cut individual parts of the plant into smaller and fine particles that are more appropriate for pressing in a briquetting press. The smaller particles go through a special screen located under the grinding chamber. The particles that are not sufficiently crushed are either crushed later or remain inside the crushing chamber, and are removed when the chamber is full. The grinding machine, including its mechanism, is pictured in the **Fig. 4** and **5** below. The experiment was carried out in premises of the Faculty of Engineering, CULS Prague.

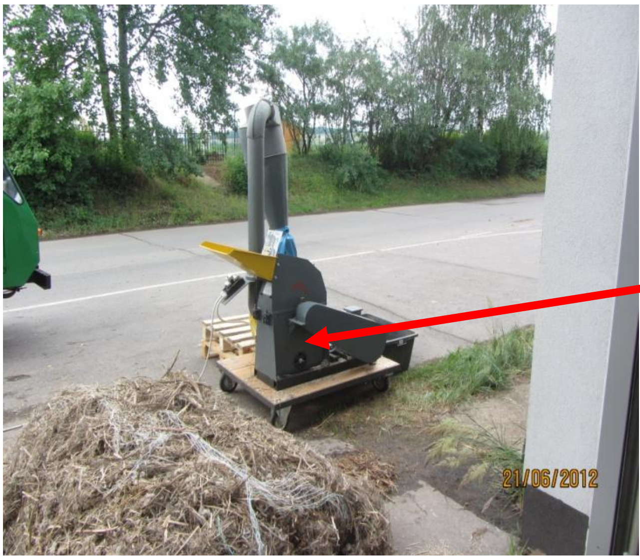


Fig. 4 – The grinder machine - hammer mill 9FQ – 40C

Fig. 5 – Chamber with the system of rotating knives

The biomass briquetting presses and grinders are generally appropriate for densifying of biomass with less than 15 % of moisture content. After the biomass is sieved through the screen, the particles exit machine into a bag, fasten up with outlet. Since the hemp's biomass contains high amount of fibers, the fibers cannot be completely disintegrated, and rest reeled inside the chamber. Once the mechanism is clogged with the fibers, it is necessary to remove the waste.

For the purposes of this experiment, the hammer mill type 9FQ – 40C was used. The hemp's biomass was ground with 5 mm screen. The grinding mill input is 5.5 kW.

The hemp's plants were separated from their seeds prior to grinding. The seeds were used separately for oil gaining. The stem biomass was ground and then put into plastic bags. The seeds' press cake gained from oil pressing, were later used along with the ground stem's biomass for preparation of mixtures.

4.3 Briquetting

The biomass briquetting was carried out with briquetting press BrikStar 50-12 (Briklis, Ltd., Malšice, Czech Republic) belonging to the FTA in premises of the FE, CULS Prague. The BrikStar is a hydraulic piston press, which allows production of briquettes of diameter 65 mm and length 30-50 mm. The scheme of the press is displayed in **Fig. 6** and the machine itself is pictured in **Fig. 7**.

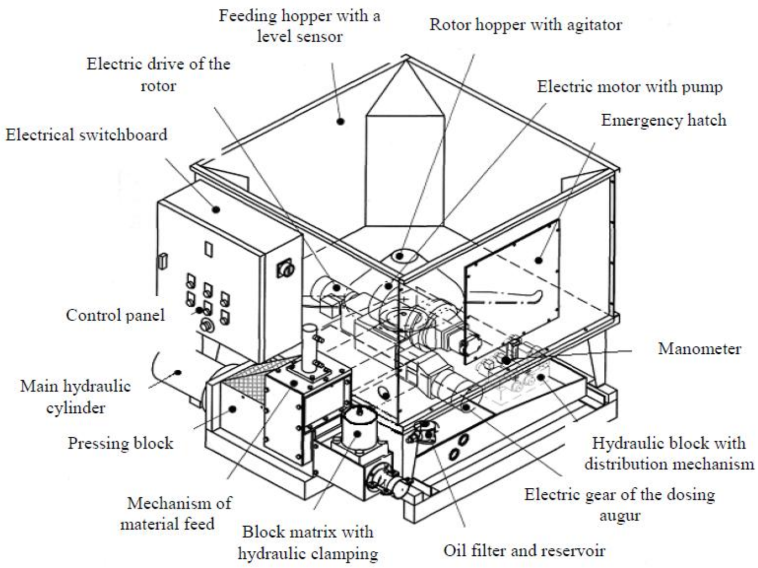


Fig. 6 – Overall layout of briquetting press BrikStar 50-12 (IVANOVA, 2012)

Fig. 7 – The pressing machine BrikStar 50-12

The significant technical parameters of briquetting press Brikstar 50-12 (IVANOVA, 2012; POBEDINSCHI et al., 2009):

- necessary voltage ………………………………….……………................ 400 V;
- control circuit voltage ……………………………….…….…............... 24 V;
- power input required ………………………………………….............. 5.6 kW;
- electric intensity of protection circuit breaker …………................ 16 A;
- pressing duration without adding hydraulic liquid ……................6 – 8 hours;
- calculated production capacity ……… …………………….................. 50 kg.hour^{-1};
- overall equipment mass ……………………………………................. 790 kg;
- raw material hopper volume ……………………………………............ 1.0 m^3;
- piston: ....6 runs.min.-1 and length of piston run……............ 180 mm;
- level of acoustic pressure ……………………………………............. 90 dB;
- expected lifetime of matrix, piston and hydraulic pump .... 2,000 hours;
- maintenance (change of filters in the hydraulic system)............ after 500 hours;
- acceptable moisture of raw materials ……………………........... 8 - 12 %;
- maximum working pressure …………………………………........... 18 MPa;
- maximum working temperature …………………………….............. 60°C;
- optimum temperature of the environment (at pressing)......... between +5 + 35 °C

For the purposes of this experiment, totally five mixtures of Polish variety *Bialobrzeskie* of various ratios of stem‘s and press cake‘s biomass were prepared. The biomass from press cake and stems were mixed in the following ratios (press cake:stem): 1:2, 2:1, 3:1, 4:1 and 5:1.[2]

The biomass pressed into form of briquettes or pellets holds together, because the Van der Waals forces are effective. During the pressing process, certain amount of heat is produced, because the distance among individual molecules is reduced to a minimum, thus, the molecules that are in a constant motion, crash each other more rapidly. The hydraulic pressure that forms the biomass must be sufficient to ensure required hardness of the briquette. If the pressure is too high, the briquette is a hard and a resistant, however, it may be costly ineffective, due to high amount of spent energy. (IVANOVA, 2012) The pressure used for the mixtures preparation was 16.3 MPa.

4.4 Mechanical durability determination

Mechanical durability is measured with using special durability drum (**Fig. 8**). The device is powered by an electric motor (located outside the drum). Durability drum is a cylindrically shaped device of 160 l of volume with following dimensions:

[2] Please, note the mixtures will be in (stem:press cake) ratio format in the entire document.

a) Inside length: $598 \pm 8\,\mathrm{mm}$

b) Inside diameter: $598 \pm 8\,\mathrm{mm}$

The drum must be made of iron sheet with straight inside surface. The drum is equipped with a steel divider of the following dimensions:

a) Length: $598 \pm 8\,\mathrm{mm}$

b) Height: $200 \pm 2\,\mathrm{mm}$

The dimensions above are set by "**ČSN EN 15210-2 Tuhá biopaliva – Stanovení mechanické odolnosti pelet a briket – Část 2: Brikety**" standard. This standard also sets the conditions and procedure of the examination and equation for final calculation of the mechanical durability.

Fig. 8 – Rotating drum (IVANOVA, 2012)

When the briquettes are put inside and the drum is closed, motor is activated and drum begins to rotate. The briquettes repeatedly fall down during each turn and impact the hard surface, thus, their inside structures are damaged and the crumbling occurs (NALLADURAI et al., 2008). Total time of the rotating is determined by required number of turns. According to above named standard, the required number of turns should be

105 ± 0.5. In case of this experiment, the time necessary to reach up to 105 turns was calculated on 4 minutes and 28 seconds.

After the process is done, the briquettes are separated from crumbled material and mechanically or manually screened via metal wire sieve (TEMMERMANN et al., 2006). Sieve dimensions are set approximately to 2/3 of briquettes diameter, but must not exceed 45 mm according to **ISO 3310-1**. The residues remaining on the sieve are then weighed. If necessary, the process can be repeated later.

The mechanical durability is calculated according to a following equation:

$$DU = \frac{m_A}{m_E} \times 100$$

where

DU - mechanical durability (%)

m_A - total final weight of the sample (g)

m_B - total initial weight of the sample (g)

KOTLÁNOVÁ (2010) claims, the mechanical durability should not decrease below 90 %, otherwise the fuel would not be much appropriate for the combustion.

4.5 Determination of moisture content

The moisture content of the biomass was measured with use of drying method in accordance with "**ČSN P CEN/TS 14774-1 (-2, - 3)**" standard in lab of the FTA, while the control measurements were carried out in labs of the RIAE in Prague. The experiment was carried out using oven MEMMERT model 100-800 (Schwabach, Germany) (**Fig. 9)** with total volume about 100 dm^3, located in the lab, belonging to the FTA. This oven is time programmable up to 24 hours.

Fig. 9 - The oven MEMMERT model 100-800

From each of the five mixtures, two smaller samples were taken and weighed as well as the samples of hemp's plants (*Bialobrzeskie* and *Ferimon*), cultivated on the experimental field. For purposes of the control measurement in RIAE labs, one sample was only taken. The samples were then inserted into the drying oven, where they were subsequently dried at 105°C for 8 hours, according to above named standard. Shortly afterwards, the samples were weighed again using laboratory scale (balance) KERN EW 3000 - 2M or DENVER INSTRUMENT MXX-2001 with preciseness up to 0.01 g (IVANOVA, 2012) (**Fig. 10)** The moisture content was calculated from the differences of the initial and final weights, according to a following equation:

$$w = \frac{m_w - m_d}{m_w} \times 100$$

where

w - the moisture content (%)

$\boldsymbol{m_w}$ - the total weight of the sample prior to drying (g)

$\boldsymbol{m_d}$ - the total weight of the sample after drying (g)

Fig. 10 – Laboratory scale Denver Instrument (IVANOVA, 2012)

4.6 Ash content measurement

The ash content was measured in muffle furnace **LAC** (**Fig. 11**), belonging to the lab of the FTA. For these purposes the same laboratory scale as in previous experiment was used. The examination was carried out in accordance with **ČSN P CEN/TS 14775** and **DIN 51 790** standard for determination of the ash content.

Fig. 11 - muffle furnace model LAC

The principle is similar to the one used for moisture content measurement. Two samples of hemp's biomass taken from each of the five mixtures were weighed prior to the measurement and put to the muffle furnace. According to above mentioned standard, the samples were first exposed to temperature of 250 °C (reached in first 40 minutes) for 60 minutes. This temperature was then being increased up to 550°C, during next 30 minutes. The final temperature was kept for last 120 minutes, until the experiment was terminated. The cooled samples were then weighed again and the ash content was calculated from gained values, according to a following equation:

$$A = \frac{m_i - m_f}{m_i} \times 100$$

where

A - the ash content (%)

$\boldsymbol{m_i}$ - the total weight of the sample prior to combustion (g)

$\boldsymbol{m_f}$ - the total weight of the sample after combustion (g)

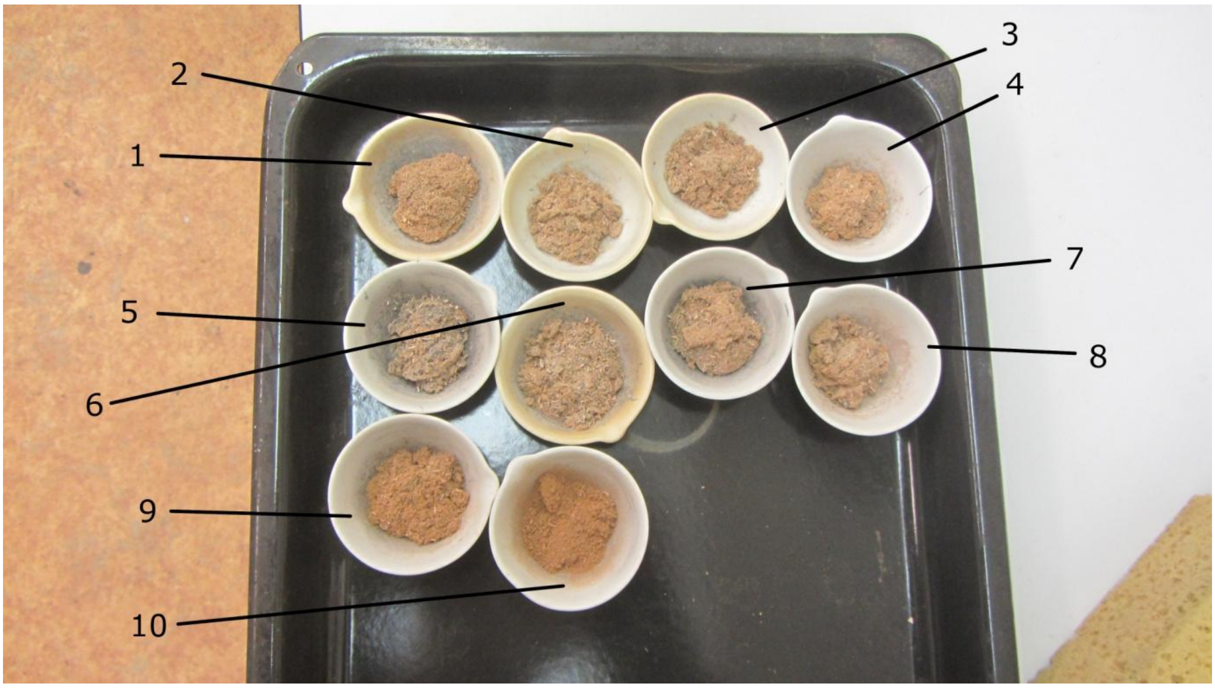


Fig. 12 – The hemp biomass samples after removal from the muffle furnace (numbers 1 and 2 – 3:1; 3 and 4 – 4:1; 5 and 6 – 1:2; 7 and 8 – 2:1; 9 and 10 – 5:1)

4.7 Determination of the net and the gross calorific values

Determination of the GCV was measured in labs of the RIAE. For the purposes of this experiment the adiabatic bomb calorimeter MS – 10A, including its accesories (calorimetric bomb, oxygen pressure gauge – up to 60 Bar, slot for the calorimetric bomb placement, oxygen cylinder with feed valve and pressure gauges, thermometer with value, range till 500 °C; tank for 2 liters of hot water – 24 °C) and laboratory scale KERN ABJ with preciseness up to 1×10^{-4} g (IVANOVA, 2012) (**Fig. 13**) were used.

Fig. 13 – The bomb calorimeter MS – 10A (left) and calorimetric bomb, oxygen pressure gauge, slot for the calorimetric bomb placement and laboratory scale KERN ABJ (right) (IVANOVA, 2012)

The technical specification of the bomb calorimeter MS – 10A (POBEDINSCHI et al., 2009 and IVANOVA, 2012):

- *volume of combustion vessel, bomb…………..300 ml;*
- *temperature resolution……….……………0,00025 K;*
- *accuracy (benzoic acid)….……………………..0,02 %;*
- *measuring range…………………………..…..3–30 KJ;*
- *adjustable measuring time……… 5,8,16,24,32 min;*
- *benzoic acid calibration mode…………….….32 min;*
- *dimensions……………………………250x320x403 mm;*
- *weight.…………………………………………..20 kg;*
- *power consumption ………………………..….55 VA.*

The GCV measurement was performed with use of the bomb calorimeter, according to **ČSN P CEN/TS 14918** standard. Biomass sample about known weight (around 5 g) was put into a stainless steel high pressure vessel, known as the bomb. The bomb was sealed off with oxygen atmosphere. The sample was put into the calorimeter with known amount of water of known temperature, electronically ignited and burned. The combustion products CO_2 and H_2O were then cooled to standard temperature. The heath of combustion is measured with exact measurement of rise of the temperature of water, calorimeter itself and the bomb inside (MCKENDRY, 2001). The gross GCV is then calculated according to the equation:

$$Q_g^a = \frac{dT_k \times T_k - c_1 \ + c_2}{m}$$

where

Q_g^a ***(GCV)*** - the gross calorific value (heat of combustion) (J/g)

$\boldsymbol{dT_k}$ - temperature jump (°C)

$\boldsymbol{T_k}$ - the heath capacity of the calorimeter (9161 J/°C)

$\boldsymbol{c_1}$ - repair of benzoic acid (20 J)

$\boldsymbol{c_2}$ - repair of the heath released by burning spark wire (70 J)

m - weight of the material sample (g)

The values obtained that way must then be converted to the net calorific value in accordance with **ČSN 44 1352** standard. The difference between the gross and the net calorific values is the water content in the analyzed sample. Accordingly the net calorific value is calculated with the following equation:

$$Q_i^a = Q_g^a - 24.42 \times (W_a + 8{,}94 \times H_a)$$

where

Q_i^a ***(NCV)*** - the net calorific value (J/g)

24.24 - coefficient of 1% of water in the sample on temperature of 25°C (J/g)

W_a - water content in the sample (%)

8.94 - coefficient for the conversion of hydrogen to water

H_a - hydrogen content in the sample (%)

4.8 Determination of flue gas emissions

Measurement of the emissions was carried out in labs of the RIAE in Prague. The experiment was performed with use of tiled stove and flue gas analyzer TESTO 350 XL equipped with a measuring probe (**Fig. 14-16**)

Fig. 14 – Tiled stove SK-2 RETAP 8 kW (author HUTLA)

Fig. 15 – Flue gas analyzer TESTO 350 XL

Fig. 16 – The measuring probe

As seen in the photographs above, the device is connected to the measuring probe. The probe is inserted to gas outlet with its spike. The spike contains gas sensor which is able to record concentrations of two, for the experiment significant gases – carbon monoxide (CO) and nitrogen dioxide (NO_2), further temperature of the atmosphere, probe temperature, velocity of the leaving gas, pressure and amount of gas leaving in given stretch of time. However, for the purposes of this experiment, the two main gases and probe's temperature are the only significant.

Measuring of each mixture took 60 minutes in total. During these 60 minutes, the probe was analyzing emissions concentrations in period of 10 minutes always followed by 5 minutes long period of the probe´s cleaning (meantime next dose of the fuel was stoked up). It means that 4 measuring periods took place during the whole time of the measurement. In the 10 minutes period the flue gas analyzer was recording values of the individual items once per every 6 seconds, therefore the gained values had to be reduced.

The result values of the measured combustion products were subsequently converted to the reference concentration of oxygen in accordance with **ČSN 07 0240:1993 čl. 5.7.20** and **5.7.23** that set the following equation and values (Department of Environment of the Czech Republic´s regulation no. 13/2006):

$$c_r = c_m \times \frac{21 - O_{2r}}{21 - O_{2m}}$$

where

$\mathbf{c_r}$ - the concentration of individual component of combustion products at the reference concentration of oxygen (ppm)

$\mathbf{c_m}$ - the concentration of individual component of combustion products at the measured concentration of oxygen (ppm)

$\mathbf{O_{2r}}$ - the reference concentration of oxygen (11%)

$\mathbf{O_{2m}}$ - the measured concentration of oxygen (%)

21 refers to approximate concentration of oxygen in the atmosphere (%)

The values of concentration were further converted to mg/m^3 according to following equation:

$$mg/m^3 = \frac{ppm}{M} \times 24.45$$

where

M – molecular weight (no unit)

24.45 – volume of a mole of a gas vapor (l)[3]

4.9 Statistics

The basic analysis of statistical quantities was performed with software Statistica, version 10 (64-bit) made by StatSoft.

[3] This value is valid for pressure of 1 atmosphere and temperature of 25°C.

5. Disscusion and results interpretation

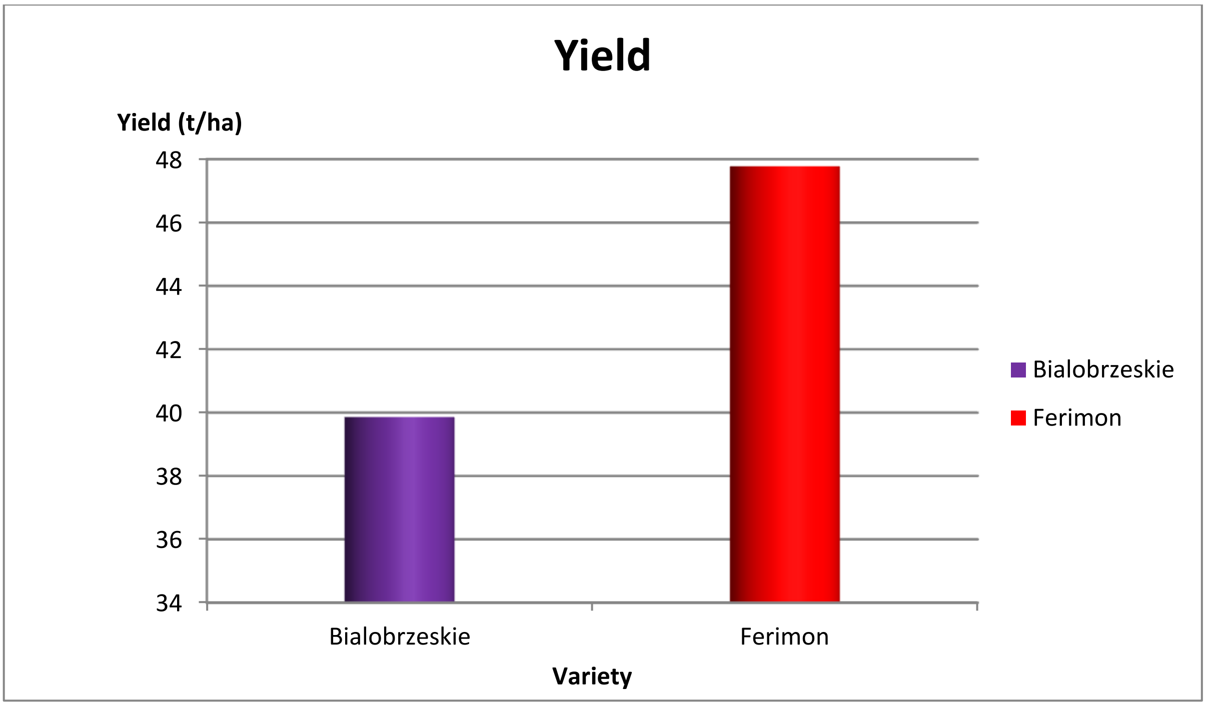
5.1 Experimental field analysis

Fig. 17 – **21** display the experimental field in various phases of growing. The pictures were acquired in following days and weeks after the field had been established (respectively on May 16th and 25th, June 11th and 21st and November 25th) as seen in the photographs. The harvest of the field took its place on October 10th. The field was irrigated once right after the sowing had been finished. From then to the harvest, the field was neither fertilized nor irrigated again.

Fig. 17, 18, 19, 20 and 21 – The experimental field

5.1.1 Yield analysis

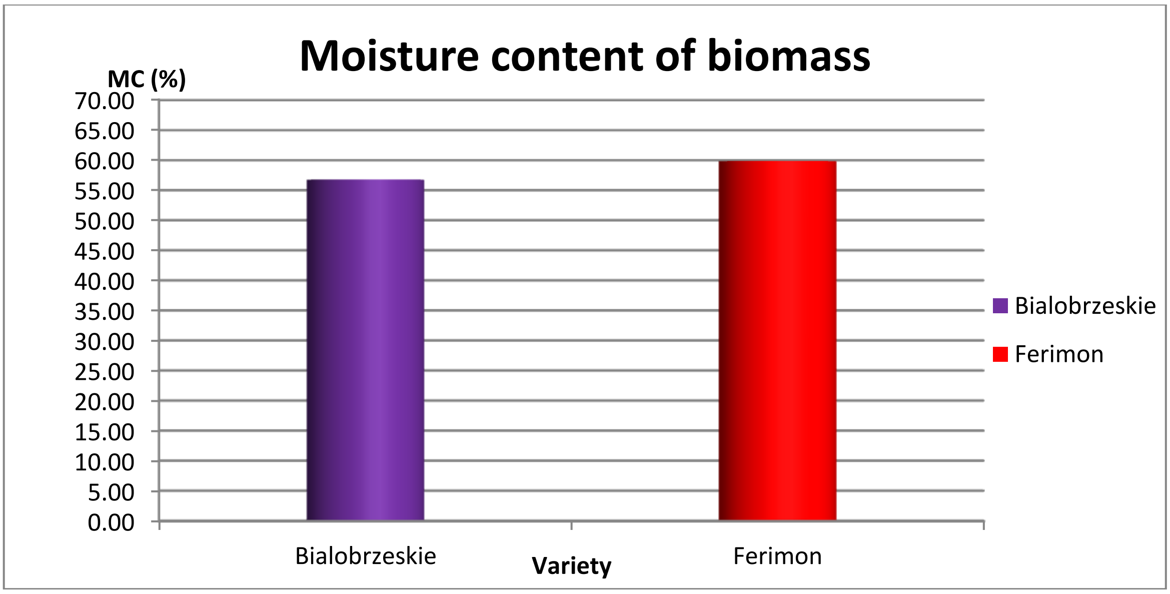
Graph 1 below shows the results of yield per hectare examined in two hemp's varieties *Bialobrzeskie* (39.86 t/ha) and *Ferimon* (47.78 t/ha). Both varieties exceeded expected yields. According to research carried out by KREJČOVÁ in 2012, the yield of *Bialobrzeskie* variety was measured and calculated as 24.3 t/ha. CAPPELLETTO et al. performed research about hemp's yield and cannabinoid composition in 2000. *Ferimon* variety's yield was measured and calculated as 28.82 t/ha in their research. These deviations may have been caused by few factors, i. e. different weather conditions, different soil composition etc.



Graph 1 – Yield per hectare of two varieties of industrial hemp

5.1.2 Moisture content analysis

Graph 2 shows calculated values of moisture content for *Bialobrzeskie* (56.76 %) and *Ferimon* (59.83 %) varieties. Both the values are very close to each other. The difference is 3.07 %.



Graph 2 – Comparison of moisture content of two varieties of industrial hemp.

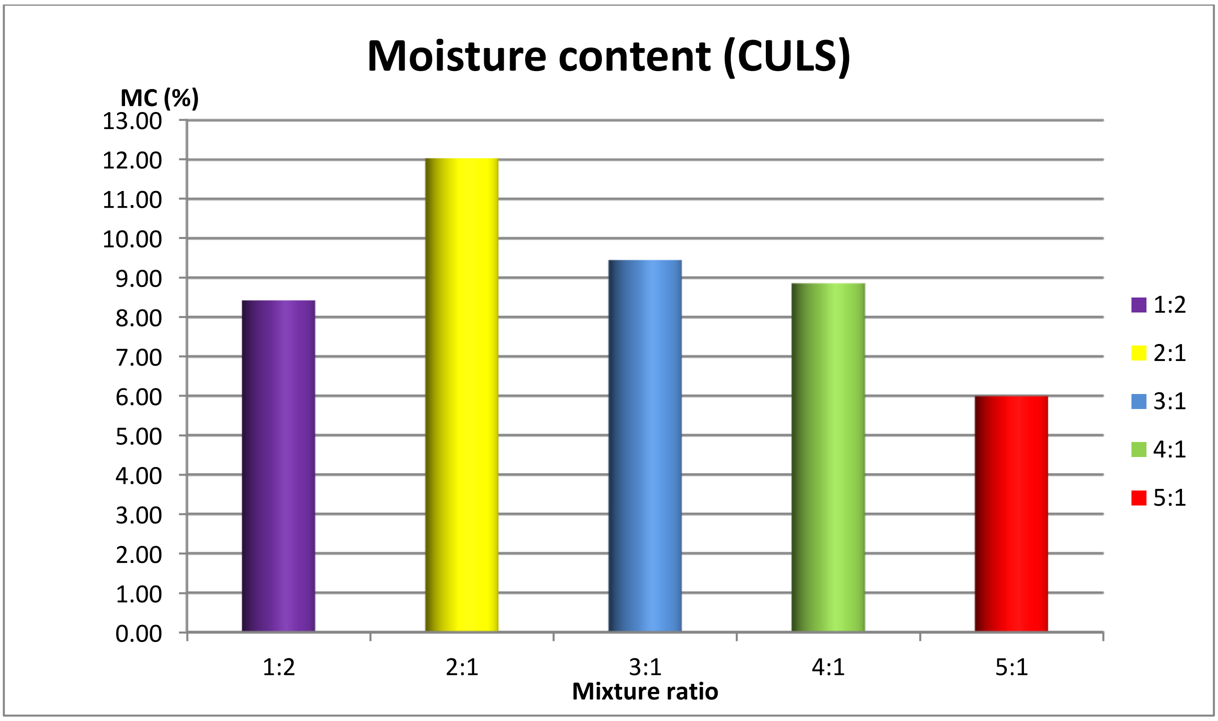
5.2 Evaluation of briquettes properties

5.2.1 Moisture content analysis

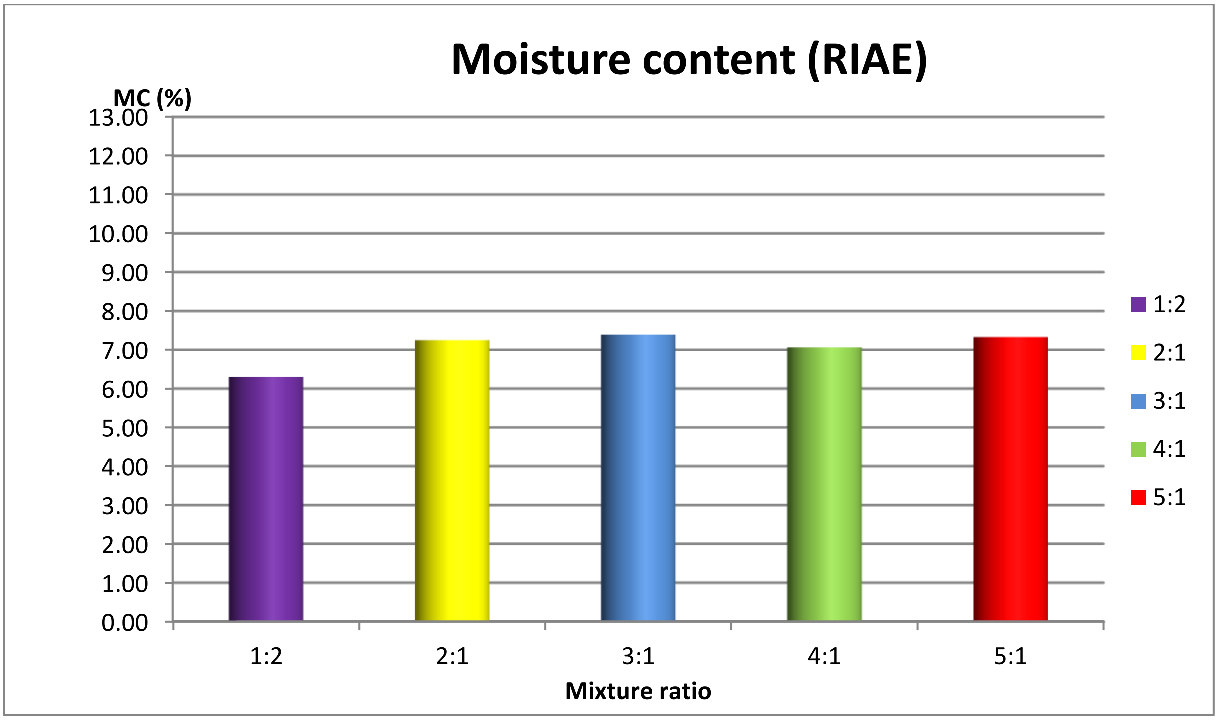
The **Graphs 3** and **4** below represent the mean percentage values of moisture content measured in the individual mixed briquettes in both CULS and RIAE labs. The comparison of the values can be seen in **Table 3** as well.

Table 3 – Comparison of average values of MC

Mixture ratio	1:2	2:1	3:1	4:1	5:1
MC % (CULS)	8.43	12.04	9.45	8.86	5.99
MC % (RIAE)	6.30	7.25	7.39	7.06	7.33



Graph 3 - Comparison of moisture content in the five mixtures (measured in CULS lab)



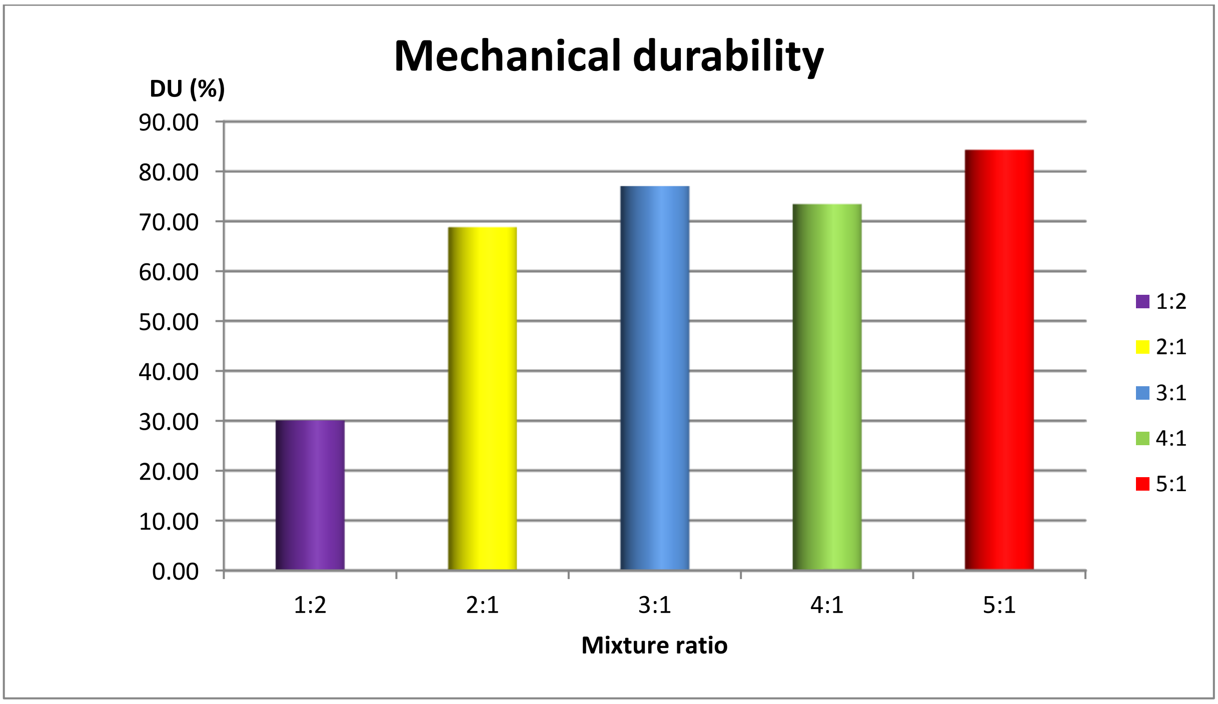
Graph 4 – Comparison of moisture content in the five mixtures (measured in RIAE lab)

As can be seen in the **Table 3** and **Graphs 3** and **4** above the moisture measured in the individual mixtures is slightly different in comparison of both experiments carried out in labs of CULS, respectively RIAE. The experiments were done in accordance with standard mentioned in chapter **Materials and methods**, thus the conditions of sample drying were the same. However, measurement in the lab of CULS was performed performed shortly after briquetting and the control measurements in RIAE were done 3 months later. During the meantime between these two measurements, the briquettes were stored in plastic bags. The bags were not, so briquettes could additionally dry out or absorb some amount of air humidity. The moisture content changes during the storage period are visible.

According to Chen et al. (2008) the optimal MC for solid biofuels should not exceed 15 %. None of the examined samples surpassed this value.

5.2.2 Mechanical durability

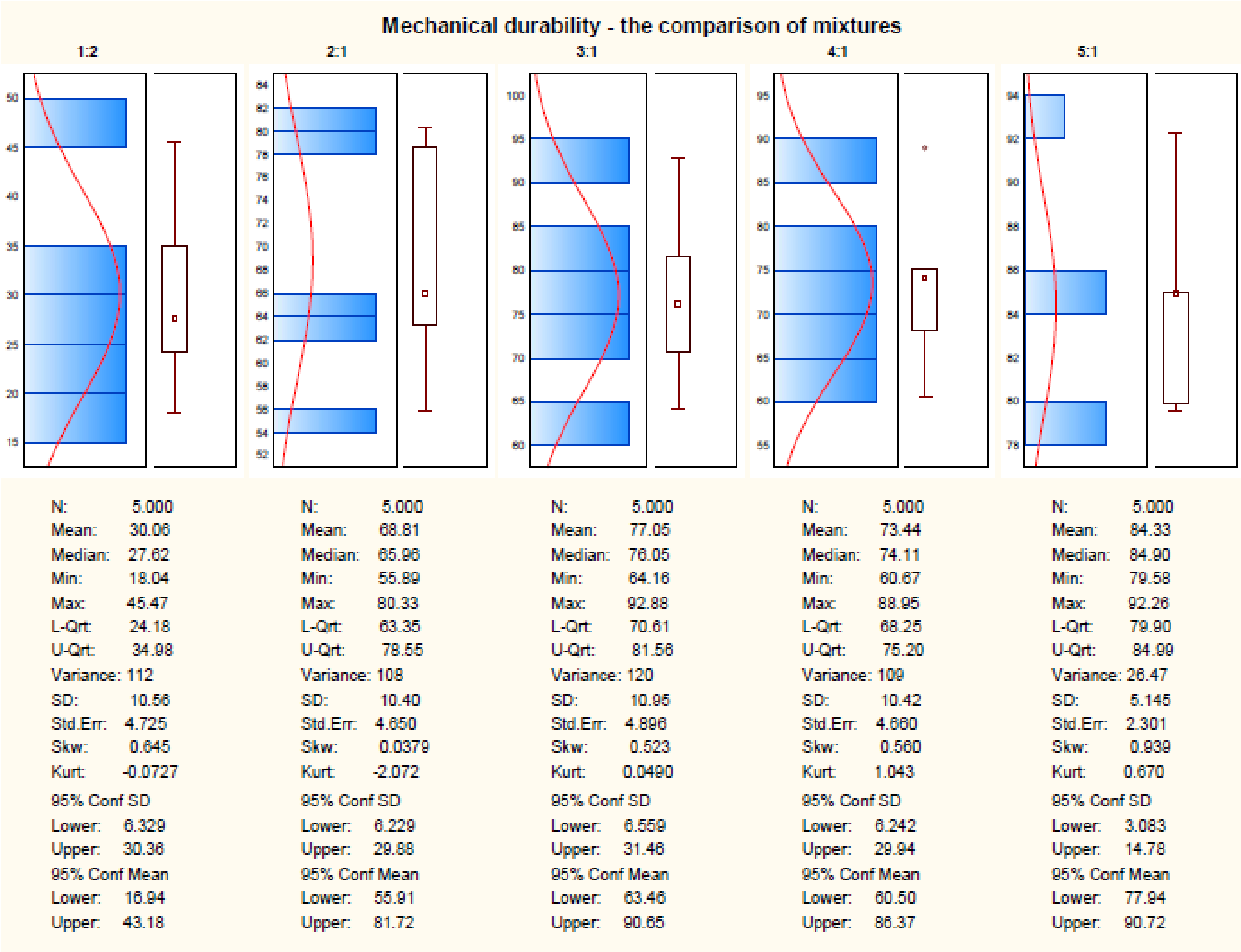
The **Graph 5** below refers to comparison of mean values of mechanical durability of the individual hemp biomass mixtures. It can be seen that the highest DU value was found in the 5:1 mixture (84.33 %), followed by 3:1 ratio (77.05 %), 4:1 ratio (73.44 %), 2:1 ratio (68.81 %) and 1:2 ratio (30.06 %). According to **ČSN EN 14961-1** all the mixtures could be categorized from mechanical durability point of view into category DU 90.0- (DU<90 %).



Graph 5 – Comparison of mechanical durability in the five mixtures

The first mixture has the lowest durability probably due to its highest content of press cake. In the other mixtures the durability tend to increase (with the exception of 4:1 ratio), because of the higher ratio of stem biomass, which contains cellulosis. Mechanical durability of 5:1 mixture is approaching to 90 %, which is considered as the minimum limit for both briquettes and pellets by KOTLÁNOVÁ (2010).

According to results of the experiment carried out by TEMMERMANN et al. (2006) the method of 105 rounds, used in my experiment as well, is the most reliable one. They further claims the mechanical durability of solid biofuels are influenced by selected method, however, the variability of results is more influenced by the fuel itself. In my opinion, the results of this examination were much influenced by the mixtures compositions.



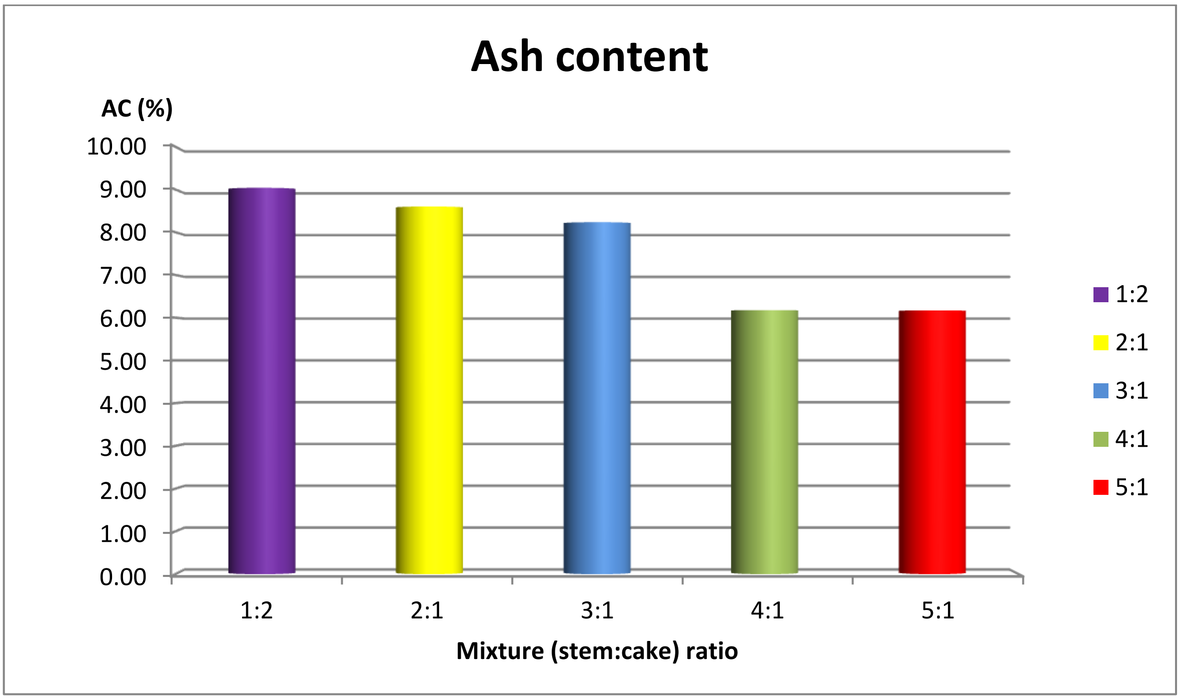
Graph 6 – Statistical summary of the mechanical durability

In the above presented survey, there are values of mechanical durability in percent. It can be noticed the vaues of DU increase with increasing content of stem‘s biomass in briquettes. The extreme values of 3:1 and 5:1 even exceed 90 % value, which is considered as minimum of high quality solid fuels. If the mean values are only considered, none of the values meet the qualitative requirements. In comparison of all mixtures, diference between the highest and the lowest means is 54.27 %.

5.2.3 Ash content

The **Graph 7** below refers to values of ash content for mixtures 1:2 (9.04 %), 2:1 (8.06 %), 3:1 (8.23 %), 4:1 (6.18 %) and 5:1 (6.17 %). None of the presented values exceed limit of 10 %, which means that all mixtures fit into the norm for non-woody biomass according to KOLÁNOVÁ (2010). According to **ČSN EN 14961-1**, the mixtures samples could be categorized from ash content point of view as follows: 1:2, 2:1 and 3:1 mixtures belong to category A10.0 (7%<AC≤10%). Mixtures 4:1 and 5:1 belong to category A7.0 (5%<AC≤

7%).

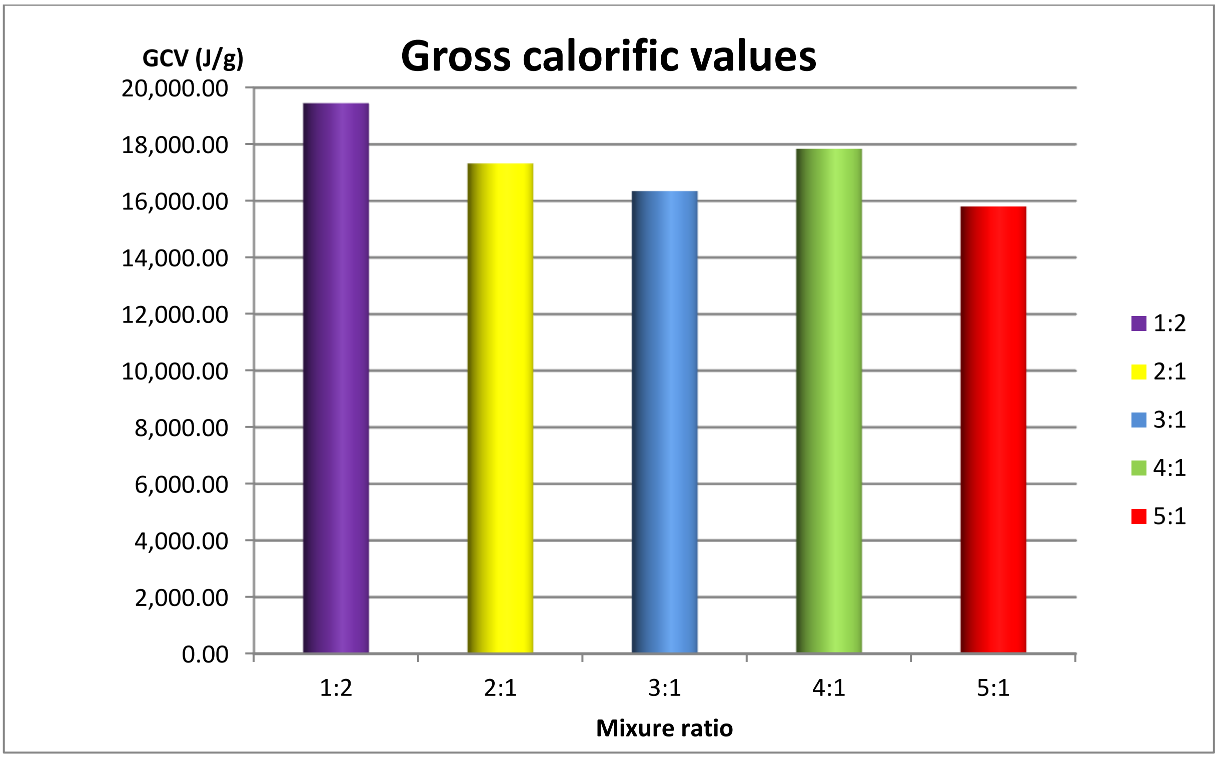


Graph 7 – Comparison of mechanical durability in the five mixtures

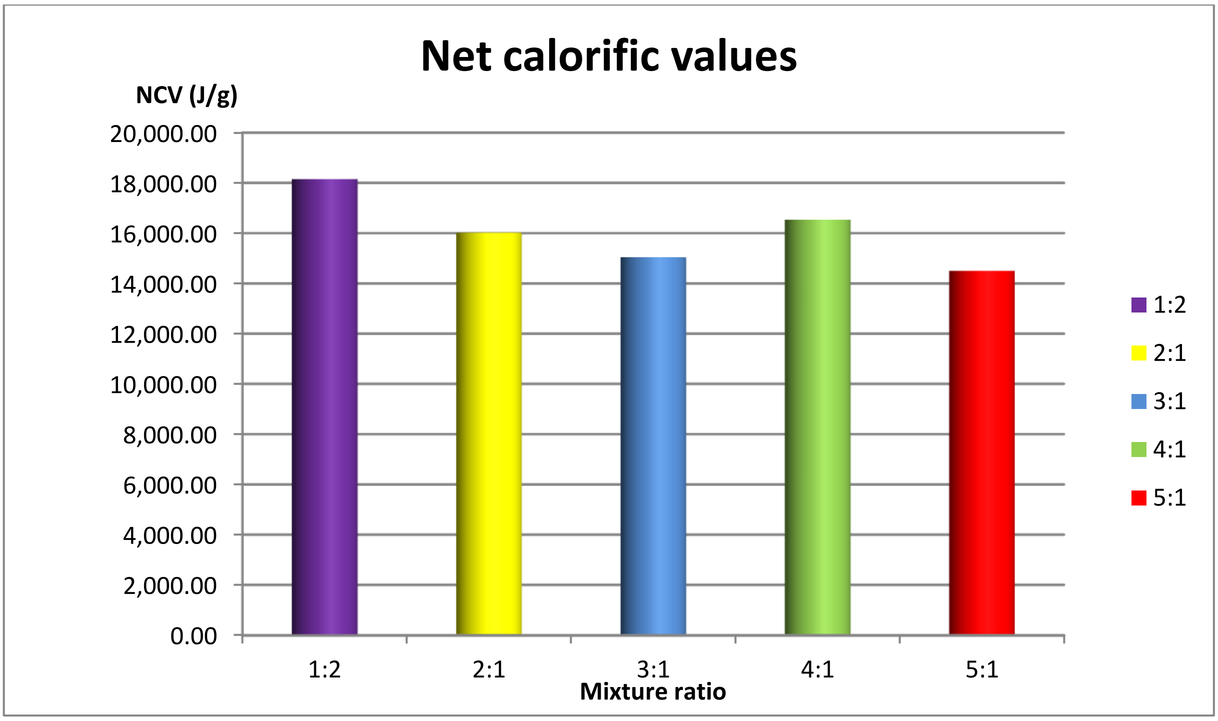
BLESA et al. published research about physiochemical and mechanical properties of smokeless briquettes in 2001. In this research they present results of measurement of ash content for coal's briquettes. They compared two unspecified sort of coal (originally from Teruel basins, Spain) pyrolyzed under temperatures of 600 °C. Their results were 20.0 % and 11.6 % respectively. Both the values are higher than any of the values of hemp‘s mixtures investigated in within this thesis, which indicates greater appropriatness of hemp‘s biomass to be used as a fuel.

5.2.4 Gross and net calorific values

Graphs 8 and **9** compare gross and net calorific values measured and calculated from data gained from the RIAE. Measured values of the GCV are 19,457.50 J/g for 1:2; 17,326.50 J/g for 2:1; 16,348 J/g for 3:1; 17,842.5 J/g for 4:1 and 15,806 J/g for 5:1 mixtures. Calculated values of the NCV from the GCV data are 18,147.61 J/g for 1:2, 16,016.61 J/g for 2:1, 15,038.11 J/g for 3:1, 16,532.61 J/g for 4:1 and 14,496.11 J/g for 5:1 mixtures. The presented values are the arithmetic means of two measured values of each mixtures sample. Two determinations were only carried out, due to low mutual difference of values (less than 120 J/g) in one lab. Differences between individual GCVs and their NCVs are not higher than 1,000 J/g.



Graph 8 – Comparison of gross calorific values



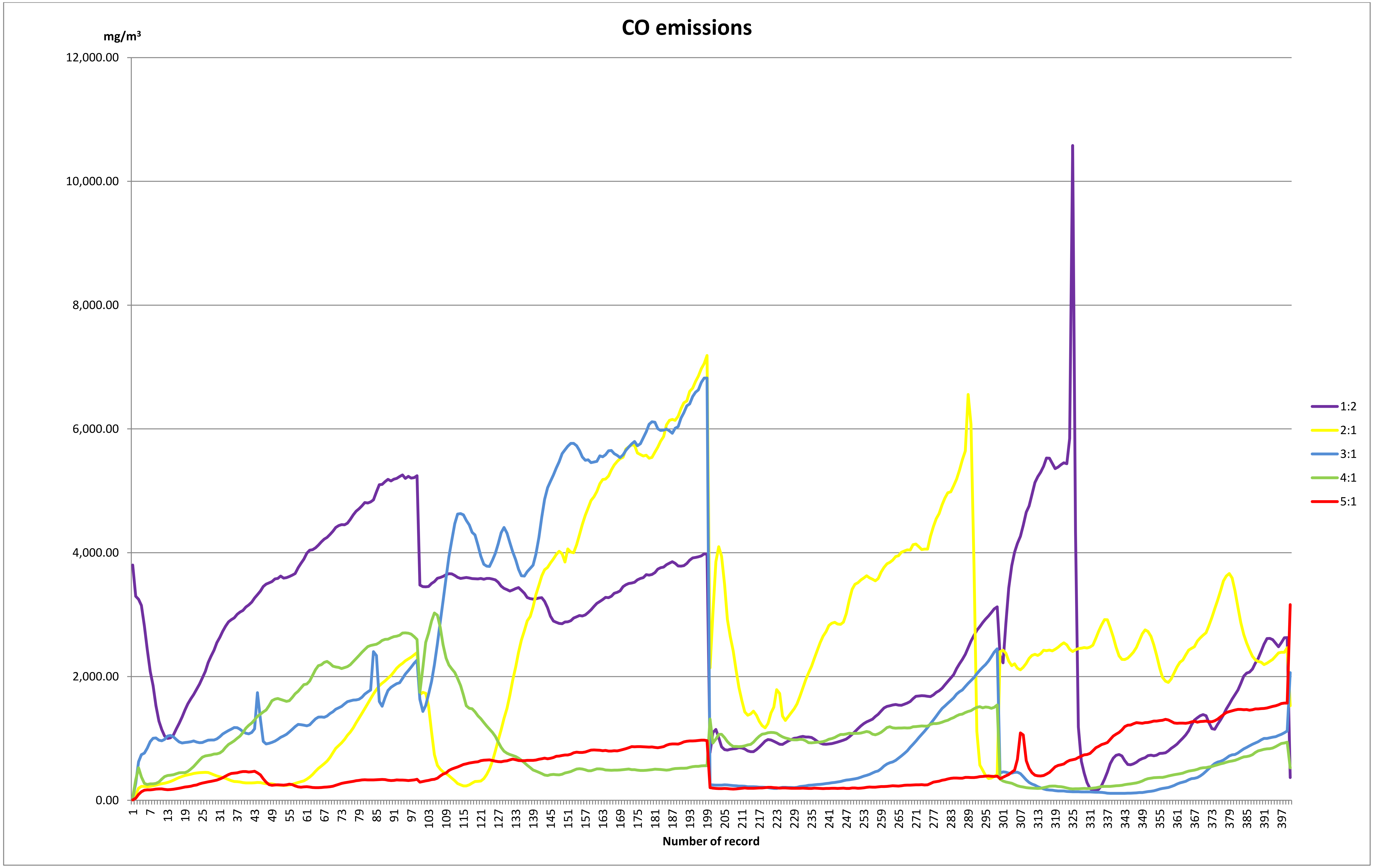
Graph 9 – Comparison of net calorific values

As can be seen in the graphs above, the highest NCV appears in the mixture 1:2, probably due to its higher amount of residual oil contained in the press cake component. NÚÑEZ-REGUEIRA et al. published study about the calorific values of forest waste biomass in 2000. They determined GCVs of leaves and branches of *Eucalyptus globules Labill* in correlation to the season in this study. They claim, if the GCV of a material exceeds 20,000 J/g, the material can be advisable to use as alternative fuel. All the GCVs determined for *Eucalyptus*'s leaves from both fall and winter seasons were above 20,000 J/g. In my experiment, none of the values exceeded this limit, however, the mixture 1:2 almost reached up to this level.

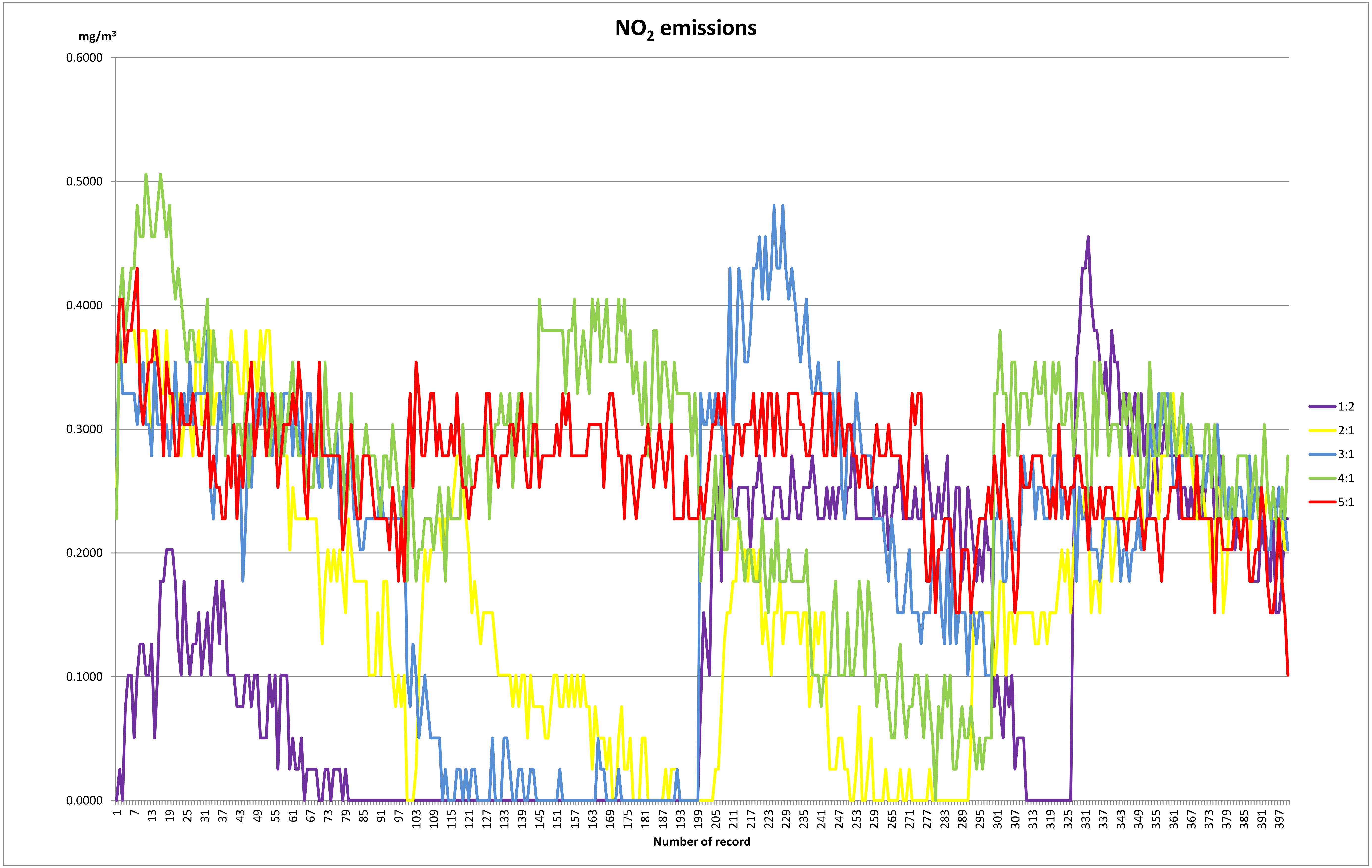
5.2.5 Flue gasses emissions

Graphs 10 and **11** below display development of four flue gases emissions in comparison of individual mixtures. As mentioned above in chapter **Materials and methods**, the measured flue gasses are CO and NO_2. The emissions data were acquired within an hour of measurement.

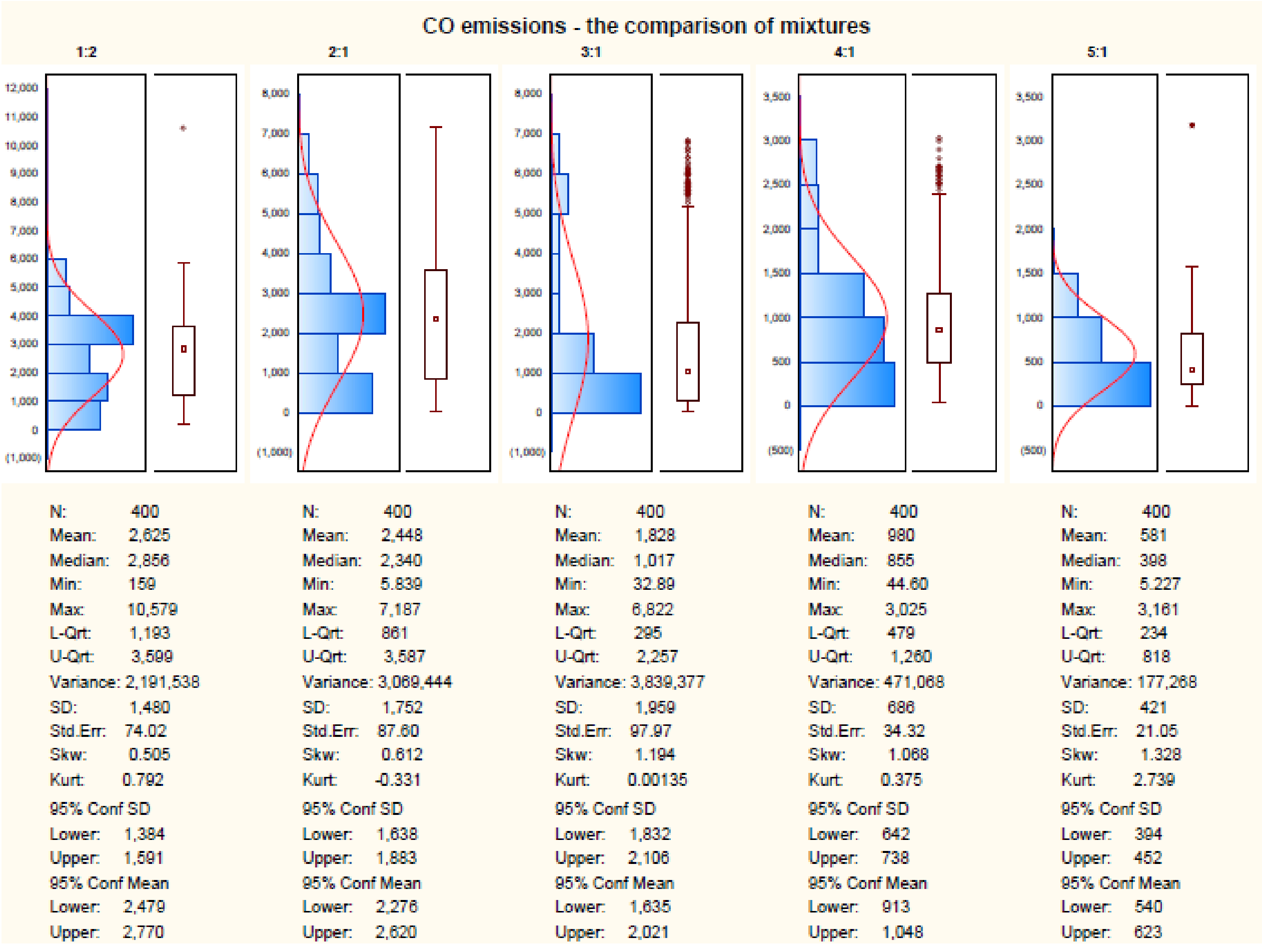
In accordance with novelized standard **ČSN EN 303-5** the emissions limits for CO, as the major pollutant, are set up to 5,000 mg/m^3. The emissions values for CO must not exceed this limit. This value is, however, valid for biomass emissions with reference O_2 content of 10 % and for stationary combustion units up to 50 kW of output capacity. The NO_2 limits are not set for low-performance stoves and boilers.



Graph 10 – Comparison of CO emissions in the five mixtures

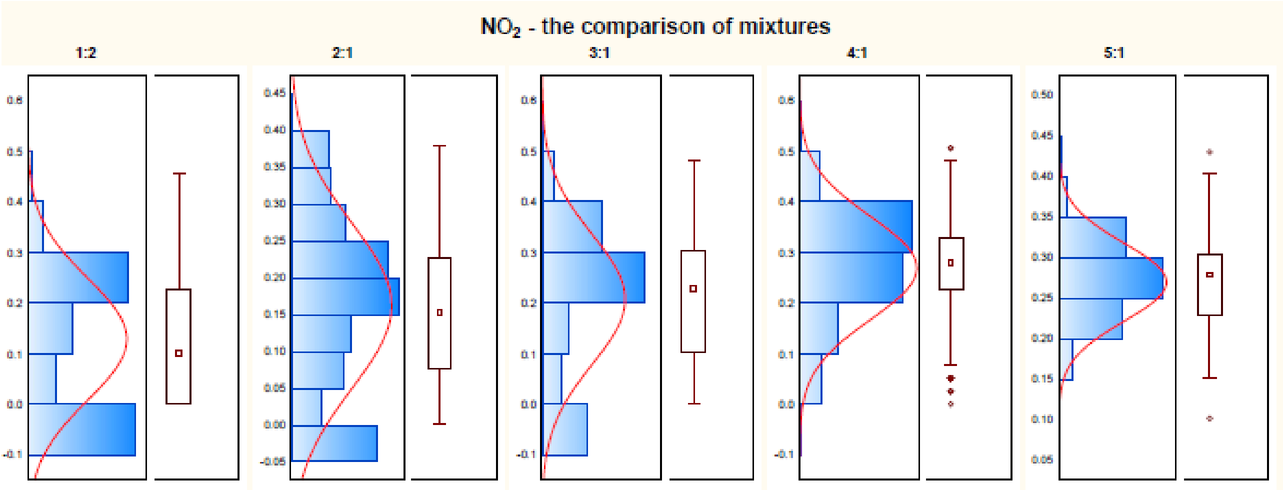


Graph 11 – Comparison of NO_2 emissions in the five mixtures



Graph 12 – Statistical summary of CO emissions

In **Graph 12**, there is a statistical survey of values for emissions of CO. The highest values of CO concentration appears in 1:2 mixture with mean 2,625 mg/m^3 with extremes of 10,579 mg/m^3, as the highest value, and 159 mg/m^3, as the lowest value. The mixture 2:1 has generally also very high values with mean value 2,448 mg/m^3, followed by the 3:1 mixture with mean value 1,828 mg/m^3, 4:1 with mean value 980 mg/m^3 and 5:1 with mean value 581 mg/m^3. The mixture 5:1 and 4:1 fully meets requirements, in accordance with the novelized standard **ČSN EN 303-5**. Mixtures 3:1, 2:1 and 1:2 have some fluctuations above 5,000 mg/m^3 with the highest one of 10,579 mg/m^3. However, since the levels of emissions are influenced not only by chemical composition of biomass they are made of, the differences in emission measurements might have been caused by uneven way of combustion process, which is given by way of fuel's stoking, as KOLONIČNÝ (2010) mentions. However, the values of CO emissions tend to decrease with increased content of the stem biomass in briquettes, according to presented results. For final assessment of suitability of hemp´s biomass and its mixtures for utilization as a biofuel, further measurements would be necessary.



	1:2	2:1	3:1	4:1	5:1
N:	400	400	400	400	400
Mean:	0.127	0.161	0.205	0.267	0.268
Median:	0.101	0.152	0.228	0.278	0.278
Min:	0	0	0	0	0.101
Max:	0.455	0.380	0.481	0.506	0.430
L-Qrt:	0	0.0759	0.101	0.228	0.228
U-Qrt:	0.228	0.228	0.304	0.329	0.304
Variance:	0.0144	0.0125	0.0162	0.0103	0.00231
SD:	0.120	0.112	0.127	0.101	0.0480
Std.Err:	0.00599	0.00559	0.00637	0.00506	0.00240
Skw:	0.316	0.148	-0.392	-0.494	-0.0901
Kurt:	-1.221	-0.942	-0.886	-0.0477	0.467
95% Conf SD					
Lower:	0.112	0.105	0.119	0.0947	0.0449
Upper:	0.129	0.120	0.137	0.109	0.0516
95% Conf Mean					
Lower:	0.116	0.150	0.193	0.257	0.264
Upper:	0.139	0.172	0.218	0.277	0.273

Graph 13 – Statistical summary of NO_2 emissions

As can be seen in **Graph 13** above, the values of NO_2 emission are generally increased with increasing amount of stem biomass contained in briquettes, unlike the values of CO. The highest mean value (0.268 mg/m^3) of concentrations of NO_2 appears in the 5:1 mixture, followed 4:1 with 0.267 mg/m^3, 3:1 with 0.267 mg/m^3, 2:1 with 0.161 mg/m^3 and 1:2 with 0.127 mg/m^3. The lowest values of individual mixtures (with exception of the 5:1) are equal (0 mg/m^3), whilst the minimum value of 5:1 mixture is 0.101 mg/m^3. The highest values don't exceed 0.5 mg/m^3, excepted 4:1 mixture with 0.506 mg/m^3. The results are relatively stable.

6. Conclusion

This thesis presents evaluation of appropriatness of the industrial hemp's biomass for production of solid biofuels, based on description and analysis of the main physical and mechanical characteristics and properties, generally examined in solid fuels. The literature review provides survey and analysis of relevant references related to this topic. The methodology describes design and development of the own experiment.

The results have shown the two examined hemp's varieties *Bialobrzeskie* and *Ferimon* have relatively high yield per hectare in comparison with other references. *Ferimon* is higher-yielding than *Bialobrzeskie*. Their moisture contents are comparable (the difference is less than 5 %).

Second part of the experiment was focused on a practical utilization of briquettes made of hemp's variety *Bialobrzeskie*. The fuel properties are studied on briquettes prepared of stem's and press cake's biomass, mixed in five various ratios (1:2, 2:1, 3:1, 4:1 and 5:1). The briquettes containing higher amount of stem biomass are more resistant for manipulation and storing, but have lower calorific value due to lower content of press cake's biomass with residuals of seed oil. The moisture contents of all mixtures fit into optimal range (5-15 %) for briquettes. All the mixtures also fit to maximum standard amount (10 %) of ash for non-woody biomass. Mixture 4:1 and 5:1 fully meet the emissions limit, set by the standard. Other mixtures have fluctuations (sometimes above 5,000 mg/m^3) in their values, but generally range up to the limit. However, further measurements would be necessary to be carried out, to prove their suitability.

Despite, the results of two, probably the most significant, properties (mechanical durability and calorific value) of solid fuels indicate positive impact of blending of stem and press cake's biomass on above mentioned properties, further additional studies would be necessary. It is recommended to focus on searching for optimal mixture ratio of hemp stem and press cake's biomass, which would provide the best possible results of all properties and thus would represent certain compromise in mechanical durability and calorific value. The possibilities of hemp's biomass, or another plant's biomass for use as a fuel alternative to the fossil fuels, are overwhelming.

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ČSN EN 15210-2 Tuhá biopaliva – Stanovení mechanické odolnosti pelet a briket – Část 2: Brikety (Solid biofuels – Determination of mechanical durability of pellets and briquettes – Part 2: Briquettes)

ISO 3310-1 Zkušební síta z kovové tkaniny (Test sieves of metal material)

ČSN P CEN/TS 14774-1 (-2, - 3) Pevná biopaliva – Metody stanovení obsahu vody – Metoda sušení v sušárně – Část 1: Celková voda – Referenční metoda (Solid bifuels – Methods of moisture content determination – Oven drying method – Part 1: Total moisture content

ČSN P CEN/TS 14775 and DIN 51 790 Pevná biopaliva – Metody stanovení obsahu popela (Solid biouels – Methods of ash content determination)

ČSN P CEN/TS 14918 Tuhá biopaliva – Metoda stanovení spalného tepla a výhřevnosti (Solid biofuels – Method of determination of gross and net calorific value)

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ČSN 07 0240:1993 čl. 5.7.20 and 5.7.23 Teplovodní a nízkotlaké parní kotle. Základní ustanovení (Heat water and low pressure steam boilers. Basic regulations)

ČSN EN 303-5 Kotle pro ústřední vytápění na pevná paliva, s runí nebo samočinnou dodávkou, o jmenovitém tepelném výkonu nejvýše 300 kW – Terminologie, požadavky, zkoušení a značení (Heating boilers - Part 5: Heating boilers for solid fuels, hand and automatically stocked, nominal heat output of up to 300 kW - Terminology, requirements, testing and marking)

8. Annex

List of annex

Annex 1 – Results of measurements

Annex 2 – Additional photographs