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Research paper

# Evaluation of selected physical and mechanical properties of briquettes produced from cones of three coniferous tree species

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ABSTRACT

The aim of the research was to determine the production viability and mechanical durability of briquettes made of shredded cones of three species: Scots pine, Norway spruce and European larch The agglomeration was carried out under constant operating conditions (at 20% of material moisture content, briquette diameter of 50 mm, at throughput of 50 kg h$^{-1}$) in an industrial briquetting press. The particle size distribution of the shredded material was determined. The produced briquettes were evaluated for their density, mechanical durability and compressive strength. At moisture content of approximately 20%, the highest briquette density (1078 kg m$^{-3}$), durability (97.87%) and compressive strength (9.69 MPa) were obtained for spruce briquettes. Pine cone briquettes showed the lowest density (938 kg m$^{-3}$) and compressive strength (2.81 MPa), while larch cone briquettes had the lowest durability (87.58%). The produced briquettes were of high quality in terms of physical and mechanical characteristics. The novelty of research was the use of crushed cones of coniferous species, which are waste in seed extraction facilities, and due to the low bulk density, they are difficult to store and transport over long distances. After agglomeration, they form briquettes with good physical and mechanical parameters that can be used in local heating plants and stoves.

## 1. Introduction

At present, the most important source of energy are fossil fuels, which release greenhouse gases into the atmosphere during combustion. However, global reserves of these fuels are limited and therefore the share of renewable energy sources that have low contribution to greenhouse gas production increases. One alternative to conventional energy sources is the use of pressed biofuels from plant biomass in the form of briquettes or pellets. Thus, the proper densification of the product is achieved, contributing to high volumetric concentration of energy, low moisture and better fuel homogenization. In the case of pellets their agglomeration allows for automation of the combustion process, so they are typically intended for use in automatic house-hold boilers. On the other hand, briquettes for end consumers are often packaged in plastic foils which prevents moisture uptake and makes them easily storable. In both cases there is a reduction in the transport and storage costs. Work safety and hygiene is another consideration favouring agglomerated fuels, since they result in lower emissions of fine particles during storage and manipulation. The combustion process is also usually cleaner, especially in smaller combustion devices, since a fuel with homogeneous size will burn at a steady rate.

The process of plant material agglomeration [1] consists of pressing fine particles into an agglomerate of certain shape and density. The formation of such agglomerate is characterized by the occurrence of intermolecular forces that result from the proximity of particles [2,3]. Kaliyan and Morey [4] distinguished five distinct binding mechanisms which are solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, and lastly interfacial forces and capillary pressure. In the pressing process, two steps can be distinguished [5] or three [6]. In the first step, the space between the particles is reduced. The deformation occurs in the second step and the plastic and elastic deformations are produced - binding forces are generated. In the third step [6] indicate a decrease in volume until the density of the agglomerate approaches the maximum density of the material. In the last step deformed particles do not change positions due to the small spaces between them. In all of these steps the lignin content plays a significant role in binding the agglomerate together as long when sufficient temperature is reached which is dependent on moisture content. Higher lignin content typically makes it possible to produce more durable briquettes [7,8].

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An appropriate initial preparation, mainly comminution to appropriate size, of the raw material is an important part of the compaction process. The pre-treatment method should cause particles fragmentation and lead to the breakage of compacted structure of the lignocellulose by damage of its microfibers. Sun and Cheng [9] report that, in addition to reducing the size of the raw material, fragmentation is also intended to improve the availability of the bioactive substances' specific surface area.

One of the determinants of the obtained agglomerate quality is durability, which depends on many factors, including material type, lignin content and water content, coefficient of friction between material and die, compaction force, length to diameter ratio, temperature and many others [4,10–13].

Good densification of plant material needs appropriate material moisture content. Too high biomass moisture content exhibits enhanced interaction between particles, but it adversely affects the agglomeration process [14] and worsen mechanical properties of agglomerates [15,16]. Optimal moisture content is in the range of 8–12%, but higher moisture up to 12–20% may be used to obtain higher densification [4]. Moisture content above ca. 24% may lead to swelling and disintegration of briquettes immediately after pressing. Mani et al. [17] reported that the moisture content of briquettes produced from biomass should be between 5% and 10%, because lower moisture increases shelf life and density [18].

Other properties of the raw material affecting the agglomerate density are coefficient of internal friction and granulometric composition. High density is obtained by using material of small particles, and that is a result of the larger contact area of smaller particles and leads to better compaction of particles [3,4,10,13,19].

The mechanical properties of briquettes are an important factors in the design of new solutions used in the process of plant materials agglomeration. The main mechanical properties of briquettes include compressive strength, tensile strength, bending, resistance to gravity discharge, hydrophobicity and others [20]. For briquettes it is important to determine the compressive strength using the Brazilian method [21], i.e. by measuring compressive strength perpendicular to the axis of the briquette. According to Borowski [22], the compressive strength depends on the direction of force relative to the fibres or layers of the material. For fine-grained materials compressive strength also depends on moisture and temperature during agglomeration process [23].

According to the literature review, there are many scientific papers on the production and physical properties of refined fuels. There are also many works on energy properties of fuels or composition of various plant materials used in the production of briquettes and pellets [24–28].

Harvesting seeds for the production of forest tree seedlings in several countries, every year gives several dozen or even several hundred tonnes of cones as reported by Aniszewska and Bereza [29]. In factories for seed extraction, powered by electric power, the cones are a waste. They can be burned in unprocessed state, but after opening they have a relatively low bulk density of 106–206 $kg\,m^{-3}$ depending on the species [30] and require large storage areas as well as ineffective transport of open cones [31].

Cones can be a good material for the production of pressed fuel. They are characterized by high gross and net calorific values in the range of 18.11–19.28 $MJ\,kg^{-1}$ [32,33] and low moisture content after seed extraction process of about 7–8% [29]. However, there are no published results of mechanical properties of agglomerates made of cones. The purpose of experimental work was to characterize the particle dimensions, assess the strength and durability of briquettes made of shredded cones of three tree species.

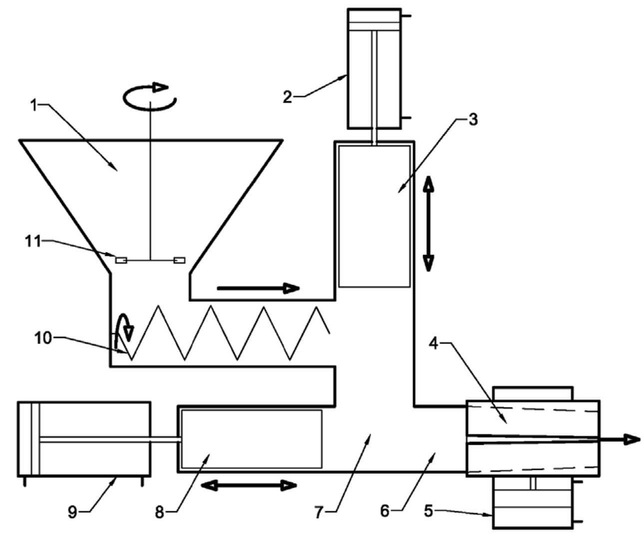


**Fig. 1.** Schematic diagram of the briquetting machine: 1 – hopper, 2, 5, 9 – hydraulic cylinders, 3 – pre-compaction piston, 4 – mechanism for regulation of the resistance, 6 – pressing chamber, 7 – pre-compaction chamber, 8 – main piston, 10 – screw feeder, 11 – mixer.

## 2. Materials and methods

### 2.1. Materials

Materials used for tests were conifer cones which remain after seed extraction in Grotniki located in the Regional Directorate State Forests in Lodz (GPS 51°53′02.7″ N 19°23′24.1″ E). The species were Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* H. Karst.) and European larch (*Larix decidua* Mill.). Shredded conifer cones had moisture content approximately of 8% (Pine - 7.54 ± 0.10%; Spruce - 8.70 ± 0.09%; Larch - 8.48 ± 0.08%). The moisture is low due to the course of the seed extraction process, where cones spend more than 50 h in heated cabinets at the temperature of about 50 °C. For a reference, opened cones found in the forest would have a moisture content about 15% [34–36].

The cones of the listed species were shredded in a 11 kW/350 $kg\,h^{-1}$ hammer mill WAR Alchemik 400 (Alchemik, Inowrocław, Poland) with a sieve of 6 mm circular holes. The Alchemik APT 40 (Alchemik, Inowrocław, Poland) briquetting press was operated at its maximum hydraulic system pressure of 210 bar. A diagram of the briquetting set-up is displayed in Fig. 1. Briquetting process was carried out with an approximate throughput of 50 $kg\,h^{-1}$. Diameter of briquettes was ca. 50 mm. The machine was working for 1 h before briquetting the tested materials. A minimum of 50 kg of material was used for producing each batch of briquettes.

The briquettes produced from the original materials had very low durability - pine 27%, spruce and larch 0%. They have disintegrated due to the too low moisture content. Based on the literature data, the highest number of briquetting studies were conducted in the moisture in the range of 10–20% [16,37,38], which enables the best pressing conditions of plant materials. It was necessary to add water to the dry material by spraying the water into a rotating drum over the course of 1 h in such amount to achieve moisture of 20%. Then the drum was closed and was rotated by 1 h for material homogenization. For this BWA 80/230 drum mixer was used (AGRO-WIKT, Opoczno, Poland).

Quality of briquettes was evaluated by determining the moisture content of the material, particle size distribution, density, durability of briquettes and performing compression tests to calculate the modulus of elasticity, compressive strength and specific deformation energy.

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