

Briquetting of used coffee grounds: bonding mechanisms, mechanical durability and energy recovery potential

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Abstract: Used coffee grounds (UCG) represent an organic waste stream with potential for energy recovery. This study investigates the briquetting of recycled UCG granulate, with emphasis on particle-size characteristics, moisture content, mechanical durability and the observed contribution of bonding mechanisms. UCG from Franck, Barcaffe and Escobar were analysed and briquetted using a Mekom MiniBrik-30. Four briquettes from each coffee brand were tested for mechanical durability after 500 rotations at 1 revolution per minute. Mean mechanical durability was $97.6 \pm 0.7\%$ for Franck, $95.4 \pm 5.2\%$ for Barcaffe and $97.7 \pm 0.6\%$ for Escobar ($n = 4$). The lower Barcaffe result was mainly associated with one briquette exhibiting 87.8% durability. A separate binder test using 5 wt.% cellulose binder (spruce sawdust) resulted in a mean mechanical durability of $97.2 \pm 0.5\%$ for the Barcaffe briquettes. The treated briquettes showed reduced variability, with all four samples exceeding the 95% acceptance criterion. The results indicate that mechanical compaction and interparticle bonding are sufficient to produce durable briquettes from the investigated UCG, while the available data do not permit the individual contributions of lignin, capillary, colloidal and adhesive mechanisms to be quantified. Under the investigated conditions, UCG could be densified into briquettes meeting a mechanical durability criterion of $>95\%$ in all four tests for Franck and Escobar, while with 5 wt.% cellulose binder, all four investigated Barcaffe briquettes met the 95% acceptance criterion ($97.2 \pm 0.5\%$), whereas one untreated Barcaffe briquette was below this criterion. The annual energy content was estimated theoretically at approximately 64.4 GWh from the estimated Slovenian UCG quantity and a literature lower calorific value of 21.08 MJ/kg; no energy-recovery experiment was performed in the present study.

Keywords: briquetting, biomass binder, energy recovery, mechanical durability, particle size, urban mining, used coffee grounds (UCG)

1. Introduction

Many recycled waste materials are in powder or granulate form due to technological recycling processes. This often causes problems in transport, packaging, and storage, especially when they are in the form of powders, due to their low bulk density and dustiness. The solution is provided by various surface reduction or agglomeration processes. Agglomeration is the process of combining small particles into larger aggregates, so-called agglomerates, such as pellets, briquettes, tablets, and sintered agglomerates, which must have certain strength properties (Kortnik, Anžič, 2026).

Surface reduction or agglomeration processes must meet several requirements, especially in the case of the necessary addition of binders to form agglomerates; no components that negatively affect the quality of the final product must enter the production process - nor must they increase the production of gaseous pollutants, especially organic compounds such as polychlorinated biphenyls (PCB) and dioxins-PCDD/PCDF or polycyclic aromatic hydrocarbons (PAH) (Spence, Shi, 2005; Zhang et al., 2018). After binding the recycled granulate, the agglomerate must remain solid and meet mechanical property requirements. Binders can be solid or liquid, organic (bitumen, tar, resin, starch, or molasses), or inorganic (lime, cement, water glass, clays). Molasses and other common binders are unsuitable for briquetting fine-grained metallurgical waste because of their phosphorus and sulfur content. In

contrast, resins are suitable – e.g., acrylic, formaldehyde, or phenolic resins (Spence, Shi, 2005; Zhang et al., 2018). The choice of binder should also depend on its impact on chemical reactions in the aggregate, especially iron oxide reduction (Drobikova et al., 2016). In addition, the formation of unwanted gaseous by-products with a potential negative impact on the environment should be limited during heat treatment.

In practice, the most common method for producing solid briquettes from recycled granulates is briquetting/tabletting. Briquetting/tabletting is a process in which the material is compressed under pressure in a forming channel. The most appropriate moisture content generally varies and depends on the physical properties of the granulate material; the usual content is between 8–12 wt.%. The maximum permissible moisture content in mechanical piston presses is around 15 wt.%, while in hydraulic presses the moisture content is up to 30 wt.%. When the moisture content is >15 wt.%, there is a risk of steam explosion due to the increase in pressure and temperature in the compression process (Kortnik, Anžič, 2026). Furthermore, particle size of the recycled granulate is important in briquette production. The particle size should generally not exceed 25% of the diameter of the final product/briquette to ensure proper strength. At this stage, superheated steam can be added to the recycled granulate, making it softer and enabling better bonding. The briquetting process is followed by applying compressive force to the granulate particles in the forming channel.

The quality of briquettes is assessed by their compressive strength, and in the case of coals also by their moisture resistance. In doing so, we follow the standard for permissible moisture and ash content in solid biofuels SIST EN ISO 17225-7, which prescribes the maximum permissible moisture content in solid biofuels of 15 wt.% and the ash content for wood briquettes below 3 wt.%, and for non-wood briquettes <10 wt.% (Kortnik, Anžič, 2026).

The strength of the briquette depends on both the pressure applied and the granulation composition and particle size of the granulate being briquetting. The main purpose of briquetting is to reduce the volume and increase the density of the solid. When densification occurs, two quality aspects must be considered. First, the briquette must remain compact until it fulfills its purpose, and second, it must achieve an adequate calorific value as a solid fuel (Briquettesolution.com, 2020).

2. Principles of briquetting

The basic mechanisms of agglomeration are shown in Fig. 1. It can proceed in three ways (Kortnik, Anžič, 2026): by adhesive bonding of granulate (pelleting) – the snowball principle (Fig. 1a), by pressing the granulate in a forming channel (briquetting or tabletting) (Fig. 1b), and by bonding bridges with the application of heat (sintering) (Fig. 1c).

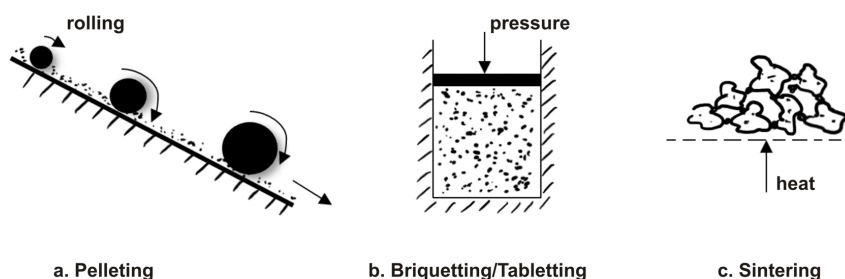


Fig. 1. Basic mechanisms of agglomeration: a. Pelleting, b. Briquetting/Tabletting, c. Sintering (Kortnik, Anžič, 2026)

Successful briquetting depends on many factors, such as moisture content, particle size, particle shape, and impurities. Several theories attempt to explain the mechanism of the briquetting process, but none comprehensively describes the actual mechanism of briquetting. Theories are divided into two basic groups: without binders and with binders (Wang et al., 2018).

In briquetting, we use compressive force, or we are talking about the compression process due to the compression of the granulate between two surfaces (Spence, Shi, 2005), as shown in Fig. 2. Since we have brought the particles very close to each other, on the one hand the distance between them decreases; on the other hand, the number of contact points increases. With appropriate humidity, we

get more liquid bridges due to reduced porosity and thus greater capillary forces. In the final stage of compression, elastic or plastic deformation of the particle surface also occurs, and due to local heat concentration, the surfaces of the solid particles fuse, or sinter.

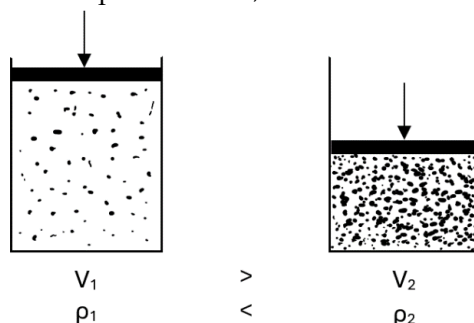


Fig. 1. Briquetting principle (V - volume, ρ - density) (Kortnik, Anžič, 2026)

Theories of briquetting without binders are mainly divided according to the different properties of the granulate for briquetting into (Wang et al., 2018) lignin briquetting theory, capillary briquetting theory, colloidal briquetting theory, and adhesive briquetting theory.

Lignin briquetting theory uses lignin as a natural binder already present in the granulate. The binder has physicochemical properties that help to bind the particles into solid, compact briquettes. Lignin is an organic binder in wood that softens and becomes a plastic substance at elevated temperatures. In the case of recycled UCG granulate, the lignin in the coffee grounds acts as a natural binder, which, under the influence of external/compressive force and temperature due to friction, binds the recycled particles into a solid briquette, as shown in Fig. 3.

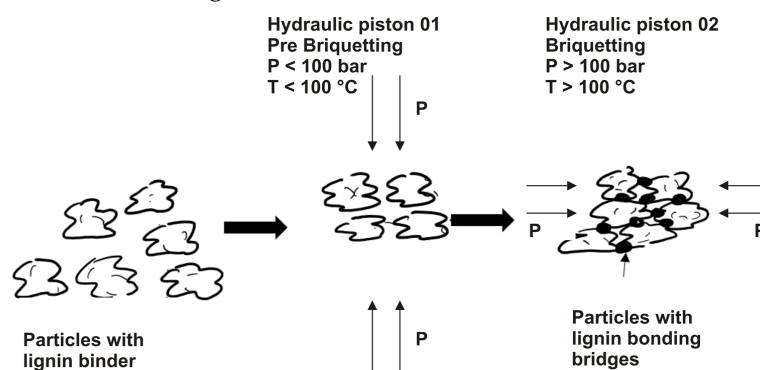


Fig. 3. The principle of binding recycled particles in the hydraulic briquetting process (P - pressure, T - temperature) (Kortnik, Anžič, 2026)

The capillary theory of briquetting assumes that there is a large amount of water-saturated capillaries in the recycle particles. During briquetting, under the influence of an external force, the capillaries are crushed, water is squeezed out of them, which covers the surface of the particles and forms a water film. The water film then fills the spaces between the particles and becomes an interaction/binding force. When the pressure is released, the capillaries expand slightly, some water re-enters the capillary, and some remains on the particle surface, where a meniscus (concave or convex) forms due to surface tension. The recycle particles are connected mainly due to capillary forces into a solid briquette.

The colloidal theory of briquetting assumes that the lignin present in the recycle consists of solid and liquid colloidal material. The solid material consists of tiny granulate of humic substance. These combine under external force and form gelatinous colloidal particles due to intermolecular cohesion in solution. Under pressure, the recycle particles connect through Van der Waals or other molecular forces; the smaller the particles, the greater their specific surface area and binding force.

The adhesive theory of briquetting assumes that the bonding of particles is a result of the pressure of water from the primary capillary pores. Water in the spaces between the recycle particles creates surface tension and thus forms a secondary capillary adsorption force. Van der Waals and capillary

forces interconnect recycle particles. When the recycle particles come close enough, a molecular bonding force forms that connects the particle surfaces.

The binder has a dual function: first, as a lubricant, it enables the redistribution of the recycle particles during briquetting, and at the same time it binds the recycle particles into a solid briquette. A suitable binder must enable strong bonding, be environmentally acceptable, and be economically affordable. Theories of briquetting using binders are divided according to the type of binder into (Wang et al., 2018) inorganic binders, organic binders, or combined binders. Inorganic binders have advantages over organic binders, mainly due to their lower cost, higher heat resistance, and water resistance or hydrophilicity. The main disadvantage of using inorganic binders is the higher ash content. The most commonly used inorganic binders for briquetting are clay, lime, gypsum, cement, and sodium silicate (Karlhager, 2008). Organic binders not only have good properties for binding granulate particles, but briquettes generally achieve high compressive strength, high mechanical resistance and lower ash content. The main disadvantage is the cost and the risk of briquettes disintegrating at high temperatures because of the binder's low mechanical strength and poor thermal stability. Organic binders can be divided into biomass binders (cellulose and starch binders), tar pitch and petroleum bitumen, lignosulfonate, and polymer binders (Wang et al., 2018). Lignin is a cellulose binder that is naturally present in woody biomass. Lignin is a complex organic compound with the chemical formula $C_9H_{10}O_2$, $C_{10}H_{12}O_3$, $C_{11}H_{14}O_4$, and is the second most common organic material on Earth after cellulose; together, they are an important component of the cell walls of woody plants. It is a polymer that plays a role in ensuring the structural strength and resistance of plant tissues, especially in perennial plants such as trees. Lignin helps plants become more rigid and resistant to mechanical stress, drought, and bacteria. Lignin is mainly used in industry as a binder, e.g., for particle boards and similar laminated or composite wood products. Lignin can also be leached, either in powder form or liquefied, because it has strong binding properties and is often used as a binder additive in briquetting. Combined binders are a combination of organic and inorganic binders, which utilize the good properties of both binders.

Depending on the operating mode and briquetting pressure, we know the following briquetting machines screw briquetting machines, piston briquetting machines, roller briquetting machines and hydraulic briquetting machines. The screw briquetting machine uses a dosing screw to transfer the compressive force to the recycled granulate, and can be additionally equipped with a heating system for the purpose of drying the input material. The granulate is dosed into a storage tank, from where the dosing screw, which also provides the appropriate briquetting pressure, transports it to the forming channel for briquetting. Depending on the forming channel shape, the granulate can be compressed into any shape (square, round, etc.). Since the roller briquetting machine does not operate with high pressure, it is necessary to add binders to form a solid briquette. The piston briquetting machine uses a piston driven by a flywheel to compress the granulate. The piston in the forming channel applies a compressive force to the granulate, and the friction causes the temperature to increase, which activates the binders and thus the bonding of the briquette particles. A roller briquetting machine uses two oppositely rotating rollers at the same speed to compress the material (Briquettesolution.com, 2020). The rollers have openings on their surfaces; as they move, two identical openings or molds are caught in the middle, where the material is compressed into the desired shape.

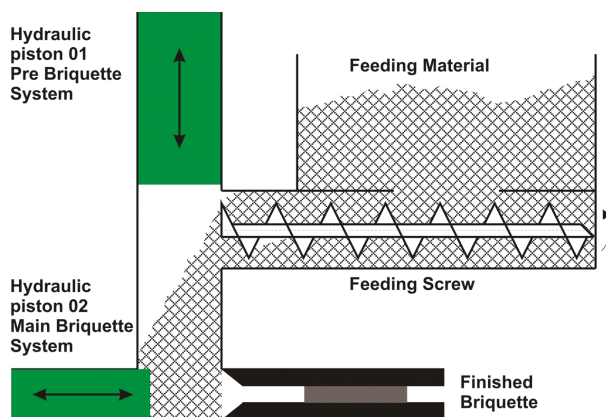


Fig. 4. Hydraulic briquetting machine (Briquettesolution.com, 2020)

The hydraulic briquetting machine (Fig. 4) operates with two hydraulic pistons, which allow high pressures to be achieved in the forming channel on the granulate, enabling the briquetting of practically all recycled materials, including metal powders. The working process begins with the feeding of powder particles/material into the hopper, from where the dosing screw transfers the material to the forming channel of the first hydraulic piston. Here, the material is compacted in one direction, and then the dosing screw transfers it to the second hydraulic piston, where the briquette is compacted in the other direction. The briquetting machine establishes pressure on the surface of the briquette, which causes deformation of the surface of the material particles and thus their bonding. During the briquetting process, the temperature in the forming channel increases due to friction, thus activating the binder, which allows better bonding of the particles into a solid briquette, as you can see in Fig. 3. A purpose-built hydraulic briquetting machine from the Hungarian manufacturer Mekom MiniBrik-30 (Fig. 5) was used to produce briquettes from recycled UCG granulate.



Fig. 5. MiniBrik-30 hydraulic briquetting machine (Kortnik, Anžič, 2026)

Compared with other briquetting machines, the MiniBrik-30 briquetting machine enables high-pressure briquetting up to 180 bar. The briquetting machine has a welded steel frame, and the consumable parts of the briquetting machine are made of hardened steel. In the hopper, which has a special trapezoidal shape for easier entry of the granulate into the dosing screw, we can insert approx. 0.5 m³ of recycled granulate, which is then transferred by the dosing screw into the forming channel. In the forming channel, first the first hydraulic piston briquetting the granulate in the longitudinal direction, then the second hydraulic piston briquetting the granulate in the transverse direction, when we obtain a solid briquette (Fig. 4).

3. Example of briquetting recycled UCG granulate

Before briquetting the recycled UCG granulate, we first had to reduce the moisture content, usually by about 70 wt.%, using a laboratory dryer with a power of 6.6 kW at a temperature of 105 ± 2 °C to a constant mass for approximately 12÷14 hours. Drying was also carried out with a fan dryer (0.22 kW) at 32 ± 2 °C to constant mass for 3-5 days. The fan dryer's advantage was mainly its 4 times lower electricity consumption for the same amount of recycled material, but its disadvantage was the up to 8 times longer drying time. Drying also represents the highest cost in briquette production. Before briquetting begins, the moisture content has to be <10 wt.% (Kortnik, Anžič, 2026). Excessive moisture can cause many problems during storage, as it leads to mold development, as shown in Fig. 6, which is even more intense in the summer months (Kortnik, Anžič, 2026). The moisture content was determined gravimetrically and with a manual Bosch Universal-Humid moisture meter.

To achieve the strength and mechanical durability of the briquettes, it is important that the recycled granulate was analysed before briquetting. The final briquette diameter was 50 mm, and the study used the criterion that the particle size should not exceed 25% of the final briquette diameter. Particle-size analysis was performed using a Fritsch Analysette 22 NanoTec laser diffraction particle-size analyser (uses the Fraunhofer diffraction theory). The analysis was performed using dry samples, and the

reported distribution is volume-based. Samples of Franck, Barcaffé and Escobar UCG, starch binder (wheat flour type 500) and cellulose binder (spruce sawdust) were analysed. The cumulative particle-size distribution is presented in Table 1 and Fig. 7.



Fig. 6. Mold and fungus growth on damp UCG granulate (Kortnik, Anžič, 2026)

Table 1. Results of particle-size analysis of UCG from Franck, Barcaffé and Escobar and of the starch and cellulose binders

Q3(x) (%)	UCG Franck (μm)	UCG Barcaffé (μm)	UCG Escobar (μm)	Starch Binder (μm)	Cellulose Binder (μm)
1	11.9	1.8	1.4	0.9	7.1
10	47.0	29.0	23.0	11.0	132.0
16	59.9	38.9	29.9	17.6	189.3
50	336.1	275.0	237.2	61.0	585.1
60	481.8	355.5	335.7	77.8	720.5
84	842.5	604.0	576.1	129.5	987.4
90	947.6	725.0	677.8	149.9	1080.1
95	1078.4	893.8	818.5	174.9	1202.0
99	1321.1	1209.5	1116.6	221.8	1475.5
Arith. Mean (μm)	421.34	320.96	292.28	71.89	591.62
Span	2.68	2.53	2.76	2.28	1.62

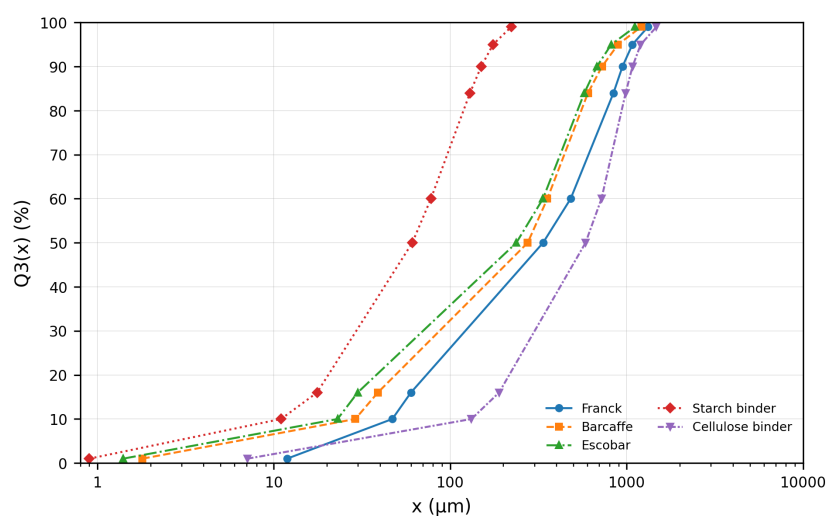


Fig. 7. Particle-size distribution of UCG granulate from Franck, Barcaffé and Escobar and of the starch and cellulose binders

Table 1 reports selected Q3(x) cumulative volume percentiles. Q3(50) corresponds to the median particle size (d50), Q3(90) to d90 and Q3(99) to d99. The d10 values were derived from the reported span values using $\text{Span} = (d90 - d10)/d50$. Particle-size analysis was performed using dry samples and volume-based laser diffraction. The analyser uses Fraunhofer diffraction theory; the dispersion pressure was not recorded.

Briquetting of recycled UCG granulate was carried out using a Mekom MiniBrik-30 hydraulic briquetting machine. The briquetting machine uses two hydraulic cylinders controlled by calibrated PLC controllers. Briquetting was performed at a pressure between 100 and 120 bar. The feed material was compacted sequentially in the longitudinal and transverse directions to form the final briquette. The hydraulic briquetting machine is manufactured in accordance with the regulations, Directive 89/392/EEC and amendments to Directives 73/23/EEC and 89/336/EEC.



Fig. 8. Device for determining mechanical durability of briquettes (Kortnik, Anžič, 2026)

The mechanical durability (compactness) of briquettes made from recycled UCG granulate was determined using the procedure described in SIST EN 15210-1:2010 – Solid biofuels – Methods for determining the mechanical durability of pellets and briquettes – Part 1: Pellets. Because the standardized procedure is intended for pellets, the procedure was adapted to the investigated briquettes using the device shown in Fig. 8. Four briquettes from each coffee brand were tested. Each briquette was subjected to 500 rotations at 1 revolution per minute (SIST EN 15210-2:2011), after which the mass loss was determined.

The mechanical durability or compactness ($Meh.$) of briquettes was calculated from the initial briquette mass and the mass loss after 500 revolutions using Eq. (1). The volume was calculated based on measurements of the diameter and height of an individual briquette.

$$Meh. = \frac{m_K \cdot 100\%}{m_Z} \quad (1)$$

where m_Z is the initial briquette Mass (g), m_K is the briquette mass after 500 revolutions ($m_K = m_Z - m_L$) (g), and m_L is the briquette mass-loss after 500 revolutions (g).

Table 2a. Mechanical durability results for briquettes produced from Franck UCG (n=4)

Briquette Sample	Volume (cm ³)	m _Z Initial Briquette Mass (g)	Density (g/cm ³)	m _L Mass-loss (g)	Mechanical Durability (%)	Moisture (wt.%)
F1	102.9	79.9	0.7763	1.7	97.9	7.8
F2	92.2	78.6	0.8525	2.3	97.1	8.4
F3	104.9	87.5	0.8341	2.7	96.9	8.4
F4	89.6	83.9	0.9367	1.3	98.5	8.2
Mean ± SD (n=4)	97.4 ± 7.6	82.5 ± 4.0	0.8499 ± 0.0664	2.0 ± 0.6	97.6 ± 0.7	8.2 ± 0.3

Table 2b. Mechanical durability results for briquettes produced from Barcaffe UCG (n=4)

Briquette Sample	Volume (cm ³)	mz Initial Mass (g)	Density (g/cm ³)	m _L Mass-loss (g)	Mechanical Durability (%)	Moisture (wt.%)
B1	129.5	122.2	0.9436	4.1	96.6	8.1
B2	117.1	111.4	0.9509	1.2	98.9	8.1
B3	111.7	108.1	0.9677	1.8	98.3	7.5
B4	112.4	107.2	0.9541	13.1	87.8	7.6
Mean ± SD (n=4)	117.7 ± 8.2	112.2 ± 6.9	0.9541 ± 0.0101	5.0 ± 5.5	95.4 ± 5.2	7.8 ± 0.3

Table 2c. Mechanical durability results for briquettes produced from Escobar UCG (n=4)

Briquette Sample	Volume (cm ³)	mz Initial Mass (g)	Density (g/cm ³)	m _L Mass-loss (g)	Mechanical Durability (%)	Moisture (wt.%)
E1	119.5	110.1	0.9214	1.9	98.3	8.1
E2	124.4	116.3	0.9347	3.2	97.2	8.4
E3	116.4	112.2	0.9637	3.1	97.2	7.7
E4	108.9	99.1	0.9096	1.8	98.2	7.9
Mean ± SD (n=4)	117.3 ± 6.5	109.4 ± 7.3	0.9324 ± 0.0233	2.5 ± 0.8	97.7 ± 0.6	8.0 ± 0.3

The mean values and sample standard deviations (SD) were calculated from four briquettes (n=4) for each coffee brand. No independent measurement-uncertainty data were available, so the differences are interpreted descriptively rather than by a formal significance test.

Across the three UCG groups, the mean mechanical durability was $97.6 \pm 0.7\%$ for Franck, $95.4 \pm 5.2\%$ for Barcaffe and $97.7 \pm 0.6\%$ for Escobar (n = 4). Barcaffe showed the largest dispersion because sample B4 had a mechanical durability of 87.8%, whereas the other three Barcaffe briquettes ranged from 96.6% to 98.9%. Thus, the Barcaffe mean is strongly influenced by one low-performing briquette. The Barcaffe series should therefore be considered provisional and not yet fully reproducible under the investigated conditions. Because no specific visible defect or forming irregularity was documented for B4, the exact cause cannot be established retrospectively. A local forming defect, particularly incomplete bonding at one end face, is a plausible explanation and should be examined in future replicate tests. This observation is important because the mean density of Barcaffe (0.9541 ± 0.0101 g/cm³) was nevertheless the highest of the three groups. The results therefore do not support a simple relationship in which higher density and lower moisture alone guarantees higher mechanical durability.

Table 3. Mechanical durability results for Barcaffe UCG briquettes with 5 wt.% cellulose binder (spruce sawdust), n=4

Briquette Sample	Volume (cm ³)	mz Initial Mass (g)	Density (g/cm ³)	m _L Mass-loss (g)	Mechanical Durability (%)	Moisture (wt.%)
B1 + 5%	148.7	140.2	0.9430	4.9	96.5	7.0
B2 + 5%	166.3	155.1	0.9324	3.8	97.5	7.0
B3 + 5%	126.9	116.3	0.9164	3.2	97.2	7.0
B4 + 5%	133.9	125.2	0.9349	3.1	97.5	7.0
Mean ± SD (n=4)	143.9 ± 17.5	134.2 ± 17.1	0.9317 ± 0.0111	3.8 ± 0.8	97.2 ± 0.5	7.0 ± 0.0

For Barcaffe UCG briquettes, we also tested additional binders experimentally. The starch binder had a substantially finer particle-size distribution ($d_{50} = 61.0$ μm) than the cellulose binder ($d_{50} = 585.1$ μm).

μm ; Table 1). The available experimental record does not contain a quantitative mechanical-durability result for the starch trial; therefore, no quantitative performance conclusion is drawn for this binder – a 5 wt.% cellulose-binder test was subsequently performed, and the mean mechanical durability increased to $97.2 \pm 0.5\%$ (Table 3).

For the Slovenian waste stream, the annual UCG quantity was estimated in the study at more than 11,000 Mg (Kortnik, Anžič, 2026). Using the lower calorific value of 21.08 MJ/kg measured for 100% spent coffee grounds by Nosek et al. (2020), the corresponding theoretical energy content is approximately 64.4 GWh/year. This value represents theoretical chemical energy content only; no calorimetric or combustion/conversion experiment was performed in the present study, and collection, drying, briquetting, and conversion losses are not included.

4. Analysis of briquetting results and discussion

The results are consistent with a combination of mechanical compaction and physicochemical particle bonding. During hydraulic compression, particle rearrangement reduces the void volume and increases the number of particle contacts. The ability of all three UCG brands to form briquettes with mean durability above 95% without an external binder provides direct experimental evidence that the material can self-bind under the investigated conditions. However, the present measurements do not isolate the individual contributions of lignin plasticisation, capillary, colloidal and adhesive bonding. No direct measurements of lignin activation, capillary pressure, surface energy or temperature at the particle contacts were performed. These mechanisms should therefore be presented as plausible mechanisms consistent with the observed behaviour rather than as independently demonstrated mechanisms. Importantly, only the Franck and Escobar groups exceeded the >95% durability criterion in all four individual tests; the Barcaffe series included the low-performing B4 briquette.

The volume-based particle-size results show clear differences between the three UCG brands. The d_{50} values reported in Table 1 are 336.1 μm for Franck, 275.0 μm for Barcaffe, and 237.2 μm for Escobar. The cumulative distribution in Fig. 7 also shows that the binder materials occupy different particle-size ranges. The smaller particle size of Escobar UCG did not result in lower mechanical durability; its mean durability was $97.7 \pm 0.6\%$. Conversely, Barcaffe had a larger d_{50} than Escobar but a lower mean durability because of the single low-performing B4 sample. The results therefore suggest that particle size is an important material characteristic, but it cannot by itself explain the observed durability differences.

To evaluate the suitability of the produced UCG briquettes, a mechanical durability of >95% was used as the acceptance criterion according to the pellet standard SIST EN 15210-2:2011. The tested UCG groups showed different behaviour: the Franck and Escobar groups exceeded 95% in all four individual tests, while the Barcaffe group contained one briquette below the criterion. The individual values are therefore more informative than the mean alone and demonstrate that raw-material variability can affect briquette quality.

It must also comply with the standard for moisture and ash content in solid biofuels SIST EN ISO 17225-7. Suitable briquettes made from recycled UCG granulate are characterized by a moisture content of <9 wt.% and an ash content of <2 wt.%, which is why they are classified as non-wood briquettes (moisture content < 12 wt.%, ash content <6 wt.%). The moisture contents of the UCG briquettes were 8.2 ± 0.3 wt.% for Franck, 7.8 ± 0.3 wt.% for Barcaffe, and 8.0 ± 0.3 wt.% for Escobar. These relatively narrow ranges do not explain the large difference between the Barcaffe samples, particularly B4. The B4 moisture content was 7.6 wt.%, which was not higher than the other Barcaffe samples. Therefore, the low durability of B4 cannot be attributed to moisture content alone. The ash content in our case was not the subject of research and will require additional attention in future research.

The additional test with 5 wt.% cellulose binder was performed on Barcaffe UCG because this material produced the lowest individual durability value. The mean mechanical durability of the untreated Barcaffe group was $95.4 \pm 5.2\%$, while the corresponding value after addition of 5 wt.% cellulose was $97.4 \pm 0.8\%$ after correction of the B4 + 5% value using Eq. (1). The binder-treated samples showed lower variability in mechanical durability, with a standard deviation of 0.5% compared with 5.2% for untreated Barcaffe briquettes. All four binder-treated samples exceeded the 95% acceptance

criterion. Based on the available four replicates, the results indicate reduced variability rather than an increase in mean durability.

Fig. 9 shows suitable briquettes (left) and unsuitable briquettes (right), which must, in addition to the requirements of both standards, have a length of at least 50 mm and a diameter of 50 mm.



Fig. 9. Final briquettes, suitable briquettes (left) and unsuitable briquettes (right) (Kortnik, Anžič, 2026)

During briquetting, we encountered a certain small proportion of unsuitable briquettes, which we managed to rehabilitate into suitable briquettes by adding 5 wt.% cellulose binder. The reason was attributed in the study to excessive moisture content in the recycled UCG granulate before briquetting. In the present work, the naturally occurring lignin in UCG is considered a potential component contributing to self-binding. Relationships between mechanical durability and density (a) and moisture content (b) for the 12 untreated UCG briquettes can be seen in Fig. 10. The pooled analysis of the 12 untreated UCG briquettes gave Pearson $r = -0.16$ for density versus mechanical durability and Pearson $r = 0.33$ for moisture content versus mechanical durability ($n = 12$). Both relationships are weak and should be interpreted descriptively; the low-performing B4 briquette also influences the moisture relationship.

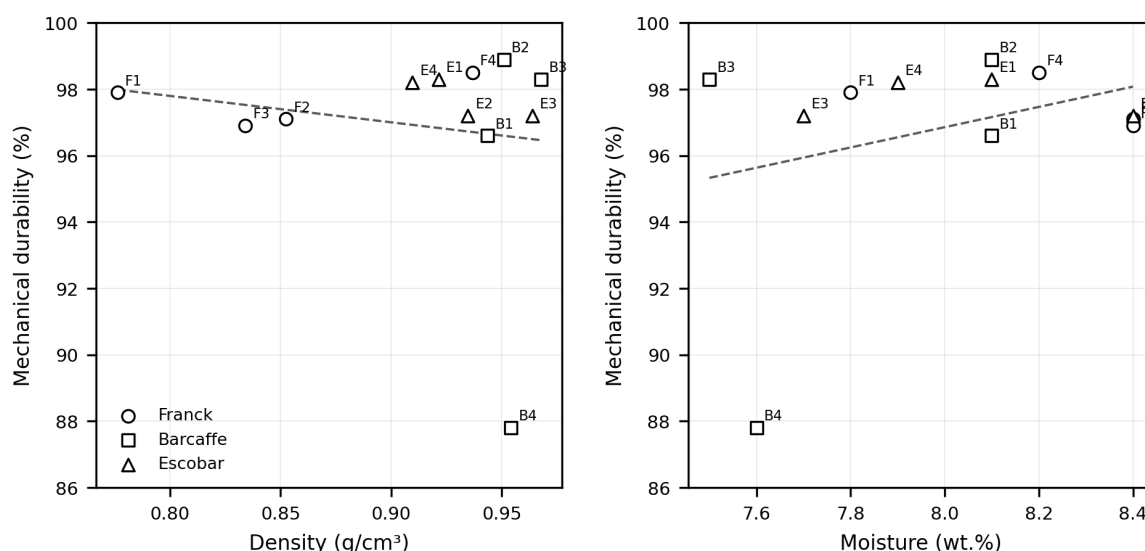


Fig. 10. Relationships between mechanical durability and density (a) and moisture content (b) for the 12 untreated UCG briquettes

5. Conclusions

In the total mass flow of waste generated in Slovenia, UCG represents a smaller share of waste, estimated in the study at around 1.5% or more than 11,000 Mg annually (Kortnik, Anžič, 2026). With an average briquette mass of 120 g, this corresponds to more than 250,000 briquettes per day. Using the

literature lower calorific value of 21.08 MJ/kg (Nosek et al., 2020), the corresponding theoretical energy content is approximately 64.4 GWh annually. This is theoretical chemical energy content, not recoverable energy, and excludes collection, drying, briquetting, and conversion losses. Experimental combustion and energy-conversion tests are required before assessing recoverable energy.

The added value of UCG briquettes compared to classic fuels from waste lies primarily in the fact that, due to their composition, they are also suitable for individual combustion chambers in households and not only for industrial combustion chambers, like conventional fuels made from waste, refuse derived fuel & solid recovered fuel (RDF&SRF).

The mechanical durability results show that UCG can be converted into stable briquettes using the Mekom MiniBrik-30 hydraulic briquetting machine. Mean durability was $97.6 \pm 0.7\%$ for Franck, $95.4 \pm 5.2\%$ for Barcaffe and $97.7 \pm 0.6\%$ for Escobar ($n = 4$). The low Barcaffe mean was caused mainly by one low-performing briquette (B4, 87.8%), demonstrating that feedstock variability can be important even when the average particle-size and moisture characteristics are similar. The Barcaffe series should therefore be treated as provisional until additional replicate tests establish reproducibility.

The 5 wt.% cellulose-binder experiment resulted in a mean mechanical durability of $97.2 \pm 0.5\%$ for the investigated Barcaffe briquettes. The addition of cellulose binder was associated with reduced variability, with all four treated briquettes exceeding the 95% acceptance criterion; however, based on four replicates, no increase in mean durability can be claimed, and further testing is required. The pooled Pearson correlations were weak for both density versus durability ($r = -0.16$) and moisture versus durability ($r = 0.33$; $n = 12$), supporting the interpretation that neither variable alone explains the observed differences. The present study therefore supports further systematic investigation of binder concentration, moisture, particle size and pressure rather than claiming a completed optimisation study.

The results support UCG briquetting as a potential route for waste densification, while the energy estimate presented here remains theoretical. The main practical challenges identified by the study are feedstock collection, moisture control, drying, and variability of the raw material. Further experiments with controlled binder dosage, larger replicate numbers, and direct combustion or calorimetric measurements are required to establish robust process conditions, assess recoverable energy, and distinguish the contribution of individual bonding mechanisms.

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