

Extruded Charcoal Briquettes with a Protective Organic Polymer Binder for Barbecue and Metallurgical Applications

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Abstract – Charcoal continues to be a strategically important carbonaceous reductant for the metallurgical industry, including the production of metallurgical-grade silicon and ferrosilicon, due to its low ash and sulphur content and its renewable origin. However, the mechanical, thermal and water-resistance properties of conventional roller-pressed charcoal briquettes are often insufficient for the demanding handling and high-temperature conditions of submerged-arc furnaces. In the present work, cylindrical extruded charcoal briquettes (20 mm in diameter, 30–150 mm in length) were manufactured on a laboratory extruder from milled hardwood charcoal fines and a self-developed protective organic polymer binder – a water-soluble, carboxyl-functional polymer – used at a low loading, and were characterised against the requirements of EN 1860-2 and DIN 51729-10. Proximate analysis gave a fixed-carbon content of 74.0 % and an ash content of 4.5 %, with a typical alkaline-earth-rich ash composition (36.76 wt-% CaO, 16.10 wt-% SiO₂, 8.59 wt-% K₂O). The briquettes withstood axial compression loads of 0.5–0.9 MPa, lost only 14.4 ± 0.56 % of mass after 30 min of drum abrasion, absorbed 36.1 % water after five days of immersion without disintegration, and retained their cylindrical shape after rapid heating to 900 °C, losing 24 % of mass. The proximate and abrasion data are means ± standard deviation of three independently produced batches (n = 3); the ash analysis is a single accredited determination, the compression result is the observed range, and the water-uptake and thermal-shock values are single determinations. The combined results indicate that the obtained briquettes meet the basic mechanical, hydrothermal and thermal-shock criteria required for both barbecue applications and for use as a carbonaceous reductant in metallurgical processes.

1. INTRODUCTION

Charcoal is one of the few carbonaceous materials that combines a renewable origin with very low ash and sulphur content, and for this reason it has been widely investigated as a partial or complete substitute for fossil reductants in the production of silicon, ferrosilicon and manganese ferroalloys (Monsen *et al.*, 2007; Surup, Trubetskaya, and Tangstad, 2020; Ringdalen, 2025). The replacement of fossil coke by charcoal in submerged-arc furnaces is

regarded as one of the most accessible short-term measures for reducing the CO₂ footprint of the silicon and ferroalloy industries (Surup, Trubetskaya, and Tangstad, 2020).

At the same time, a significant fraction of industrial charcoal is generated as fines (typically below 6 mm) during carbonisation, screening, transport and storage. According to data reported for the silicon industry, more than 10 % of the charcoal feed can be lost as fines during processing, which is normally too small to be charged directly into the furnace and is therefore discarded or used as a low-value by-product (Makgobelele *et al.*, 2021). Conversion of these fines into mechanically and hydrothermally stable briquettes is therefore both an economic and an environmental objective.

A wide range of organic and inorganic binders has been proposed for charcoal briquetting, including starches, molasses, lignosulphonates, polyvinyl alcohol (PVA), bentonite and combinations thereof (Korol and Yankovych, 2025a; Yankovych and Korol, 2025). Recent work by the authors has shown that the binder molecular structure and the densification pressure jointly govern the mechanical integrity of charcoal briquettes, with modified polysaccharides offering the best compromise between cold mechanical strength, ash contribution and cost (Yankovych and Korol, 2025). Polyvinyl-alcohol-based binder systems, in particular, have been shown to give a useful combination of dry strength and water resistance when combined with molasses and a small amount of surfactant (Korol and Yankovych, 2025a). At the same time, the surface chemistry of the charcoal fines and the influence of mild chemical pre-treatments on their adhesive interaction with binders have also been studied (Korol and Yankovych, 2025b).

Most of the published work, however, has focused on roller-pressed or piston-pressed briquettes. Extrusion, by contrast, allows higher and more uniform compaction pressures and longer residence times in the die, which in principle reduces the amount of binder required and yields more compact briquettes. The shape obtained, a cylinder of well-defined diameter, is also better suited to bulk handling and to the gas-permeability requirements of metallurgical furnaces.

The objective of the present work is to characterise a new type of extruded charcoal briquette manufactured at the Perechin Timber and Chemical Plant (Ukraine) using an alternative technology based on a protective organic polymer binder. The proximate composition, elemental composition of the ash, compression strength, abrasion resistance, water resistance and thermal-shock behaviour of the briquettes are evaluated against the requirements of EN 1860-2 (CEN, 2005) and the elemental-analysis standard DIN 51729-10 (DIN, 2011), and the results are discussed in the context of barbecue and metallurgical applications.

2. MATERIALS AND METHODS

2.1 Sample preparation

The briquettes were manufactured from hardwood charcoal produced by Perechin Timber and Chemical Plant from 100 % hardwood feedstock of legal origin. The raw material for briquetting was the charcoal fines fraction (0–6 mm) generated during carbonisation, screening, handling and storage. Before briquetting the fines were milled and homogenised, and the particle-size distribution of the milled feed was determined by dry sieving in triplicate; it is given in Table I. The distribution is markedly bimodal: 35 wt-% of the material lies in the coarse 2.00–6.00 mm fraction, while 50 wt-% is finer than 0.50 mm, with a pronounced minimum of only 3 wt-% in the 0.50–1.00 mm interval. The mass-median size d_{50} is accordingly 0.50 mm and the d_{90} is approximately 4.4 mm. A bimodal feed of this kind is favourable for

extrusion: the fine mode fills the interstices between the coarse particles and so raises the packing density of the extrudate, while the coarse particles carry the load and limit shrinkage during drying. Together with the continuity of the binder film, this packing behaviour governs the compactness, the cold mechanical strength and the abrasion behaviour of the finished briquette.

Table I: Particle-size distribution of the milled hardwood charcoal fines used as the feed for extrusion, determined by dry sieving ($n = 3$). The mass-median size d_{50} falls on a sieve aperture and requires no interpolation; d_{90} was obtained from the cumulative undersize curve by linear interpolation on a logarithmic size scale, the coarsest fraction being taken as 2.00–6.00 mm.

Size fraction	Mass fraction (wt-%)
2.00 – 6.00 mm	35
1.00 – 2.00 mm	12
0.50 – 1.00 mm	3
0.25 – 0.50 mm	22
0.125 – 0.25 mm	7
< 0.125 mm	21
Mass-median size, d_{50} (mm)	0.50
d_{90} (mm)	4.4

The protective organic polymer binder used in this work is a self-developed, water-soluble organic polymer that carries a high density of carboxyl groups along its chain, used as the sole binding component: no co-binder, plasticiser or surfactant is added. It is dissolved in the process water at room temperature and introduced at a loading well below the 15–25 wt-% that the pressed formulations of our earlier work require (Yankovych and Korol, 2025). The binder and process parameters are collected in Table II. Two features of this chemistry bear directly on the results reported below. First, polymers of this class are efficient film formers: on drying they leave a continuous, cohesive film that bridges the charcoal particles, which is what allows a mechanically coherent extrudate to be obtained at so low a binder loading. Second, the carboxylate groups of the polymer can form ionic crosslinks with the alkaline-earth and alkali cations that are abundant in hardwood charcoal ash — the ash of the present material contains 36.76 wt-% CaO and 8.59 wt-% K₂O (Table IV). The calcium salts of polycarboxylates are sparingly soluble in water, so the crosslinked film is not removed by immersion. We propose this in-situ ionic crosslinking as the mechanism underlying the water resistance reported in Section 3.4, where the briquettes retained their shape after five days of full immersion. The proposal is consistent with the behaviour observed, but a direct spectroscopic confirmation was outside the scope of the present study and is planned as part of the continuing programme. This binder therefore works by a different mechanism from the hydrogen-bond-dominated polysaccharide and polyvinyl-alcohol systems examined in our earlier work (Korol and Yankovych, 2025a; Yankovych and Korol, 2025): ionic crosslinking rather than hydrogen bonding. Those studies established that polysaccharides give the highest cold strength, but none of the five binders screened there delivered water resistance at a low loading, which is what motivated the change of binder chemistry reported here.

Table II: Composition of the protective organic polymer binder system and the extrusion and drying parameters used for the briquettes characterised in this work.

Parameter	Value
Binder type	self-developed, water-soluble organic polymer bearing carboxyl groups
Co-binder, plasticiser or surfactant additions	none – single-component binder system
Preparation of the binder	dissolved in the process water at room temperature
Binder loading and exact composition	commercially protected – see text
Separate mixing stage	none – mixing takes place inside the extruder
Extruder	laboratory single-screw extruder, model PBE-133
Drive	5.5 kW; motor 1500 rpm through a two-stage gear reducer (Ts2U-160)
Die diameter (mm)	20
Barrel and die heating	none – the mass is warmed by shear during repeated passes
Nameplate throughput (kg h ⁻¹)	300
Throughput achieved on charcoal fines (kg h ⁻¹)	≤ 5
Machine dimensions (mm) and mass (kg)	1600 × 1050 × 850; ≤ 300
Drying regime	ambient air, to constant mass
Moisture content of the dried briquettes (wt-%)	4.3

The exact composition of the binder system, and its loading on dry charcoal, are commercially protected by Perechin Timber and Chemical Plant and are not disclosed here. Table II therefore reports the functional chemistry of the polymer, the preparation route and the complete set of machine and process parameters, but not the formulation itself. We recognise that this places a limit on strict reproducibility, and we state it openly rather than leaving it implicit: the results below can be reproduced qualitatively with a commercial water-soluble polycarboxylate of comparable charge density on the equipment described, but the exact values will depend on the grade and loading chosen.

No separate mixing stage was available: the milled charcoal fines, the dissolved binder and the process water were fed directly to a laboratory single-screw extruder (model PBE-133, 5.5 kW, motor speed 1500 rpm through a two-stage gear reducer), in which mixing, densification and shaping all take place. The barrel is not externally heated; the mass is warmed by shear, and homogenisation is achieved by passing the charge through the extruder several times before the final pass through the 20 mm die. This is the main process limitation of the present work and it is quantified in Table II: against a nameplate throughput of 300 kg h⁻¹, no more than 5 kg h⁻¹ could be achieved on charcoal fines, because the mixture has to be prepared and warmed inside the extruder itself. Continuous operation would require a heated, agitated mixing vessel upstream so that a ready, warm mass is delivered to the die in a single pass. The extrudates were cut to the required length and dried under ambient conditions until the final moisture content was stabilised at 4.3 wt-%. The resulting briquettes are cylindrical agglomerates with a diameter of 20 mm and a length of 30–150 mm, the length being adjustable according to customer requirements. The general appearance of the briquettes, together with a calliper verification of the nominal diameter, is shown in Figure 1.



Figure 1: General appearance of the extruded charcoal briquettes and calliper verification of the nominal 20 mm diameter.

2.2 Proximate and ash analysis

The proximate composition (moisture, ash, volatile matter, fixed carbon) of the briquettes was determined in accordance with EN 1860-2 (CEN, 2005). The elemental composition of the ash was determined by Ruhr Lab GmbH (Germany) following DIN 51729-10 (DIN, 2011) and is reported as oxide percentages.

2.3 Compression (strength) test

Cylindrical briquettes were placed in a hydraulic press and loaded both along (axial) and across (radial) the cylinder axis (Figure 2). The pressure at which a briquette failed was recorded with a calibrated pressure gauge and converted into a nominal compressive stress.



Figure 2: Compression test on the extruded charcoal briquettes: hydraulic press with pressure gauge (left), briquette under axial load (centre) and broken sample after failure (right).

2.4 Abrasion (tumble/drum) test

Mechanical durability under handling was assessed by a tumble test. A weighed sample of briquettes was placed in a rotating drum of 30 cm internal diameter and rotated at 40 rpm for 30 min. After the test the sample was removed and sieved through 3.35 mm and 0.5 mm sieves, and the mass fraction of each size class was calculated relative to the initial mass (Figure 3).

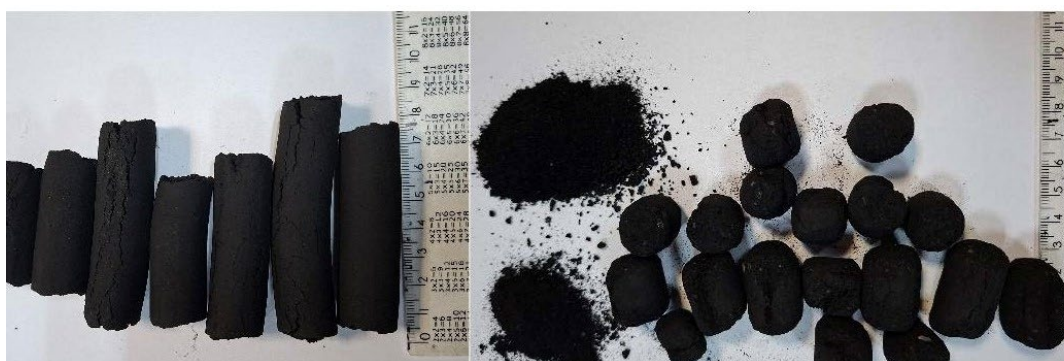


Figure 3: Abrasion (tumble) test: briquettes before testing (left) and after 30 min in the rotating drum at 40 rpm together with the fines and broken fragments generated (right).

2.5 Water-resistance test

To assess the protective effect of the organic polymer binder, weighed briquettes were fully immersed in a container of distilled water at room temperature for five days (Figure 4). At the end of the immersion the briquettes were removed, the surface water was wiped off, and the samples were weighed and visually inspected for cracking and disintegration. Water uptake was calculated as the relative mass gain with respect to the initial dry mass.



Figure 4: Water-resistance test: extruded charcoal briquettes after five days of full immersion in distilled water, with no visible disintegration of the cylindrical agglomerates.

2.6 Thermal-shock test

Thermal-shock behaviour was evaluated by rapid heating in an oxygen-free sealed container at 900 °C for 10 min, followed by cooling under oxygen-free conditions to room temperature (Figure 5). The samples were inspected for shape retention, and the relative mass loss was determined gravimetrically.



Figure 5: Thermal-shock test sequence: muffle furnace at 900 °C (left), briquettes in the sealed oxygen-free container during heating (centre-left), the container during cooling (centre-right) and the briquettes after cooling with shape retention (right).

2.7 Statistical analysis and repeatability

The replication of the individual tests differs, and is stated here explicitly rather than left to be inferred. The proximate analysis and the abrasion test were each carried out on three independently produced batches of briquettes, manufactured from the same charcoal lot and the same binder formulation under nominally identical conditions ($n = 3$); for these indices the results are given as the arithmetic mean $\pm$ one sample standard deviation, the SD being calculated with the $n - 1$ denominator, and the values appear in Tables III and V. The ash analysis of Table IV is a single determination carried out under accreditation by an external laboratory (Ruhr Lab GmbH) on the batch characterised here; rather than replicate it, we quote in Section 3.1 the range observed over eight production batches analysed in the same campaign, which is the more informative measure of the variability that a furnace operator would actually encounter. The compression test was carried out on several individual briquettes, and the result is reported as the observed range of failure stresses rather than as a mean with a standard deviation: the failure of a brittle cylindrical agglomerate is governed by

the largest defect present in the particular specimen, so the distribution is markedly non-Gaussian and a standard deviation would convey a misleading impression of precision. The water-resistance and thermal-shock results are single determinations on one charge of briquettes each, and are therefore quoted without a dispersion estimate; mass changes were determined gravimetrically to ± 0.01 g. Extending the water-resistance and thermal-shock measurements to full triplicate determination, and establishing the specimen statistics of the compression test, are part of the continuing work.

3. RESULTS AND DISCUSSION

3.1 Proximate composition and ash chemistry

The proximate analysis of the extruded charcoal briquettes is summarised in Table III; all values are means of three independently produced batches, with the corresponding standard deviations. The fixed-carbon content (74.0 %) exceeds the 60 % minimum required by EN 1860-2 for charcoal briquettes, and the ash content (4.5 %) is well below the maximum value of 18 % allowed by the same standard (CEN, 2005). The total moisture content (4.3 %) is consistent with values reported for industrially dried charcoal briquettes. The volatile-matter fraction of 21.5 % is somewhat higher than that of pure metallurgical-grade lump charcoal, which can be attributed to the residual organic polymer binder; this is acceptable for barbecue applications and is not detrimental for metallurgical use, since the volatiles are released in the upper part of the furnace shaft before the briquettes reach the reaction zone. It is instructive to set these figures beside those of the conventional roller-pressed briquette manufactured at the same plant from the same hardwood charcoal, which has a moisture content of 5.5 %, an ash content of 4.5 %, a volatile-matter content of 24.5 % and a fixed-carbon content of 71.5 % at an apparent density of 0.34 g cm^{-3} . The ash contents of the two products are identical, as they must be when the charcoal and its source are the same, but the extruded briquette is drier, contains three percentage points less volatile matter and correspondingly more fixed carbon. Both differences follow from the process rather than from the feedstock: the low binder loading contributes less volatile organic matter than the 15–25 wt-% of polysaccharide required by the pressed product, and the shear-heated extrudate leaves the die warm and dries to a lower residual moisture. For a metallurgical reductant, both differences are in the useful direction.

Table III: Proximate composition of the extruded charcoal briquettes, determined in accordance with EN 1860-2. Values are means of three independent batches ($n = 3$); SD = sample standard deviation. Ash, volatile matter and fixed carbon are given on a dry basis.

Parameter	Value (wt-%)	SD ($\pm$, wt-%)
Moisture content	4.3	0.72
Ash content	4.5	0.33
Volatile matter	21.5	0.56
Fixed carbon (C-fix)	74.0	1.96

The elemental composition of the ash is given in Table IV. The ash is dominated by CaO (36.76 wt-%), SiO₂ (16.10 wt-%) and K₂O (8.59 wt-%), with smaller amounts of MgO, P₂O₅, SO₃, Na₂O and Fe₂O₃. This alkaline-earth-rich, low-iron ash chemistry is typical of hardwood charcoal and is advantageous for silicon metallurgy: the low Fe₂O₃ content (0.97 wt-%) limits iron contamination of the silicon product, while the high CaO/K₂O ratio is favourable for slag basicity control. Two qualifications belong with these figures. Table IV is a single accredited determination on the batch of briquettes characterised here, and the ash chemistry of hardwood charcoal varies appreciably from batch to batch: in the same laboratory campaign, eight production batches of charcoal briquettes from this plant, of which the present sample is one, gave 23.0–46.1 wt-% CaO, 8.6–27.5 wt-% K₂O and 2.5–16.1 wt-% SiO₂. The silica content

of the present batch is therefore the highest of that set, and the 16.10 wt-% in Table IV should not be read as typical of the product; the batch mean over the eight was 6.0 wt-%. The Fe_2O_3 content, by contrast, was consistently low across all eight batches (0.62–1.58 wt-%, mean 1.01 wt-%), so the argument on iron contamination does not rest on a single favourable analysis. The CaO and K_2O contents were above 23 and 8.5 wt-% respectively in every batch, which matters for the crosslinking mechanism proposed in Section 2.1: the cations required for it are present in abundance whatever the batch.

Table IV: Elemental composition of the ash of the extruded charcoal briquettes, determined according to DIN 51729-10. Single accredited determination on the batch characterised here; the batch-to-batch range over eight production batches is given in the text.

Oxide	Value (wt-%)
CaO	36.76
SiO_2	16.10
K_2O	8.59
MgO	2.32
SO_3	2.30
P_2O_5	1.80
Fe_2O_3	0.97
Na_2O	0.72

3.2 Compressive strength

The extruded briquettes withstood axial and radial loads in the range 0.5–0.9 MPa before failure – the observed range over the individual specimens tested, reported as a range rather than as a mean with a standard deviation for the reason given in Section 2.7, with the typical failure mode shown in Figure 2 (right). For hydraulically pressed charcoal briquettes intended for use as a carbonaceous reductant in silicon production, Makgobelele *et al.* (2021) reported cold compressive strengths of 2 kg cm⁻² (0.20 MPa) without binder, 40 kg cm⁻² (3.9 MPa) at 3 wt-% PVA and 115 kg cm⁻² (11.3 MPa) at 5 wt-% PVA after seven days of curing, against 31 kg cm⁻² (3.0 MPa) for the parent lump charcoal, and quoted 3.8 kg cm⁻² (0.37 MPa) as the compressive strength accepted industrially for coal briquettes. The values obtained in the present work therefore exceed that industrial acceptance threshold by a factor of 1.4 to 2.4 and are an order of magnitude above a binderless agglomerate, while remaining below the heavily PVA-loaded pressed briquettes and below the parent lump charcoal; a fuller comparison is given in Section 3.6. The comparison is nevertheless an imperfect one, since the binder chemistry differs and the binder loading of the present briquettes is not disclosed. It should also be noted that the failure load of a 20 mm cylindrical extrudate is not strictly comparable with values measured on short pressed pellets of a different geometry. The level of strength obtained is sufficient to allow the briquettes to be handled, bagged, transported and charged into a furnace without significant breakage, and is consistent with the general observation that hydraulically pressing or extruding the charge produces briquettes two to four times stronger than the equivalent roller-pressed product (Yankovych and Korol, 2025).

3.3 Abrasion resistance

After 30 min in the rotating drum, the briquettes broke approximately in the middle but the resulting pieces retained their cylindrical shape, as visible in Figure 3 (right). The mass fractions obtained after sieving are summarised in Table V. The total mass of material lost as fines below 3.35 mm is 14.4 ± 0.56 % (mean $\pm$ SD, $n = 3$) (11.3 % below 0.5 mm and 3.14 % in the 0.5–3.35 mm range), with a further 0.3 % in the >3.35 mm fines fraction. This corresponds to a mechanical durability of 85.6 ± 0.83 %, which is acceptable for industrial handling and, as

shown in Section 3.6, is of the same order as the abrasion resistance index of 85 % reported for hydraulically pressed charcoal briquettes bound with 3 wt-% PVA, although still below the 96 % of the parent lump charcoal (Makgobelele *et al.*, 2021). The relatively high amount of very fine material (<0.5 mm) is associated with surface attrition of the cylindrical extrudates rather than with bulk fracture, and could be further reduced by optimising the binder/charcoal ratio and the curing time, as discussed by Korol and Yankovych (2025a).

Table V: Particle-size distribution of the briquette fines generated by the abrasion (drum) test. Values are means of three independent tests (n = 3); SD = sample standard deviation.

Fraction	Mass loss (wt-%)	SD ($\pm$, wt-%)
0.0 – 0.5 mm	11.30	0.74
0.5 – 3.35 mm	3.14	0.13
> 3.35 mm	0.30	0.06
Total below 3.35 mm	14.44	0.83

3.4 Water resistance

After five days of full immersion (Figure 4), the briquettes retained their original cylindrical shape and did not disintegrate. The water uptake corresponded to 36.1 % of the initial dry mass; as stated in Section 2.7, this is a single determination and is therefore quoted without a dispersion estimate. This behaviour is in good agreement with the protective effect expected from the organic polymer binder. As set out in Section 2.1, the polymer film is expected to be ionically crosslinked in situ by the calcium and potassium released from the charcoal ash, and the calcium carboxylate so formed is only sparingly soluble; the film therefore survives the immersion and continues to hold the agglomerate together, while water is still taken up through the open pore network of the charcoal itself. The uptake measured here is thus a measure of pore filling rather than of binder dissolution, which is consistent with the complete absence of disintegration. Comparable five-day water uptake values of the order of 30–40 % have been reported for PVA- and PVA/molasses-bound briquettes (Korol and Yankovych, 2025a). It is also instructive to compare these figures with the values obtained on the same type of test by Makgobelele *et al.* (2021), who measured a five-day water absorption of 42 % for lump charcoal and of 25–27 % for hydraulically pressed briquettes containing 3–5 wt-% PVA, while their binderless briquettes disintegrated completely (water-resistance index 0 %). The present briquettes therefore take up less water than the parent lump charcoal and, unlike a binderless agglomerate, survive the immersion intact. The combination of full shape retention and moderate water absorption is sufficient for outdoor storage in temperate climates, although a protective packaging is still recommended for prolonged exposure to rain.

3.5 Thermal-shock behaviour

After rapid heating to 900 °C in an oxygen-free environment and subsequent cooling (Figure 5), the briquettes retained their cylindrical shape and showed no through-thickness cracking. The associated mass loss was 24.0 % of the initial mass; this is a single determination on one charge of briquettes, and its extension to triplicate measurement is part of the continuing work (Section 2.7). This value is consistent with the release of residual moisture, volatile matter and pyrolysis products of the organic polymer binder, and is in the range expected for carbonaceous materials of the present composition. For comparison, Ringdalen (2025) reported that charcoal heated to 800 °C generated only about 2 % of fines below 3.35 mm and that biocarbon agglomerates remained largely undecrepitated, which is consistent with the complete shape retention observed here. The shape retention is the property of practical interest for metallurgical use, since it indicates that the briquettes will not collapse to fines in

the upper, low-temperature zone of a silicon or ferrosilicon submerged-arc furnace, where rapid temperature gradients of the same order of magnitude are encountered. The result therefore supports the suitability of the present extruded briquettes as a carbonaceous reductant in metallurgical processes, in line with the broader trend of substituting fossil reductants by biocarbon-based materials (Surup, Trubetskaya, and Tangstad, 2020; Ringdalen, 2025).

3.6 Comparison with lump charcoal and other carbonaceous materials

Since the briquettes are intended to substitute both lump barbecue charcoal and part of the fossil carbon charged to a submerged-arc furnace, it is useful to place the values measured here in the context of the corresponding data for lump charcoal, for conventionally pressed charcoal briquettes, for binderless agglomerates and for fossil reductants. Such a comparison is collected in Table VI.

Table VI: Comparison of the extruded charcoal briquettes of the present work with lump charcoal, conventionally pressed charcoal briquettes, binderless agglomerates and fossil reductants. Compressive strengths taken from the literature have been converted from kg cm⁻² (1 kg cm⁻² = 0.0981 MPa). For rows 2–5 the abrasion figure is the abrasion resistance index (mass % retained) defined in the cited study; for the present work it is the mass % retained above 3.35 mm after 30 min at 40 rpm. The two procedures differ in detail, so the comparison is indicative rather than strictly quantitative.

Material	Fixed C (wt-%)	Ash (wt-%)	VM (wt-%)	Compressive strength (MPa)	Abrasion / durability (%)	Water uptake, 5 d (%)	Source
Extruded charcoal briquettes, 20 mm	74.0	4.5	21.5	0.5 – 0.9	85.6	36.1	This work
Lump (coarse) hardwood charcoal	66.1	2.5	19.2	3.0	96	42	Makgobelele <i>et al.</i> (2021)
Pressed charcoal briquettes, 3 wt-% PVA	63.3	7.7	22.0	3.9	85	25	Makgobelele <i>et al.</i> (2021)
Pressed charcoal briquettes, 5 wt-% PVA	62.6	6.6	20.6	11.3	82	27	Makgobelele <i>et al.</i> (2021)
Binderless charcoal briquettes	58.3	8.0	22.8	0.20	3	disintegrated	Makgobelele <i>et al.</i> (2021)
Fossil reductant (coal / coke), typical requirement	> 85	< 12	–	–	–	–	Surup <i>et al.</i> (2020)
EN 1860-2, barbecue charcoal briquettes	≥ 60	≤ 18	–	–	–	–	CEN (2005)
EN 1860-2, lump barbecue charcoal	≥ 75	≤ 8	–	–	–	–	CEN (2005)

Chemically, the extruded briquettes are closer to lump charcoal than to a conventional briquetted product. Their ash content of 4.5 wt-% is only about twice that of the parent coarse charcoal (2.5 wt-%) reported by Makgobelele *et al.* (2021), less than half the 6.6–8.0 wt-% measured for the PVA-pressed and binderless briquettes of the same study, and far below the 18 wt-% permitted for briquettes by EN 1860-2 (CEN, 2005). The fixed-carbon content of 74.0 wt-% is higher than that of any of the briquettes in the cited work (58.3–63.3 wt-%) and even higher than that of the parent coarse charcoal itself (66.1 wt-%); it falls only marginally short of the 75 wt-% minimum that EN 1860-2 sets for lump barbecue charcoal, a class in which the present product is not required to qualify. Relative to fossil reductants, for which a fixed carbon above 85 wt-% and an ash content of up to 12 wt-% are typical (Surup, Trubetskaya, and Tangstad, 2020), the briquettes offer a lower carbon density but a markedly cleaner, alkaline-earth-rich and low-iron ash, and a sulphur content roughly two orders of magnitude below that of metallurgical coke (Ringdalen, 2025).

Mechanically, the ranking is the one expected for an agglomerate. Lump charcoal remains the strongest and most abrasion-resistant material of the set (3.0 MPa, abrasion resistance index 96 %), but it cannot be produced from fines, cannot be given a defined shape and absorbs more water (42 %) than the present briquettes. Binderless agglomerates sit at the opposite extreme, at 0.20 MPa, an abrasion resistance index of only 3 % and complete disintegration in water. The extruded briquettes of the present work occupy an intermediate position, with a durability of 85.6 ± 0.83 % that matches the 85 % reported for hydraulically pressed briquettes containing 3 wt-% PVA, and a water uptake of 36.1 % with full shape retention. Their unconfined compressive strength of 0.5–0.9 MPa is lower than that of lump charcoal and of the heavily bound pressed briquettes, but it is 1.4 to 2.4 times the value of 3.8 kg cm^{-2} (0.37 MPa) quoted as the industrially acceptable compressive strength for coal briquettes (Makgobelele *et al.*, 2021). It should also be borne in mind that the failure load of a 20 mm cylindrical extrudate is not strictly comparable with values measured on short pressed pellets of a different geometry. Overall, Table VI shows that the present technology recovers the chemical quality of lump charcoal from a material that would otherwise be discarded, at a handling durability equivalent to a well-bound pressed briquette and with far better water resistance than a binderless product, at the cost of a lower single-particle compressive strength.

3.7 Implications for industrial use

Taken together, the results presented in sections 3.1–3.6 show that the extruded charcoal briquettes meet the EN 1860-2 requirements for barbecue charcoal briquettes (CEN, 2005) with a fixed-carbon content well above 60 % and an ash content well below 18 %, and that their mechanical, hydrothermal and thermal-shock properties are adequate for routine industrial handling. The low ash and very low Fe_2O_3 content, together with the shape retention at 900 °C, also make these briquettes a credible candidate as a partial substitute for fossil coke in silicon and ferrosilicon production. Additional pilot-scale testing in a submerged-arc furnace will be required to confirm the reactivity (Boudouard) and electrical-resistivity behaviour of the briquettes, in line with the experimental approach recently described for biocarbon by Ringdalen (2025). Finally, given the importance of carbonaceous materials in the wider field of separations and adsorption, it can be noted that the same hardwood charcoal feedstock has been shown to be an effective precursor of activated carbon for the removal of organic micropollutants from aqueous and ethanol solutions (Korol *et al.*, 2026).

4. CONCLUSIONS

A new type of cylindrical extruded charcoal briquette (diameter 20 mm, length 30–150 mm) has been manufactured on a laboratory extruder from hardwood charcoal fines and a protective organic polymer binder, and has been characterised against the requirements of EN 1860-2 and DIN 51729-10. The replication of the individual tests differs and is stated in Section 2.7: the proximate and abrasion indices are means $\pm$ standard deviation of three independently produced batches ($n = 3$), the ash analysis is a single accredited determination reported together with the batch-to-batch range, the compressive strength is reported as the observed range of failure stresses, and the water-resistance and thermal-shock results are single determinations. The main conclusions of the work can be summarised as follows.

The proximate analysis gave a fixed-carbon content of 74.0 % and an ash content of 4.5 %, both well within the EN 1860-2 limits for charcoal briquettes. The ash is dominated by CaO (36.76 wt-%), SiO_2 (16.10 wt-%) and K_2O (8.59 wt-%), with a very low Fe_2O_3 content (0.97 wt-%) that is favourable for silicon metallurgy.

Mechanically, the briquettes withstand compression loads of 0.5–0.9 MPa, and lose only 14.4 ± 0.56 % of mass as fines below 3.35 mm after 30 min of drum abrasion at 40 rpm, which corresponds to a mechanical durability of 85.6 ± 0.83 %.

The protective organic polymer binder gives a clear water-resistance benefit: after five days of full immersion the briquettes retained their cylindrical shape and showed no disintegration, with a moderate water uptake of 36.1 % of the initial dry mass (single determination).

Under rapid heating to 900 °C in an oxygen-free environment the briquettes retained their shape with a mass loss of 24.0 % (single determination), demonstrating acceptable thermal-shock resistance and supporting their suitability as a carbonaceous reductant in metallurgical applications, including silicon and ferrosilicon production.

The results reported above are, however, subject to a number of limitations that should be borne in mind when interpreting them and that define the boundaries of the present study. First, the briquettes were produced in discrete batches on a laboratory single-screw extruder; a continuous industrial extrusion line differs in shear and thermal history, throughput, die wear and drying regime, so the strength, durability and water-resistance values reported here must be confirmed on industrially produced material before they can be transferred to plant scale. The throughput actually achieved is itself a limitation of the present configuration: against a nameplate capacity of 300 kg h⁻¹, no more than 5 kg h⁻¹ could be produced from charcoal fines, because the charge has to be warmed and homogenised by repeated passes through the extruder itself. Closing that gap requires a heated, agitated mixing vessel upstream of the die rather than a change to the binder or to the formulation, and this is the first step of the planned scale-up. Second, the thermal-shock test was carried out at 900 °C, which reproduces the rapid heating experienced by the charge in the upper, low-temperature zone of a submerged-arc furnace but is well below the temperatures prevailing in the coke bed and in the reaction zone of silicon and ferrosilicon production; the behaviour of the briquettes at those temperatures, together with their Boudouard (CO₂) reactivity and their electrical resistivity, has not been assessed here and is the subject of ongoing work. Third, the abrasion test generated 11.3 wt-% of material below 0.5 mm, which is higher than desirable for a furnace feed and would represent a real material loss in industrial handling; reducing this very fine fraction — most probably by increasing the binder dosage, extending the curing time or introducing a short thermal-curing step — remains the single most important target for further optimisation. Finally, all data reported here refer to one binder formulation and one hardwood charcoal source, so the sensitivity of the results to feedstock variability and to binder composition still has to be established. A further limitation concerns the reporting itself: the water-resistance and thermal-shock results rest on single determinations and the compressive strength is given as an observed range, so only the proximate and abrasion indices carry a measured dispersion; and the exact binder composition and loading are commercially protected, which restricts strict reproduction of the formulation by other laboratories.

Further work will focus on pilot-scale testing of the briquettes in a submerged-arc furnace and on the optimisation of the binder formulation in order to reduce the proportion of very fine material generated during abrasion, while preserving the favourable water-resistance and thermal-shock characteristics demonstrated in the present study.

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