

Two-Phase Removal (Oil and Water) from Agate Sawdust Residue by Mechanical Compression

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Abstract

In the processing of agates, geode sawing generates a residue comprising diesel oil, moisture, and fine agate fragments. This process is usually carried out by small companies and the waste material generally accumulates in courtyards, waiting for a suitable destination to be determined. In this context, the aim of this work was to study the removal of the liquid fraction (oil and some water) from this agate sawdust residue (ASR) by mechanical compression. The experimental work included waste material characterisation and fluid removal assays. The oily residue was processed by compressing it at a laboratory scale, where the main variables were pressure (2.0 MPa, 4.2 MPa, and 6.4 MPa) and temperature (5°C, 23°C and 60°C). The experiments were performed in triplicate and the differences between means were statistically analysed. Thereafter, the treatment of oily residue was also carried out in an industrial hydraulic press (11.7 MPa at 23°C). The ASR sampled for this work was a solid-in-water-in-oil sludge, comprising (by w/w) 19.0% diesel oil, 8.5% water and 72.5% silica (SiO₂). The laboratory and industrial trials showed that the removal of liquids is a function of the applied pressure-the higher the pressure, the higher the fluid removal-and the best temperature, which occurred at 23°C. Pressures above 6.2 MPa changed the ASR composition to approximately 3.6% oil and 3.5% water, corresponding to approximately 80% of liquid removal, by weight. The process allowed a reduction in volume, increased oil recovery, and an improvement in the material's handling properties. Regarding the solid fraction, it was now in a better condition to be used in red ceramics or co-processing in cement production kilns.

Keywords

Silica, Fine Particles, Diesel Oil, Environment Protection

1. Introduction

One of the world's most significant agate deposits is in Brazil, where agate geodes are characterised by their large size and intricate banding, making them sought after for both jewellery and ornamental use [1]. The municipality of Soledade, Brazil, concentrates the major part of the gem processing operations. The activities are carried out by local lapidary workers, incorporating a certain degree of mechanisation [2].

Vilasbôas *et al.* [3] summarised the operations involved in a detailed description, involving selection, washing, cutting, dyeing, and finishing operations. A more in-depth look at the art of agate dyeing can be found in the works of Sampaio and Tubino [4], Silva *et al.* [5], Yazdi *et al.* [6], and Ericksson *et al.* [7] [8]. **Figure 1** shows finished plates of Umbú variety agate, on display.



Figure 1. Pieces of Brazilian agates prepared for ornamental purposes.

After selecting a geode, sawing is the next operation on the production line. This is carried out with diamond saws powered by electric motors. Diesel oil is applied over the stones, for the purposes of cooling and lubrication. Inside the machines, very fine fragments of the oil-soaked rock accumulate. Periodically, it is necessary to clean the machines, giving rise to an agate and oil/water sludge which will be referred to in this work as “agate sawdust residue—ASR”. Waste generation from the cutting machines varies from 0.10 to 0.15 kg of ASR per kg of geodes processed [3]. This material is classified as a hazardous residue, according to NBR 10.004/2024 in Brazil, because of the presence of diesel oil [9] [10].

The proper disposal of ASR is adverse. The legal guidance is to ship such wastes to specific oil recovery and recycling units, which are away from the Soledade region. Co-processing in cement production kilns is also acceptable but it involves feasibility studies, long-distance transportation, and processing costs. Therefore, the waste frequently is stored in plastic drums, awaiting for a safe destination.

Some producers partially recover the oil by stirring water into the ASR. The procedure forms two layers: a superior layer, with oil, and an inferior layer, with a mixture of agate powder, water, and oil. Definitely, this is not a solution. Alkaline hot extraction procedures can reach oil removal efficiencies of over 95% but it is a process that uses water and requires further treatment [11]. The only known process that achieves oil removals close to 100% is extraction with organic solvents, which is operationally sophisticated and potentially dangerous in the current production routines.

In this context, any action that removes fluids, whether they be oil and/or water, and improves the handling properties of the material, is beneficial. In order to succeed, the objective of the present work was to study the removal of fluids, at least at a rough stage, by means of mechanical compression. This work details the characteristics of the waste and evaluates the efficiency of the mechanical compression process as a function of temperature and pressure at a laboratory and industrial scale. Finally, the results are discussed, in terms of the both the efficiency of fluid removal and the potential uses of the remaining silica rich fraction.

2. Materials and Methods

2.1. Agate Sawdust Residue—ASR

Samples of ASR were collected from a small company located in the municipality of Soledade, Brazil (coordinates 28°49'06"S/52°30'37"W). The company only performs the geode cutting stage, employing family labour. The process is carried out using diamond saws with the aid of diesel oil as a cooling and lubricating agent. The sample collection (≈ 100 kg) was conducted following the procedures of the Brazilian Standard NBR 10007 (ABNT, 2004) [12]. The material was obtained from 8 cleaning operations carried out on two agate cutting machines (16 clearances) over a period of 2 months. The material was gradually accumulated and mixed in a plastic drum until it was transported to the location of the experimental study. In order to provide material for solid phase characterisation, 50 g of the sample was subjected to heating at 105°C, for moisture removal and then oil extraction in Soxhlet, using hexane as an organic solvent. The solid phase was analysed in terms of its particle size distribution, specific mass, elemental composition, and mineralogical constitution. The procedures also allowed the measurement of the oil and water content in the primary ASR.

2.2. Laboratory Compression Studies of the Residue

To separate the solid and liquid phases at laboratory scale, a cylindrical container was constructed to accommodate 300 g of ASR, with an internal diameter of 100 mm and a height of 70 mm. The device was designed so that the fluid would be collected by a lateral tube, like a drain. The lid was 30 mm high and had a diameter of 95 mm with a cylindrical pin through which the force was transmitted. **Figure 2** shows the details of the unit used for compressing. To prevent solids from being

carried along with the fluid during pressure application, the ASR was placed in a polypropylene fabric bag.

The laboratory-scale extraction tests were performed using an automatic loading machine with the following characteristics: a nominal capacity of 50 kN, a precision of 0.023 kN, a constant speed of 1.44 mm min^{-1} , and visual determination of the applied force using an analogue gauge. The variables studied were pressure and temperature. The temperatures applied were 5°C , 23°C , and 60°C , while the pressures applied were 2.0 MPa, 4.2 MPa, and 6.4 MPa. The compression was maintained until the fluid flow stopped. In all conditions, the compression time was less than 2 minutes. Temperature was monitored with a thermometer immersed in the container that received the drained liquid, and variations did not exceed $\pm 2^\circ\text{C}$. After finishing the compression stage, the drained volume and the oil and water content in the remaining solid fraction were analysed. The specific mass (density or mass per unit volume) before and after compression was measured gravimetrically considering the final volume of residue in the cylinder.

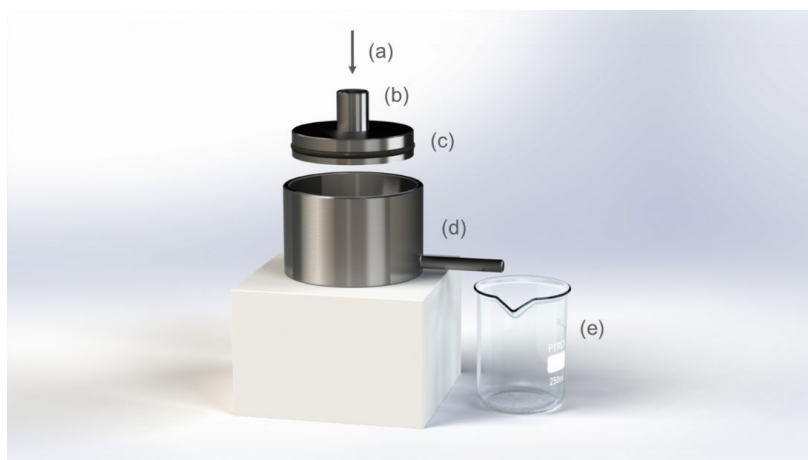


Figure 2. Device used for the separation of oil from agate powder by mechanical compression: (a) applied force; (b) plunger for ASR compression; (c) rubber ring for sealing; (d) cylindrical cavity with the ASR; and (e) beaker for collecting the fluids.

2.3. Compressing with Industrial Equipment

The horizontal industrial hydraulic press used was made by Hidraumatic (model PK60H; Novo Hamburgo, Brazil). This machine has a cylinder for placing the material to be pressed, with a length of 1000 mm and a diameter of 200 mm. Testing with an industrial press were carried out on 1 kg of ASR at an applied pressure of 11.76 MPa. The experiments were carried out in three repetitions. As with the laboratory testing, the obtained solid fraction was analysed in relation to the oil and water content.

2.4. Analysis

The particle size distribution of the solid fraction was assessed by laser diffraction

using a CILAS 1180 particle size analyser (Compagnie Industrielle des Lasers, France). Elemental composition was measured by X-ray fluorescence using a Rigaku spectrometer, model RIX 2000 (Rigaku Corporation, Japan). X-ray diffraction was carried out in a Siemens (Bruker AXS, United States) X-ray diffractometer, model D-5000 (θ - 2θ), equipped with a fixed Cu anode tube, operating at 40 kV and 25 mA, with an incident radiation of 1.5406 Å. The angular range was analysed from 3° to 80°, 2θ with a step size of 0.02°/3 s using divergence and anti-scattering slits of 2.0 mm and 0.2 mm in the detector.

Moisture determination was carried out gravimetrically, according to ASTM Standard Test D2216-19 [13]. To quantify the oil content, a separate amount of the same sample was subjected to oil extraction in a Soxhlet device, using hexane as an organic solvent [14].

2.5. Statistical Analysis

The results are shown in terms of the arithmetic mean and standard deviation. The fluid removal data obtained through residue compression were submitted to the Shapiro-Wilk normality test. Since it was confirmed that the data follow a normal distribution, variance analysis (ANOVA) was performed. The difference in means was evaluated using Tukey's test with a significance level of significance $p \leq 5\%$ (0.05). The statistical analysis and the creation of the fluid removal graphs over pressure were carried out using Minitab 21 Statistical Software (Minitab, LLC) [15].

3. Results and Discussion

Some features of the agate sawdust residue sample (ASR) used in this work are shown in **Table 1**. The sample presented 27.5% of liquid phase and 72.5% of solid phase. The liquid phase comprised approximately 70% oil and 30% water. The oil-free solid phase presented a particle size distribution ranging from 0.04 to 60 μm , with a D_{50} of 10 μm . The mineralogical composition, obtained by X-ray diffraction (XRD), indicated quartz as a unique crystalline phase. The particle size distribution graph and the X-ray pattern of ASR can be found in **Supplementary Material 1**. X-ray fluorescence analyses yielded the following composition: Si—46.61%, Fe—0.13%, Ca—0.05%, Mn—0.01% and O plus other minor elements (by difference)—53.2%. This means that the solid fraction of the residue is a very fine white/slightly grey powder rich in crystalline and cryptocrystalline silica, in the form of quartz at a purity level of 99.7%.

Table 1. Characteristics of the agate sawdust residue sample (ASR).

Property	ASR
Phase distribution	
Diesel oil (%)	19.0
Moisture (%)	8.5

Continued

Agate powder (%)	72.5
Crystalline components	Quartz (unique mineral phase identified)
Particle size	
Size distribution (μm)	0.04 - 60
D ₉₀ (μm)	26
D ₅₀ (μm)	10
D ₁₀ (μm)	1.5
Elemental composition	
Si (%)	46.61
Fe (%)	0.13
Ca (%)	0.05
Mn (%)	0.01
O and minor components	53.20

Fluid removal as a function of pressure and temperature, at laboratory scale, is shown in **Table 2**. Individual values and the result of analysis of variance (ANOVA) are depicted in **Supplementary Material 2**. Both oil and water removal are dependent on the applied pressure, temperature, and the interaction of both variables. It can be observed that the higher the applied pressure, the greater the volume of fluid removed. With regard to temperature, the best results occurred at 23 °C, for all applied pressures. However, the difference between the volumes removed at 5 °C and 23 °C, as well as those between 23 °C and 60 °C, decreased as the pressure increased. Statistically, all of the means showed significant differences, at a significance level of 0.05, except for the values obtained at temperatures of 23 °C and 60 °C, with the pressure at 6.4 MPa.

We consider that the best results were obtained with a pressure of 6.4 MPa at 23 °C, with an average removal of 260 mL kg⁻¹ of ASR.

Table 2. Mean ($\bar{x}$) and standard deviation (σ) of fluid removal in mL kg⁻¹ of agate waste residue (ASR) as a function of pressure and temperature ($n = 3$).

Pressure	Temperature					
	5 °C		23 °C		60 °C	
	μ	σ	μ	σ	μ	σ
2.0 MPa	123.3 _a	5.4	193.3 _b	13.4	146.7 _c	9.8
4.2 MPa	180.6 _d	10.4	235.0 _e	3.6	213.3 _f	8.3
6.4 MPa	225.5 _g	32.0	259.5 _h	5.65	255.1 _h	9.5

Note: Means that differ significantly are indicated by different lower-case letters (Tukey's test, $p \leq 0.05$). The comparison was made between the means among all treatment's combinations.

Table 3 presents the mean and standard deviation of residual oil and water content (weight/weight, w/w) in the solid phase after bench scale experiments at a pressure of 6.4 MPa and temperature of 23 °C. The individual results and the mass balance are organised in **Supplementary Material 3**. Laboratory compression of ASR removed the initial oil content by approximately 85.3% and the moisture content by 69.4%. Considering both fluids, there was a reduction of 80.4%. Likewise, **Table 4** shows the results obtained after industrial-scale experiments at a pressure of 11.4 MPa at the same temperature. The individual results and the mass balance are detailed in **Supplementary Material 4**. Industrial compression of the oily residue purged the initial oil content by approximately 89.0% and the moisture content by 67.1%. Considering both fluids, there was a reduction of 82.2%.

By gathering all of the data, **Figure 3** shows the behaviour of the residual concentration of fluids (oil, water, and the sum of both) as a function of the applied pressure at a temperature of 23 °C. It can be seen that, starting from a pressure of 6.4 MPa, the concentration of oil and water practically stabilises, so that any additional mechanical effort results in hardly any gains in fluid removal.

Table 3. Mean ($\bar{x}$) and standard deviation (σ), in percentage (w/w), of the final content of oil and water after the application of a pressure of 6.4 MPa at a temperature of 23 °C ($n = 3$) in bench scale compression trials.

	Raw sample		Treated sample	
	$\bar{x}$	σ	$\bar{x}$	σ
Oil content (%)	19.0	1.4	3.6	0.1
Water content (%)	8.5	0.6	3.5	0.8
Total (%)	27.5	2.0	7.1	0.9

Table 4. Mean ($\bar{x}$) and standard deviation (σ), in percentage (w/w), of the final content of oil and water after the application of a pressure of 11.4 MPa at a temperature of 23 °C ($n = 3$) in industrial compression trials.

	Raw sample		Treated sample	
	$\bar{x}$	σ	$\bar{x}$	σ
Oil content (%)	19.0	1.4	2.7	0.4
Water content (%)	8.5	0.6	3.7	0.3
Total (%)	27.5	2.0	6.4	0.7

The characteristic banding of agates is heavily dictated by alternating zones of high and low porosity. More porous layers generally consist of disordered fibrous chalcedony with interstitial water; whereas, less porous bands transition into dense macrocrystalline quartz [16] [17]. The vast majority of the interconnected pores measure between 0.01 μm and 0.20 μm (10 to 200 nanometers) [18]. Liquid-rich fluid inclusions, vapour-rich fluid inclusions, and in less extension multi-phase fluid inclusions are also found in agates [19]. The sawing process probably

cracks or breaks these structures in fine particles, which explains the water content found in the residue.

The compaction process in the press mainly consists of the repacking of the initial particles, followed by pore compression and, finally, permeation or extrusion of the fluids. The result is the formation of a dense solid mass with reduced oil/moisture content [20]. The process changes the material's specific mass. The ASR before processing has a value of 2.15 g/cm³, and after compression, this value goes up to 2.5 g/cm³. There were also changes in the consistency state due to the applied pressure, going from liquid-viscous, to plastic, and then to semi-solid. Images of the ASR before and after pressing, with the indication of the material's consistency states, are shown in **Supplementary Material 5**.

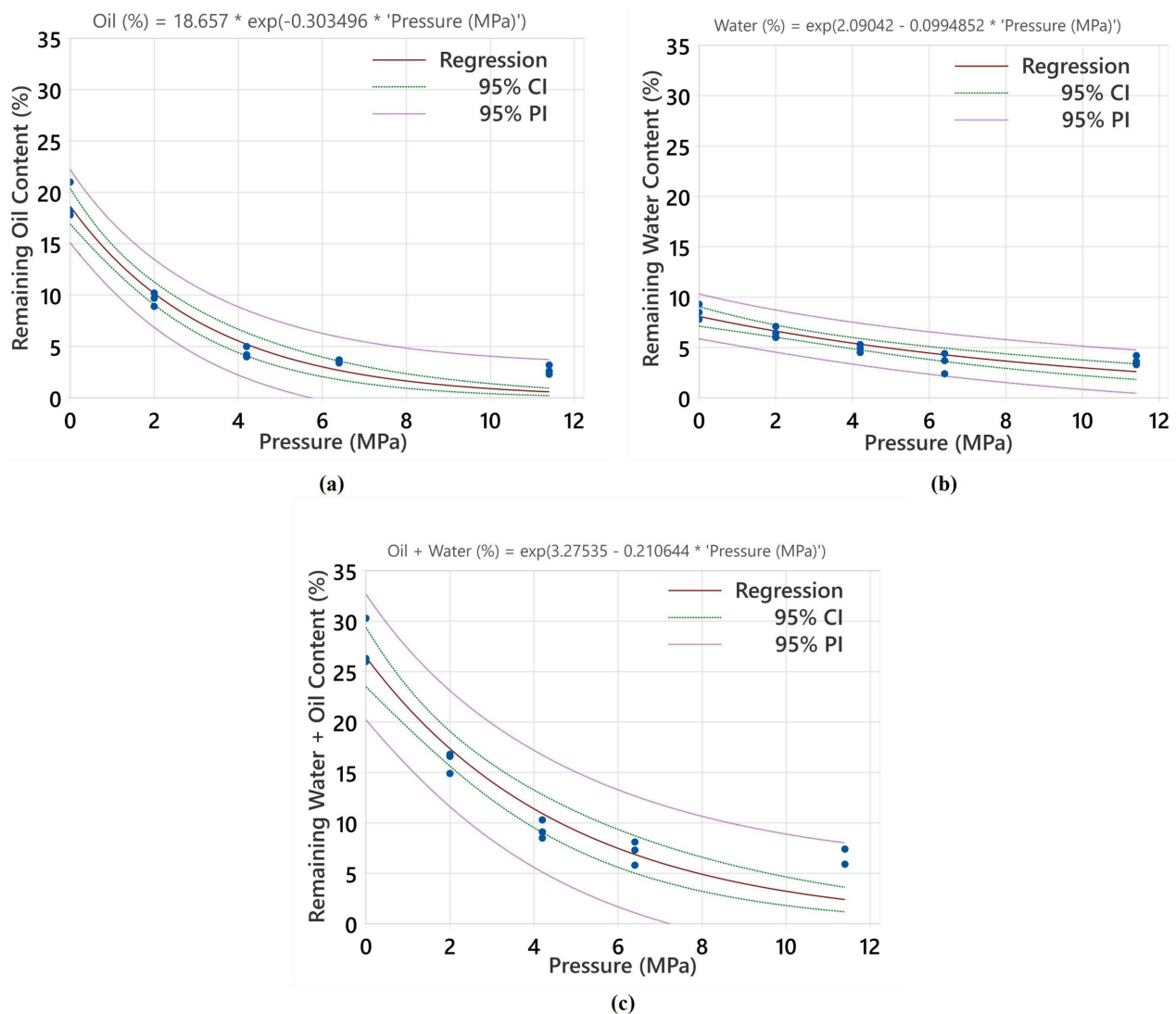


Figure 3. Effect of mechanical pressure at (a) oil, (b) water, and (c) total fluid (water + oil) content in ASR at a temperature of 23°C.

It was expected that the removal of fluids would increase with the raising of

pressure and temperature (**Table 2**). Pressure would compact the particles, reducing inter-particle voids, and force the fluids to flow off. Raising temperature would decrease the density and viscosity of the fluids, improving their drainage. In this work, concerning the pressure, there was an increase in fluid removal with an increase in the applied effort. Regarding the temperature, there was an increase in fluid extraction when the temperature was raised from 5°C to 23°C. However, the same was not observed in the tests conducted at 65°C; on the contrary, a reduction in the average values was observed, compared to the values obtained at 23°C.

The influence of temperature on the adsorption and diffusion of oil in quartz nanopores has been the subject of previous molecular dynamics studies [21]. Chen *et al.* noticed that a temperature increase leads to the saturated molecules of oil desorbing from the nanopore surface. However, at the same time that the rise in temperature reduces the density and viscosity of the oil, the rising pressure increases density and viscosity. In addition, at solid surface film level, the pressure might help push some of the fluids into empty cavities. Finally, the authors highlight that the expected dynamic behaviour of oil occurs differently when it is inside a nanometric quartz cavity. Thus, the complexity of factors involved in the system described by Chen *et al.* supports the behaviour identified in the separation of oil and water from the silica matrix through mechanical compression achieved in this work.

Extracting a biphasic mixture of oil and water from silica particles using mechanical pressure also relies on exploiting the capillary forces that bind liquids to solid surfaces and varying the wettability of the solid [22]. Quartz' natural hydrophilicity (due to surface silanol groups) tends to attract water and repel oils [23] [24]. We realized that it is harder to remove water than oil; the water/oil proportion in the solid phase gradually increases as much as the fluid removal process takes place. This indicates that, when the fluid removal process occurs as a thin film on the surface of solids, silica particles hold the water rather than oil.

In practical terms, it was observed that, at 23°C and pressures above 6.4 MPa, there will be a $\approx 80\%$ (w/w) removal of fluids, which will result in a 20% volumetric reduction of the residue as a whole. The original material, with 19.0% oil and 8.5% water, will end up containing 3% - 4% oil and 5% water, changing from hard-to-handle solid-in-water-in-oil sludge to a semi-solid consistency. This can make the storage and transportation of ASR to its final destination much easier. The current generation of this waste is approximately 4,000 kg per month⁻¹, which means that about 720 L per month⁻¹ of diesel oil could be removed (≈ 610 kg month⁻¹, considering the oil density as 0.85 kg L⁻³), which might otherwise contaminate the soil and nearby water resources. It is worth remembering that the agate-producing hub is located near a river headwaters region, feeding the Taquari River basin. The process could be carried out in batch-operated presses [20]. Equipment with a capacity of 25 to 30 kg h⁻¹ could process ASR at a regional level, considering a work schedule of 22 days per month at 8 hours per day.

Safe destinations for ASR after the compressing step could be incorporation

into ceramic materials or co-processing in cement kilns. The incorporation of oily residues into red ceramics can be associated with advantages to clay body processing, saving in fuel consumption and enhancing the mechanical properties [25]–[28]. In the case of being incorporated into the cement industry, the material with a lower water content can contribute to the Portland cement mix as a source of silica [29] [30]. Furthermore, the material can be subjected to processes for the complete removal of oils, such as solvent extraction [31]. The feasibility of the use of the material for those purposes should be the subject of future studies.

Assured that the oil has been removed, and presuming that all silicon is in the form of quartz, the material presents 99.7% SiO₂. Pan *et al.* [32] listed applications for quartz with contents of SiO₂ between 90% and 99%, including its use as a raw material in refractory bricks and for smelting ferrosilicon alloy in the iron and steel industry. The high melting point of quartz sand makes it important for applications in the mechanical casting industry. In the chemical industry, it is used for the production of sodium silicate, silica gel, catalysts and other products. The high SiO₂ grade of the material encourages the development of purification processes for higher-value applications, such as silica glass, silica ceramics, semiconductors and as a raw material for the photovoltaic, electronic, lighting, and fibre-optic communication industries [32] [33].

4. Conclusions

Agate sawdust residue (ASR) that was used in this study is a solid-in-water-in-oil sludge comprising 19.0% diesel oil, 8.5% water, and 72.5% of silica (SiO₂), by w/w. The material is difficult to handle and poses a high risk of environmental contamination.

Based on the data obtained from mechanical compression laboratory-scale tests, it is possible to remove approximately 74.2% of the fluids. The resulting material only contains 3.6% oil and 3.5% water. The best output was obtained with a pressure above 6.4 MPa and a temperature of 23 °C. Similar results were obtained with an industrial press at 11.4 MPa at same temperature, reaching 2.7% oil and 3.7% water. The process drastically changes the material's consistency, reducing its adhesiveness and cohesiveness.

It can be concluded that mechanical compression can turn out to be a satisfactory and viable method for recovering the oil present in agate sawdust residue. The recovered liquid should be characterized and its subsequent handling specified. The compressed solid fraction still requires controlled management because residual diesel remains. However, it presents better conditions for further use in red ceramics or co-processing in cement kilns. The solid fraction should be the subject of subsequent studies on complete oil removal, to enable the production of a fine powder with a silica content exceeding 99%.

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Author Contributions

Conceptualization, M.F.M.B., F.S.V. and I.A.H.S.; methodology, M.F.M.B., F.S.V. and I.A.H.S.; validation, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; formal analysis, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; investigation, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; resources, F.S.V. and I.A.H.S.; data curation, I.A.H.S.; writing—original draft preparation, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; writing—review and editing, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; visualization, M.F.M.B., F.S.K., F.S.V. and I.A.H.S.; supervision, I.A.H.S.; project administration, I.A.H.S.; funding acquisition, I.A.H.S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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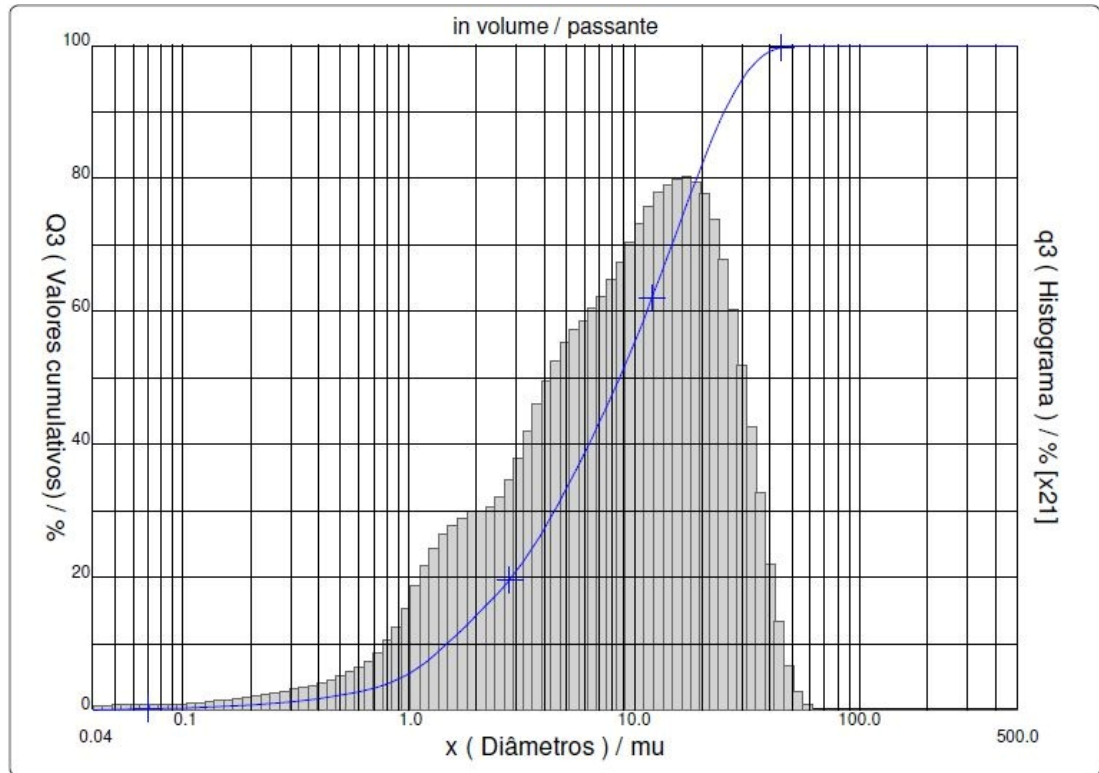
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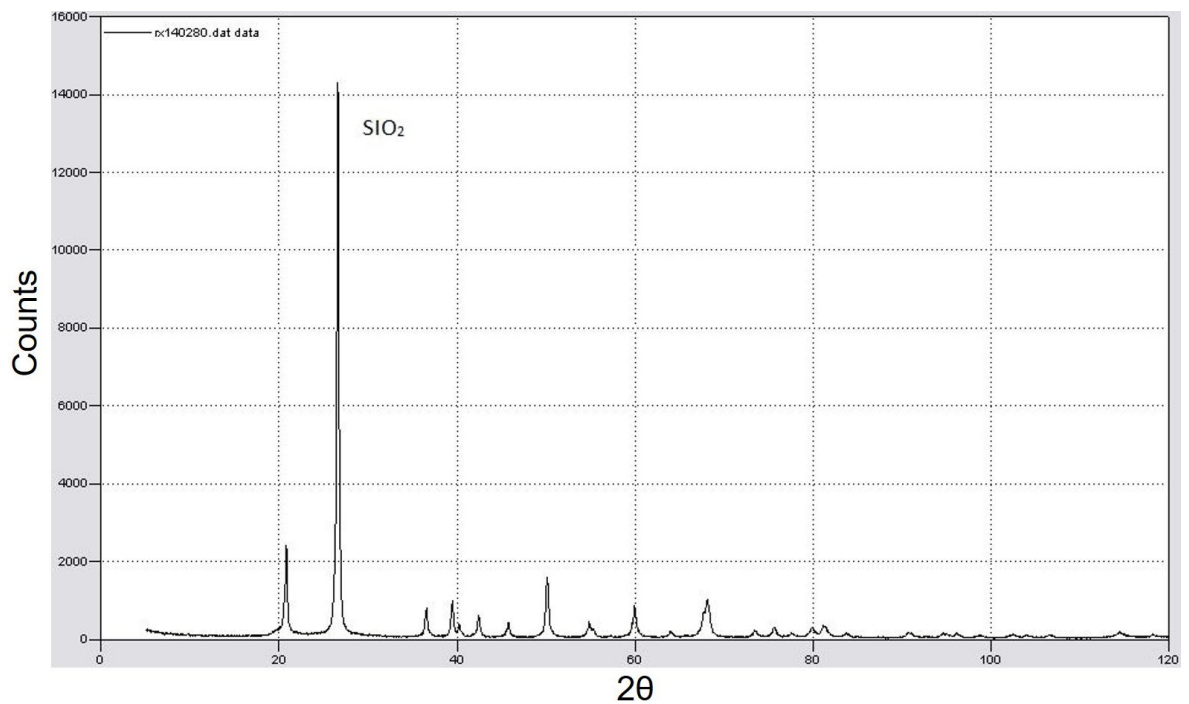
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Appendix

Supplementary Material 1



Particle size distribution graph attained by laser diffraction of the oil-free agate sawdust residue (ASR).



X-ray pattern of the oil-free agate sawdust residue (ASR).

Supplementary Material 2

Fluid removal values from agate sawdust residue (ASR) by mechanical pressure expressed in mL kg⁻¹.

Pressure	Repetition	Temperature		
		5°C	23°C	60°C
2.0 MPa	1	116.7	175.0	160.0
2.0 MPa	2	130.0	206.7	136.7
2.0 MPa	3	123.3	198.3	143.3
	μ	123.33	193.33	146.67
	σ	5.43	13.41	9.81
4.2 MPa	1	183.3	240.0	201.7
4.2 MPa	2	166.7	231.7	218.3
4.2 MPa	3	191.7	233.3	220.0
	μ	180.57	235.00	213.33
	σ	10.39	3.60	8.26
6.4 MPa	1	223.3	251.7	243.3
6.4 MPa	2	233.3	261.7	266.7
6.4 MPa	3	220.0	265.0	255.2
	μ	225.53	259.47	255.07
	σ	31.98	5.65	9.55

Supplementary Material 3

Oil and moisture concentration of the raw and after pressing the agate sawdust residue (ASR) at a temperature of 23°C and a pressure of 6.4 MPa at laboratory scale.

Condition	Repetition	Concentration		
		Oil (%)	Moisture (%)	Total fluid (%)
Raw ASR	1	21.0	9.3	30.3
	2	17.8	8.5	26.3
	3	18.2	7.8	26.0
	μ	19.00	8.53	27.53
	σ	1.42	0.61	1.96
ASR after mechanical pressure (23°C and 6.4 MPa) at laboratory scale	1	3.7	4.4	8.1
	2	3.6	3.7	7.3
	3	3.4	2.4	5.8
	μ	3.56	3.50	7.06
	σ	0.12	0.83	0.95

Mass distribution of the remained solid phase and liquid drained in g per 100 g of ASR.

Condition	Solid phase			Drained-liquid mass	
	Silica	Oil	Water	Oil	Water
Raw ASR	72.5	19.0	8.5	-	-
Laboratory compression 6.4 MPa, 23 °C	72.5	2.8	2.6	16.2	5.9

Specific weight of raw and compressed ASR.

Condition	Specific weight (g cm ⁻³)
Raw ASR	2.16
Laboratory compression 6.4 MPa, 23 °C	2.53

Supplementary Material 4

Oil and moisture concentration of the raw and after pressing the agate sawdust residue (ASR) at a temperature of 23 °C and a pressure of 11.4 MPa in an industrial press.

Condition	Repetition	Concentration		
		Oil (%)	Moisture (%)	Total fluid (%)
Raw ASR	1	21.0	9.3	30.3
	2	17.8	8.5	26.3
	3	18.2	7.8	26.0
μ		19.00	8.53	27.53
σ		1.42	0.61	1.96
ASR after mechanical pressure (23 °C and 6.4 MPa) at laboratory scale	1	2.3	3.6	5.9
	2	2.6	3.3	5.9
	3	3.2	4.2	7.4
μ		2.70	3.67	6.4
σ		0.37	0.33	0.71

Mass distribution of the remained solid phase and liquid drained in g per 100 g of ASR.

Condition	Solid phase			Drained-liquid mass	
	Silica	Oil	Water	Oil	Water
Raw ASR	72.5	19.0	8.5	-	-
Industrial compression 11.4 MPa, 23 °C	72.5	2.1	2.8	16.9	5.7

Specific weight of raw and compressed ASR.

Condition	Specific weight (g cm ⁻³)
Raw ASR	2.16

Continued

Industrial compression
11.4 MPa, 23°C

2.54

Supplementary Material 6



Agate sawdust residue (ASR) from cutting machines.
(L-V)



Fluid recovered by compressing
ASR.

Temperature: 5°C



6.4 MPa (P) 4.2 MPa (P) 2.1 MPa (P)

Temperature: 23°C



6.4 MPa (S-S) 4.2 MPa (S-S) 2.1 MPa (P)

Temperature: 60°C



6.4 MPa (S-S) 4.2 MPa (S-S) 2.1 MPa (P)

Images of solid phase resulting from compressing ASR
under various temperature and pressure conditions at
laboratory scale.

Temperature: 23°C



11.8 MPa
(S-S)

Solid phase after industrial
compressing.



Industrial press Hidraumatic model
pK60H

Consistency state: liquid-viscous (L-V), plastic (P), and semi-solid (S-S).