Automation of Ramming Process for Aluminum Reduction Cell

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Abstract

Newly installed cathode blocks in an aluminum reduction cell expand due to rapid increase in temperature when passing high current at the start-up of the cell. High thermal stresses may result if cathode blocks are lined without gaps, and this can lead to cracking of the cathodes and failure of the cell. On the other hand, leaving gaps would cause failure due to molten metal infiltration in the gaps. To overcome these problems, carbon-based ramming material is used to fill these gaps. Filling currently is carried out manually or partially automated, but this needs to be fully automated in line with Industry 4.0. The broad objective of this project is to establish the characteristics of ramming paste under different conditions so that one can make decisions to improve the life of the carbon paste in the cell. This will help to reduce the process duration, and the number of compacted layers. Experimental analysis was carried out to visualize and investigate the compaction of ramming paste in the gaps and to identify forms and defects after compaction. Subsequently, characterization of ramming paste was carried out under different conditions by varying applied pressure and paste mold to obtain favorable operational parameters. Produced paste blocks were baked at different temperatures, and their behavior was investigated. Further, Principle of Fused Deposition Modeling was used to extrude ramming paste using a nozzle with different nozzle profiles and variable applied loads. This set of experiments concluded that ramming paste cannot be injected using a nozzle as it gets compacted at the nozzle exit. The paste does not flow because of its non-viscous physical property and the resulting solidification under pressure. Following this, an ongoing attempt is currently being carried out to extrude ramming paste using a two-stage process comprising of a screw conveyor to uniformly convey the material and a roller to compact the material as a second stage. These findings can assist the development of automated filling of the ramming paste in the gaps.

Keywords: Aluminum reduction cells, Ramming paste, Automation of cell ramming, Cell relining, Extrusion of ramming paste.

1. Introduction

Gaps are left between newly installed cathode blocks in aluminum reduction cell because of the expansion resulting from the rapid increase of temperature due to the high current at the start-up. Carbon-based ramming material is used to fill these gaps because (i) lining without gaps would cause high thermal stresses resulting in cracking of the cathodes and failure of the cell and (ii) leaving gaps would cause failure due to molten metal infiltration in the gaps [3]. The filling at present is carried out manually or partially automated. For efficient production of aluminum, the current process needs to be fully automated, and automation of ramming process is gaining research attention. The research presented in this paper aims to explore new ways of injecting compacted ramming paste into the gaps to produce better compacted paste and to reduce the process duration. Backed by detailed literature search and analysis, experimental investigations were carried out in the following stages:

1. Forms and defects in manual compaction were experimentally investigated by compacting the paste between two transparent plates, in the same way as practiced in industry.
2. Characterization of ramming paste was carried out under different applied pressures and paste molds to obtain favorable operational parameters.
3. Characterization of ramming paste was carried out under varying temperatures to comprehend the behavior at elevated temperatures for baked samples.
4. Injection of ramming paste through a nozzle with different profiles to obtain precise material filling without waste following the concept of 3D-printing.
5. Following the results, an ongoing attempt is currently underway to extrude ramming paste using a two-stage process, comprising of a screw conveyor to uniformly distribute the material and a roller to compact the material at a second stage.

1.1 Objectives

Main objective: The main objective of this project is to establish the characteristics of ramming paste under different conditions to make decisions to improve the life of the carbon paste in the cell. This will help to reduce the process duration and the number of compacted layers.

Specific objectives: To achieve the main objective, the following specific objectives are identified:

1. Study the behavior of the paste, by creating a transparent mold that has two plates, with the same gap and height filled by the ramming paste in the industry and filling them in layers and ramming the layers as done in industry.
2. Investigate the relationships between applied pressure, density of the block formed due to the pressure, and its structural properties like Young’s modulus and yield stress.
3. Understand and explain the behavior of the baked paste blocks under varying temperatures.
4. Support the experimental work with the available knowledge on each of the topics of interest by detailed literature search.

Each of these specific objectives was carried out using relevant findings from literature search and experimental set-ups. The following sections describe them.

2. Literature Research

Aluminum industry is focused on the development of pot cell technologies with higher amperages to maximize the production rate. Such developments of pot cells necessitate the development of ramming machines with better operability, process, and quality control. However, a core problem for such development is ramming paste compaction [1]. Ramming mixes mainly consist of metallurgical coke, petroleum coke or anthracite, and tar binder [2], and they are used in high temperature processes such as in steel and aluminum industries. Since ramming paste can absorb deformation [3], it is used to fill the voids between cathode blocks to absorb the expected deformation and to avoid damage. This is because the thermomechanical properties of cathode blocks used in aluminum pots allow them to expand when exposed to high temperatures, and this expansion would cause structural damage if cathode blocks were lined without voids between them. Ramming paste is applied to the joints between the cathode blocks and the monolithic slope and between the blocks and cell’s side walls [4]. The sealing of ramming paste around cathode block voids plays an important role in the determining the life and energy efficiency of reduction cells. Also, premature cell failure occurs due to molten metal infiltration into the joints filled with ramming paste [4]. Infiltration can be due to insufficient sealing of ramming paste.

Furthermore, ramming paste absorbs the thermal expansion of the cathode blocks during the pre-heating and start-up process, passing through series of chemical and physical changes. Ramming paste is initially soft and viscous due to softeners added to coal tar-based binder; then with temperature increase, it swells due to devolatilization which is caused by gas reactions. Devolatilization is at its highest between 450 °C to 550 °C. After that, during carbonization, the ramming paste starts shrinking until the mass loss nearly reaches a plateau. Dehydrogenation occurs until completion of binder solidification and ramming paste is fully baked [5] this statement agrees with the experimental observations during samples heating.

In some studies, to avoid fume problems, cold and tepid ramming paste has been used because low ramming temperature reduce fume emissions [2]. Cold ramming paste is cohesive, porous, and granular, a combination of static pressure and medium frequency vibration has been determined as the best way to homogeneously compact thick layers of the paste [1]. Proper compaction of ramming paste will reduce the porosity of ramming paste and slow the penetration of the bath through the lining. The density of rammed layers will affect the mechanical, thermomechanical, and electrical properties of the baked paste [6]. Moreover, the height of the cathode lining in the industry is 200 mm per layer before compaction, and it is suggested to perform trials with thicknesses of 300 mm and 400 mm to explore possibilities of decreasing the number of layers and to reduce lining duration thus cost [1].

To test ramming paste properties, cylindrical laboratory samples of 50 mm diameter and 50 mm height are used under a compaction load of 20 MPa to obtain densities between 1.35 – 1.77 g/cm^3, the acceptable range of values [7]. During testing, the samples were covered with coke to avoid oxidation according to the standard ISO20202 [5].

Before the automation of the compaction process, the behavior of manual ramming of the paste needs to be understood as a starting point. To the best of authors' knowledge, there is no information in the literature; so, this study is initiated with an experiment to visually illustrate the manual compaction of ramming paste. In the next stage, the physical properties of the material were obtained by producing and testing samples in the MTS machine. In addition, the concept of Fused Deposition Modeling (FDM) is adopted in this study to inject the material [8]. In FDM, material is passed through a heated nozzle, converting it to molten state as it reaches the melting temperature [9]. For this purpose, it is important to study how the material behaves at elevated temperatures to determine the best temperature for injection. Therefore, in this work, experiments that involve heating of samples under controlled conditions were conducted in the lab. Experiments were conducted to extrude material through a nozzle at room temperature. Experiments at elevated temperatures are not conducted because of dehydrogenation observed in the previous experiment. Finally, to transport the material at a controlled rate and to have a steady flow, a screw conveyor was used in this study as it is best for granular material [10].

3. Potential Contributions and Limitations of the Study

This research is dedicated to developing methods for automation of the ramming process in aluminum cell lining. For this purpose, the concept of 3D printing FDM was adopted in addition to the use of a screw conveyor as an alternative for ramming paste injection. The expected impact for the aluminum industry is: (1) increased safety of the ramming process, (2) reduction of cell relining shutdown duration, (3) cost saving, (4) ability to select operating parameters, and (5) improved compaction of ramming paste.

4. Investigations on Ramming Process in Layers as Practiced Now

Current practice of ramming paste application can be described as shown in Figure 1. A typical pot design with dimensions of 14896 x 4350 x 1320 mm and cathode blocks of 3800 x 445 x 480 mm requiring around 28 cathodes is considered. The joints therefore are of dimensions 40 ∓ 2 mm. The joints are made up of ramming paste filled and rammed in five layers. The objective of this experiment is to see the filling and its characteristics.

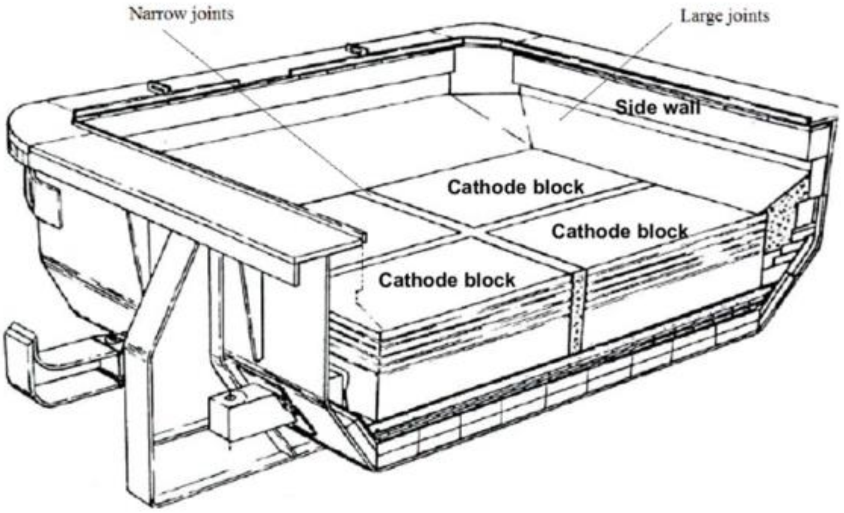

Figure 1. Cathode blocks and ramming paste filling.

4.1 Experimental Set-up and Procedure

A mold was built using a transparent material, and a steel rammer was also fabricated to manually compress the ramming paste. One face is removable and secured with screws as shown in Figure 2 to allow the extraction of the compressed ramming paste from the mold after ramming.

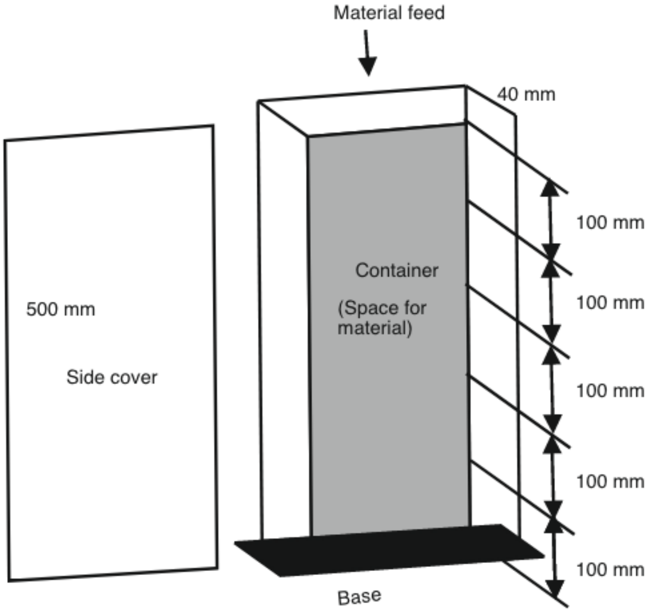

Figure 2. Schematic of the mold.

Three layers of ramming paste were compacted manually using a steel rammer. Each layer was compacted to a height of 100 mm using 950 g of bulk material. The height of each layer is marked before the manual ramming to trace the layer movement as another is added, the first and second layers are shown in Figure 3.

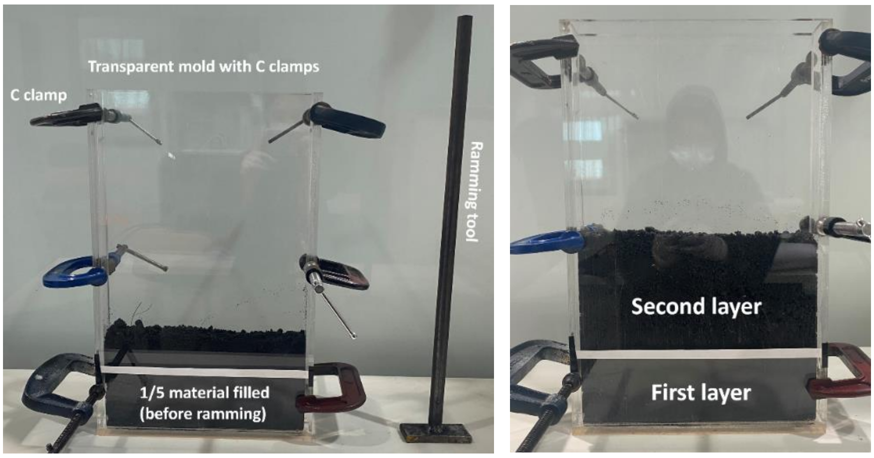

Figure 3. Manual ramming set-up with transparent mold showing (a) first layer filling (b)second layer filling.

4.2 Results and Discussion

- The densities of the layers from bottom to top were 1.57, 1.55 and 1.41 g/cm^3, respectively with manual ramming.
- The number of strokes varied with varying applied force; the strokes were 95, 39 and 50 for each layer s ramming process was controlled by the resulting height of each layer.
- Lower rammed layers continued to compact as other layers are added and rammed. As illustrated in Figure 4, the grain size is finer at the bottom layers.

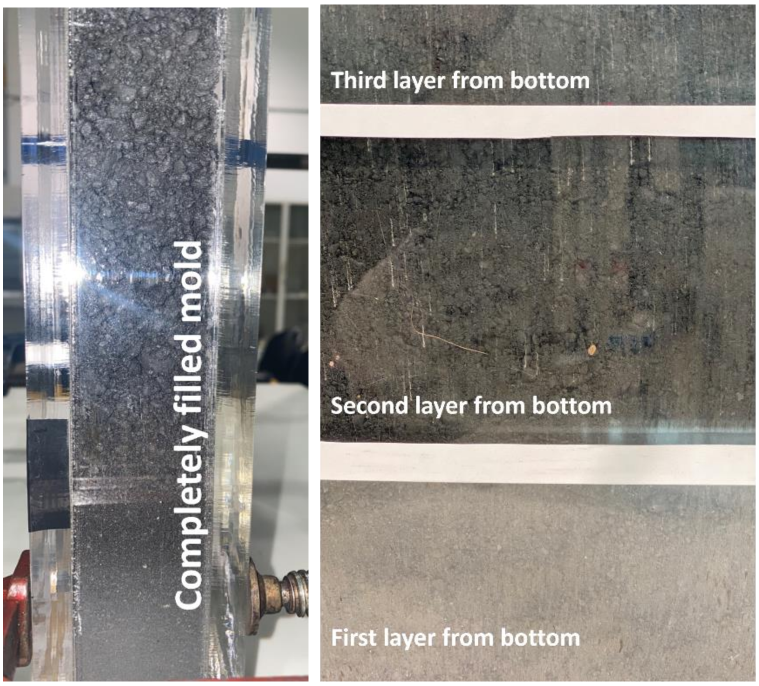

Figure 4. Grain size of ramming paste across the layers.

- Material did not bond at the plane separating two adjacent layers. Separation line was visible on the surface of rammed paste as shown in Figure 5. It was easy to break the layers at the plane that separate the layers.

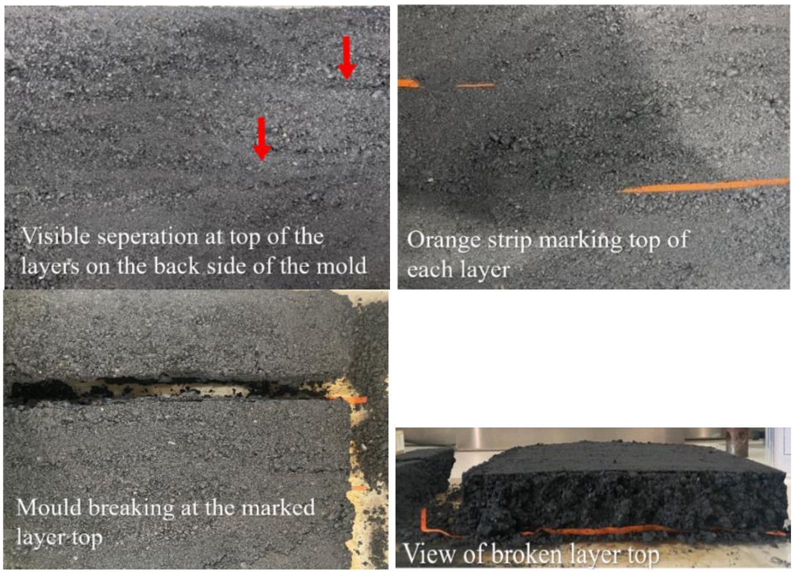

Figure 5. Breaking of layers at the planes separating them.

4.3 Analysis

- Applied force to achieve the same level of compaction varies according to the strength of the person, which is a pertaining source of error in manual ramming.
- As the ramming paste continues to compact with added pressure, different level of compaction might be required to achieve uniform density across the layers at the end of the ramming process; otherwise, ramming paste will act as a heterogeneous material.
- At the separation plane between the layers, the grain size is different affecting the material's ability to bond and merge. Separation lines present a potential to speed up the metal infiltration and thus cause the premature failure of aluminum cell. Therefore, reducing the number of ramming paste layers will result in enhancing the life of aluminum pot.

5. Characterization of Ramming Paste Under Different Applied Pressures and after Baking at Different Temperatures

5.1 Experimental set-up and Procedure

Set-up to ram the raw material was designed, consisting of a rammer and a steel piston with a disc inserted in piston to facilitate taking out the rammed sample. Figure 6 shows the experimental set-up where MTS machine was used to ram the material. All samples were produced using the same procedure as explained in the following sections.

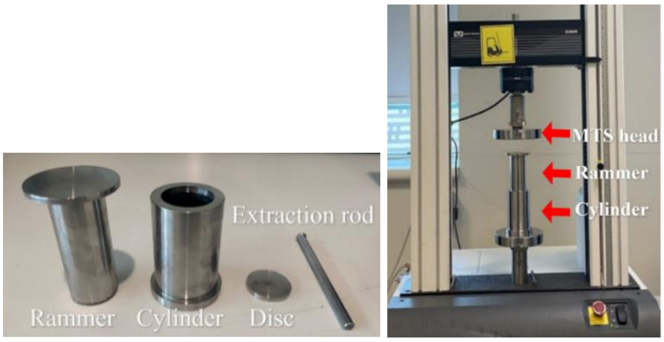

Figure 6. Sampling set-up fixed on an MTS machine.

- The desired sample was obtained over two trials. The first trial was to find the sample height obtained from a known material quantity then the result was used in a second trial to extrapolate the required material quantity to obtain a sample of 50 mm height with a mold of 50 mm diameter.
- Compression tests were conducted on the produced samples at a rate of 1 mm/min, and the stress-strain curve was obtained to determine ramming paste's Young's modulus at different compression loads.
- Then, the density was calculated for 20 cylindrical samples at different loads using four samples per load. The sample loads used are 25 kN, 30 kN, 35 kN, 40 kN, and 45 kN. This is followed by the testing of the strength of the samples at room temperature.
- Two other sets were tested after baking to different temperatures; set of 16 samples that were compressed at loads of 45 kN and set of 12 samples that were compressed at 40 kN and then tested for strength after baking to different temperatures: 200 °C, 400 °C, 500 °C (only for 40 kN samples), and 600 °C; four samples per temperature with a heating rate of 2 ºC/min. Samples were not covered with coke to test heating effect on ramming paste characteristics.

5.2 Results and Discussion

Material with an initial weight of 85.6 g at a load of 45 kN resulted in a sample of 26.62 mm height at a compaction rate of 0.5 mm/min to obtain the desired sample, 160.8 g of bulk material was used and resulted in a height 50.1 mm as shown in Figure 7. The density obtained in this trial was 1.59 g/cm^3 which falls in the accepted range.

Figure 7. Sample height.

A Stress-Strain curve for compression test of unbaked samples is obtained from the MTS machine as shown in Figure 8. The graph shows a rapid change in the change of specimen height at the beginning of the compaction process; and then, as the ramming paste is more compacted, the resistance to deformation increases rapidly, reaching nearly a linear relation.

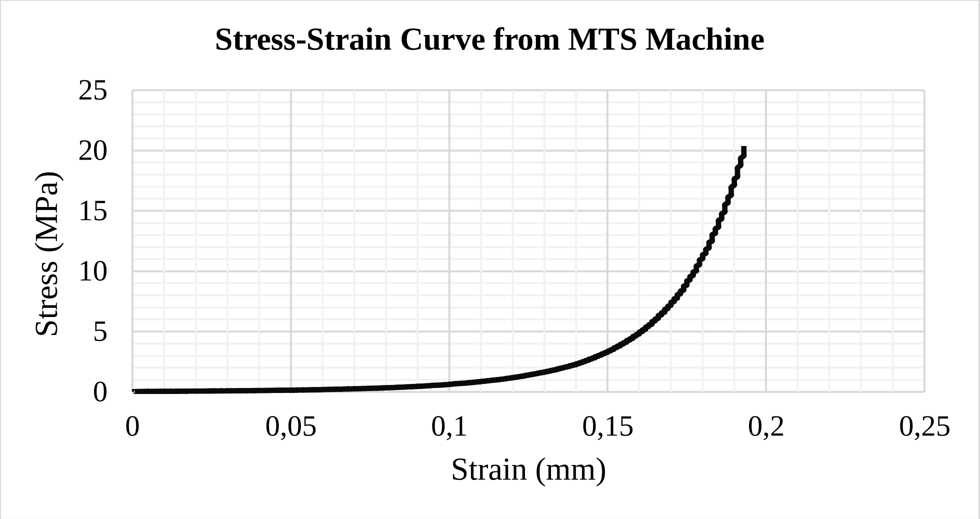

Figure 8. Stress-Strain curve for ramming paste compression up to 21 MPa.

The value of Young's modulus was calculated on the linear region by obtaining the slope to the tangent of the curve for each load and the value found to be between 6.5 – 12.5 MPa as shown in Figure 9.

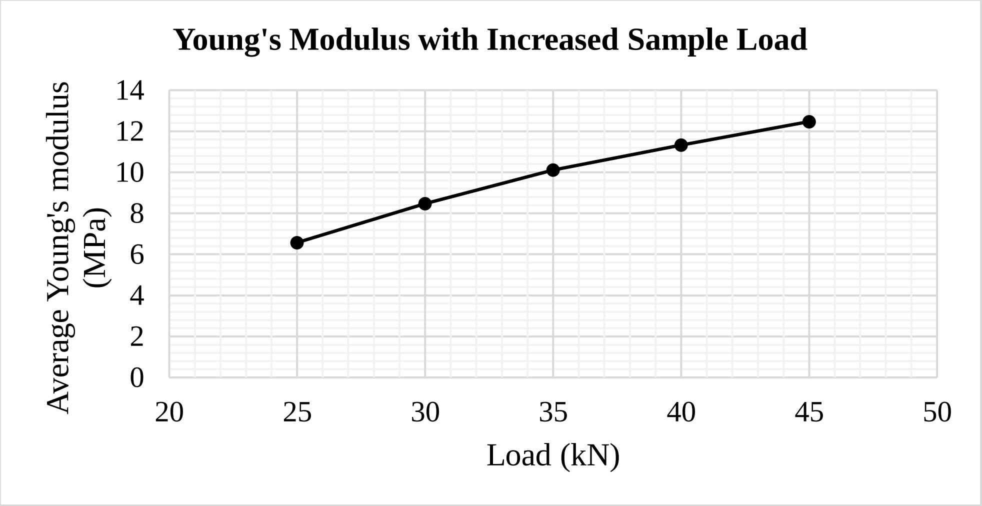

Figure 9. Average Young's modulus value at different loads.

In addition, the density of ramming paste samples was between 1.57 – 1.6 g/cm^3 which is acceptable. Figure 10 shows the densities that were obtained using four readings per load. The density drops between 30 – 35 kN and then increases again; however, the change is very small and still within the acceptable range.

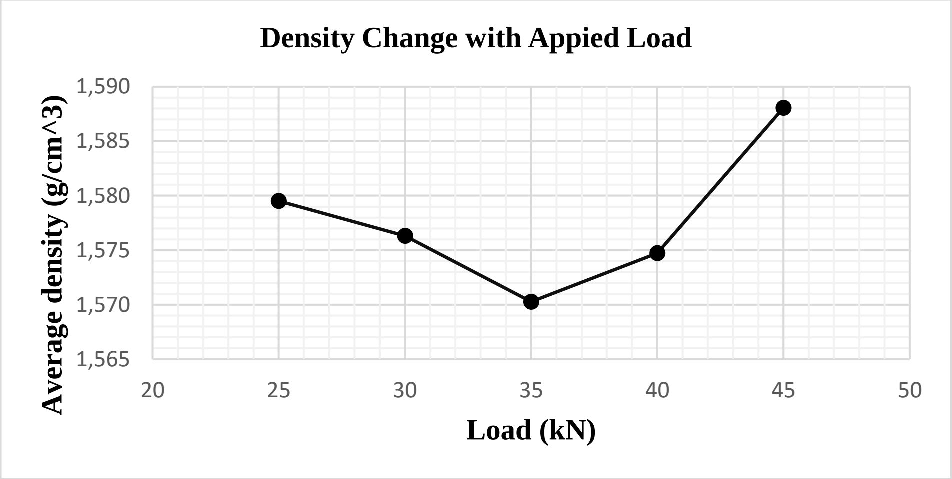

Figure 10. Density values at different applied loads.

The yield for unbaked samples compressed at room temperature are shown in Figure 11 for each compression load. The samples compressed at loads of 35 kN and 40 kN failed at higher applied loads showing higher strength than others.

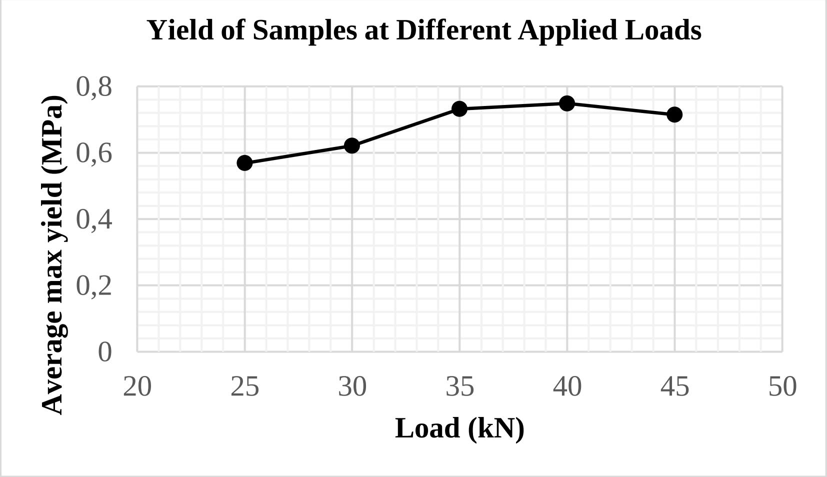

Figure 11. Yield for samples tested at room temperature.

Also, the samples compressed at room temperature cracks in random directions which sometimes is called failure like a matrix or concrete matrix. Typical failure pattern of ramming paste samples at room temperature is shown in Figure 12.

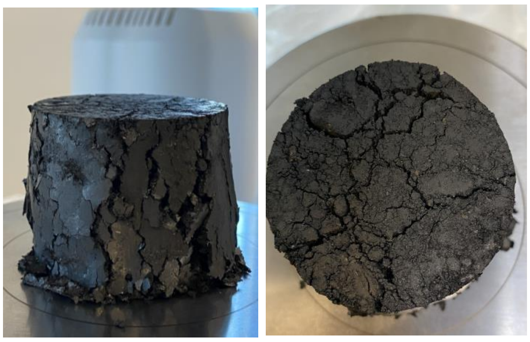

Figure 12. Pattern of samples failed under compression at room temperature.

The next set of experiments was then carried out and the samples were fabricated using two loads as mentioned previously then baked at different temperatures. The results of the strength test of baked samples at loads of 40 kN and 45 kN are shown in Figure13. At each load, it is shown that samples heated to 400 °C can withstand loads higher than those at 600 °C. Furthermore, comparing the results at each temperature shows that the material possesses higher strength at lower compression loads.

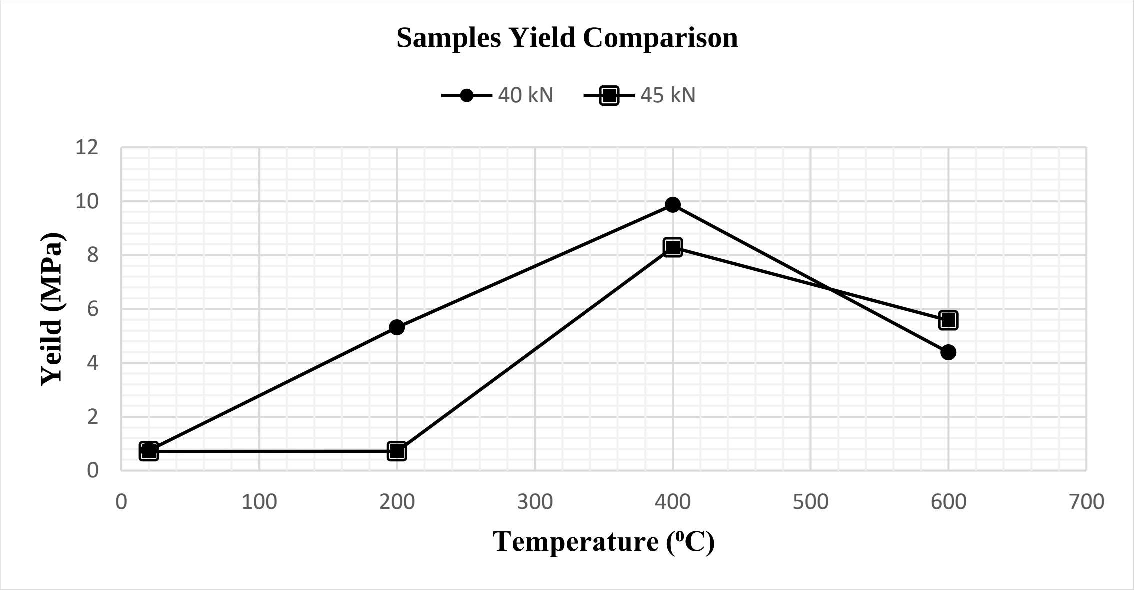

Figure 13. Comparison of yield at room temperature and different baking temperatures for samples at 40 kN and 45 kN.

Also, for both loads (40 kN and 45 kN), similar results were obtained when the samples were baked at 400 °C as shown in Figure 14 (failed, in conical shape). Such failure happens when the material bonds and solidifies as one bulk. On the other hand, samples baked at 600 °C was powdery and brittle as shown in Figures 15 and 16. The density for the samples was between 1.54 – 1.57 g/cm^3. Similar results were observed for samples compressed at 40 kN as shown in Figure 17.

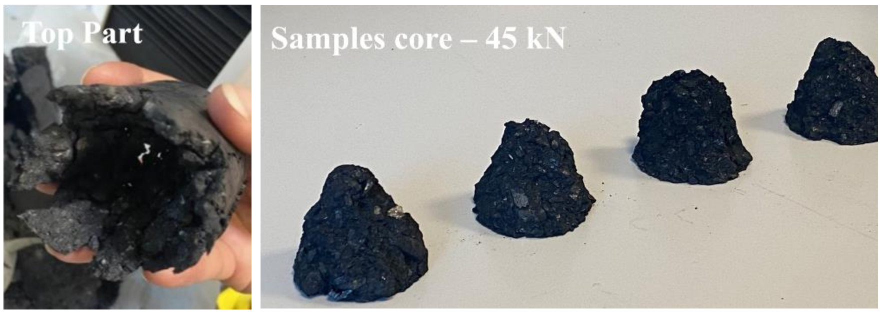

Figure 14. Failure of samples baked at 400 ⁰C at 45 kN.

Figure 15. Before the compression test of 45 kN, Samples baked at 600 °C.

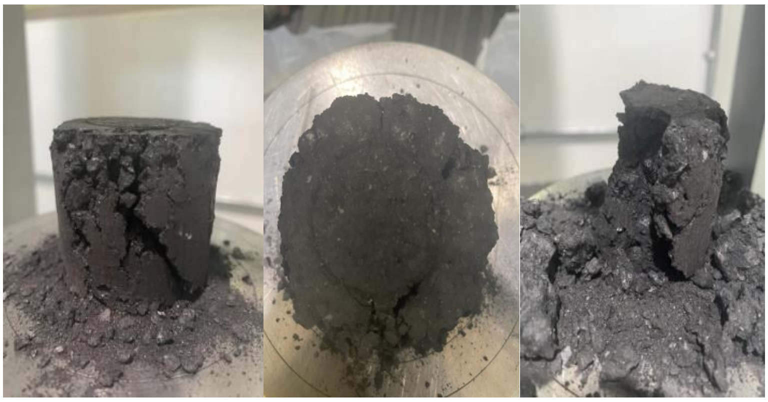

Figure 16. After the compression test of 45 kN, Samples baked at 600 °C.

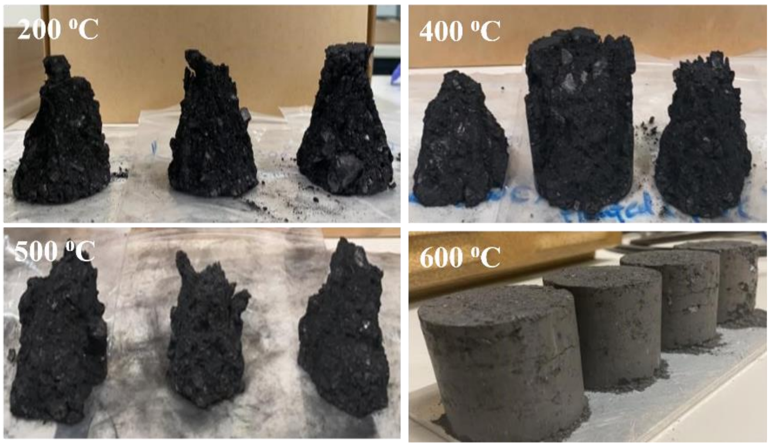

Figure 17. Form of failure for samples baked at different temperatures at 40 kN.

5.3 Analysis

- At the beginning of the compaction, there is a rapid change in the height. Then as the ramming paste is more compacted, the resistance increases and the force increases rapidly with a smaller change in height and starts to become linearly increasing where Hook’s law can be applied to obtain the modulus of elasticity.
- As expected, with higher loads applied to compact the material, Young’s modulus average value increased, which means the material is getting stiffer at higher loads. According to these results, it is best to use lower compression loads for better flexibility of ramming paste in case the paste was to be extruded through a nozzle.

- As 45 kN is the highest load that can be achieved with the set-up, the possibility of obtaining acceptable density values at higher loads was not tested. Nevertheless, obtaining such density at lower loads is preferable for lower power consumption. The desired density can be achieved at a load of 35 kN. Also, the flexibility will be achieved as mentioned earlier.
- Young's modulus increases as density increases. This means physical behavior of ramming paste changes as density change, therefore having different densities across the layers will also affect Young's modulus values and the homogeneity of the material.
- In addition, the samples compressed at a load of 45 kN might have cracked internally during compaction, which resulted in less strength than those at 40 kN.
- Ramming paste at room temperature behaved as a granular nonhomogeneous material, similar to the behavior of cement.
- Baking the material showed reduction in strength due to oxidation at 600 °C where the samples became very soft and powdery on the surface. On the other hand, the samples at lower temperatures failed to form a solid material due to shear stresses. The material started to expand and bond; however, it lost its strength once the oxidation took place. Both sets of samples resulted in similar results in terms of strength and texture; the samples failed under shear stresses from 200 °C to 400 °C and oxidized at temperatures 500 °C – 600 °C. At 600 °C, the samples were too fragile and powdery on the surface, the samples failed as a matrix in the test.
- The yield that was achieved at higher temperatures was also obtained at room temperature, which means that samples with high strength can be achieved at room temperature as well.
- These results show that the samples can be compacted at lower compression loads and at room temperature without baking. Thus, a nozzle can be tested for feasibility of extrusion of compacted material at room temperature.

6. Ramming Paste Injection Through Nozzle with Different Profiles

6.1 Experimental Set-up and Procedure

An experiment was designed to attempt the injection of ramming material through a nozzle to obtain the desired density. The set-up, shown in Figure 18, consisted of a piston as rammer, cylinder, changeable nozzle, base, and a slide to consistently move the injected material. Two different nozzles were made: (a) slit outlet to extrude the material for the gap full length in one stroke and (b) circular outlet where filling can be done with several runs. In this experiment, four attempts with different nozzle profiles were carried out.

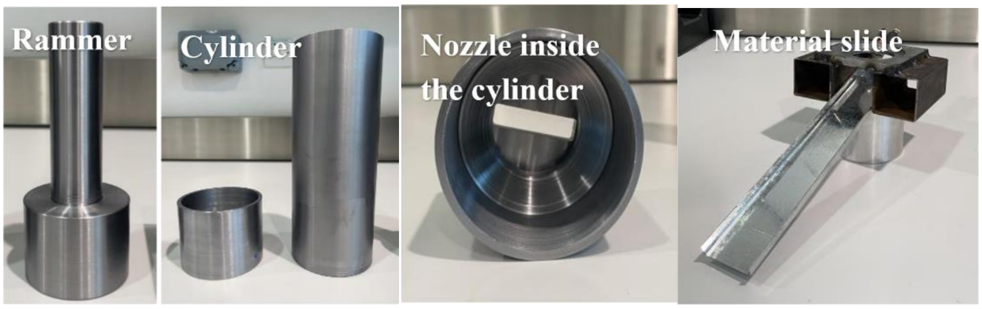

Figure 18. Set-up of injection experiments.

Four trials were carried out with different nozzle profiles. The material was filled in the cylinder and the target was to extrude compacted ramming paste with a force of 35 kN. The nozzle in the first trial was made with an angle of 90º and an outlet with a 40 × 20 mm slit, which is the dimension of the gap between the cathode blocks in aluminum pot. 1096 g of material was used and the pressure was applied to ram the paste at rate of 5 mm/min.

In the second trial, the nozzle outlet was changed with 20 mm circular one. The nozzle degree of inclination remained 90º, the amount of material was fixed, as well as rate of compaction. After, a steeper nozzle angle was used to provide a downward material flow with a nozzle of 60º angle and slit outlet. The final trial was done to confirm the results of injection tests, with a 60º angle nozzle having circular outlet of 42 mm diameter.

6.2 Results and Discussion

In the first trial, the applied force by MTS machine was gradually increased, but no material was extruded at the targeted load of 25 kN; so, it was further increased to 33 kN, ramming paste started to compact when experienced reduction in the cross-sectional area of the path. It was rammed and took the shape of the mold as shown below in Figure 19.

Figure 19. Graph from MTS machine showing load value of nearly 35 kN (left), no extrusion of the paste (middle and right).

The same scenario was repeated for the next three trials, so the load was gradually increased, and the test was performed until the load reached 25 kN then further increased to higher loads. However, there was no flow of ramming paste, and it took the shape of the mold as shown in Figures 20 to 23.

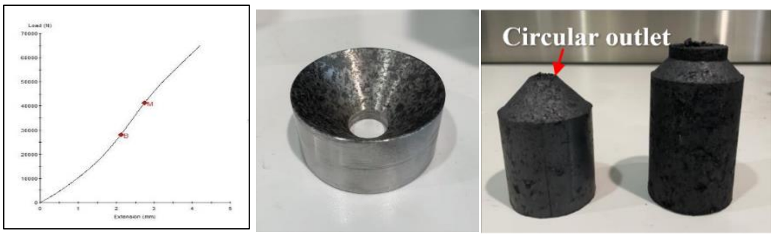

Figure 20. MTS showing load value up to 65 kN (left), with circular nozzle outlet (middle), similar results compared to first trial (right).

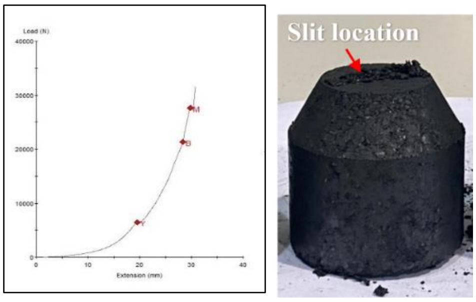

Figure 21. Third Trial with a load of 35 kN.

Figure 22. No extrusion at 25 kN.

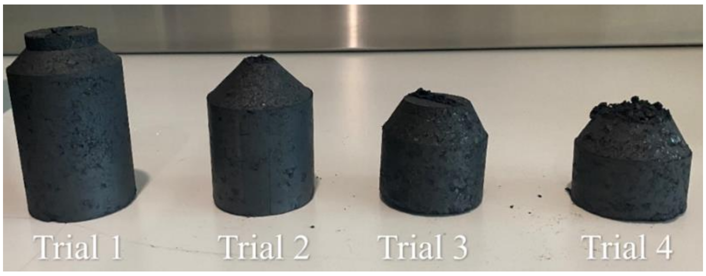

Figure 23. Form of ramming paste after injection experiments.

The material at the free end was not compacted as accumulation occurred at the top layers only, leaving the below layer loose and falling as chunks as shown in Figure 24.

Figure 24. Ramming paste at the nozzle exit, sliding in the form of chunks.

6.3 Analysis

- This set of experiments shows that the characteristics of ramming paste are not appropriate for the 3D-printing approach of FDM (that is, heating while injecting through a nozzle) as heated ramming paste is not as fluid as the ramming paste at room temperature and the ramming paste immediate compacts with reduction in the path area. Ramming paste started compacting only when a significant change in cross-sectional area is encountered. The material accumulated in the nozzle and then compacted without flowing out of the nozzle, causing an increase in the resistance and thus the value of the applied load.

- Also, the comparison of injection results with those of the manual compaction experiments shows that the paste compacted at the bottom layers first then at the top layers when rammed in the manual compaction experiments whereas its behavior was completely opposite in injection experiments and the ramming paste compacted at the top layers first in the nozzle. This is shown in Figure 25. This shows that the ramming paste behaves differently when passed through a nozzle and lacks fluidity.

Figure 25. Compaction of paste comparison: injection through nozzle (left) and manual ramming (right).

7. Conclusions

Ramming paste layers do not bond at the plane between the layers, due to different grain sizes between each rammed layer and the added layer on the top. In addition, ramming paste continues to compact under pressure until fully solidified, resulting in more compaction at the bottom layers as more layers are added to the top. Furthermore, ramming paste with acceptable density and strength can be obtained at room temperature with a load as low as 25 kN with the advantage of having flexible ramming paste deformable at lower loads.

On the other hand, heating ramming paste solidifies it and turns it into a brittle material in the presence of oxygen. Moreover, ramming paste accumulates and compacts with introduced reduction in cross sectional area of the nozzle causing compaction on the top layers and leaving the ramming paste at the exit uncompacted. This happens regardless of the shape and size of the nozzle. Hence, adopting the 3D-printing concept of injecting while heating in FDM is not feasible for ramming paste. In addition, the extrusion of ramming paste requires introducing flow to the system which can be done using a screw conveyor and then compacting the material at the exit with a roller. In continuation of this research, a device is designed to introduce positive flow and pressure; it consisted of a screw conveyor and a roller at the exit followed by a channel to guide the material flow. Ramming paste was successfully extruded and compacted to the desired density. It allowed the control of the density of the material exiting the screw conveyor.

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