

Testing of Six Clays for Extrusion 3D Printing

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Introduction

Clay as a natural material is not uniform across all its sources, offering different characteristics from deposit to deposit and type to type. For extrusion 3D printing clay can be used as dug, after cleaning and preparation or be a composite of many clays and or other additive materials such as grog and fluxing materials. The aim of this research was to give some practical measurements to what characteristics are desirable for clay 3D printing.

The approach taken was to mix six different clays to the same consistency and to then undertake the same tests on each sample. It is the rheology, the character, the deformation and flow of the clay mixed as a paste that was to be studied. The clay consistency was judged initially by eye and feel, as this is how clay for printing has generally been evaluated.

Note: All images have been produced at high quality to enable zooming to see detail. (Ctrl + mouse wheel)

Clays Tested

China Clay (Kaolin Clay) - Grolleg China Clay, mined in Cornwall, UK was used. The sample was mixed from powder clay. Too much water was added so the mixture was left overnight to dry out until the desired standard consistency was reached.

Porcelain Clay - this was a recycled mix of a number of commercially supplied porcelain bodies. The sample had been stored at the desired paste consistency in plastic.

Ball Clay - an off white secondary plastic clay, Hyplas 71 was used- mined in Devon, UK . Mixed from a powdered state, it was mixed softer than required to ensure thorough wetting and left to dry overnight to the desired consistency.

Fine Stoneware Clay - a clay I like to use, 164 ARTE/PRAI White Stoneware Clay from Spanish supplier Sio-2 that has 40% fine grog (0 - 0.2 mm). Water was added to clay of throwing consistency and mixed to a paste.

Coarse Stoneware Clay - Ivanhoe, supplied by Potclays UK, a clay I have used for large 3D printed objects. Buff in colour it has 20% grog sieved to 40# grade (0 - 0.5 mm).

Red Clay - a mixture of recycled red clay that is sandy but fine and smooth. Stored in a soft consistency.

Clay Paste Consistency

Each sample was thoroughly mixed by hand so each felt and looked to be of the same consistency. This consistency is not so soft that the clay looks wet on the surface but also not so hard that when

handfuls are slapped into a stack that there is not some give to each layer. With clean, dried hands the balls of clay can just be handled without too much clay sticking to the hands but a stickiness will build up on the hands as a ball is knocked into shape - the clay paste is soft, but just stiff enough to be handled.



Test Procedure and Equipment

There were a number of aims to this research -

- To assess the clay to water ratio in clay mixes of the same paste consistency.
- To develop a simple tool to give measurements to soft clay consistency.
- To measure the pressure or force required to extrude soft clay of the same consistency through a narrow nozzle.
- To measure the comparisons of the flow rate of the different clay samples in a 40 cm long narrow tube.
- To sample the 3D printing characteristics of each clay.
- To measure the shrinkage of the different clays when dry, when fired at 1000° c and 1220° c.

Water Ratio

A 200gm sample of each clay of the same consistency was dried out and reweighed when bone dry, as dry as possible in a domestic atmosphere. From this the water content of the paste could be calculated.

Clay Consistency - Drop Spike

A simple dropping spike tool was made that has proved to be reasonably consistent and accurate. Dropped onto the clay sample, down a guide tube from a constant height, the length of penetration would be averaged over four attempts and recorded. To my surprise the six clay samples, mixed to be adjudged the same consistency by hand and eye were all within 5% of each other on the 'Spike' measurement.



Syringe Pressure Extrusion

A 60ml syringe was adapted to have a removable end plate and nozzle. An 8mm nozzle was fitted so not too great a pressure was required to judge when extrusion or flow was attained. The extrusion

force was measured by pressing the syringe plunger down onto a bathroom scale. This test was more specifically to aid an understanding of clay rheology for printers where the clay bulk is carried near or on the printhead.



Tube Pressure and Flow Rate

A 500ml container was filled with each of the clay samples, pressurised and the flow rate from an attached 40cm long, 6mm inside diameter plastic tube was measured. This test offers quite different results from the Syringe Extrusion results above and is designed to aid those printers where the clay bulk is carried alongside the printer and the clay paste is forced through a length of tube to the printhead. Clear comparisons of the flow rate across all six clays could not be gained as the Coarse Stoneware and Red Clay required more pressure to reach the 40cm tube length. The Chine Clay, Porcelain, Ball Clay and Fine Stoneware Clay were all tested at a pressure of 3 bar (43 psi) while the Coarse Stoneware and Red Clay were tested at 4 bar (58 psi) of pressure.



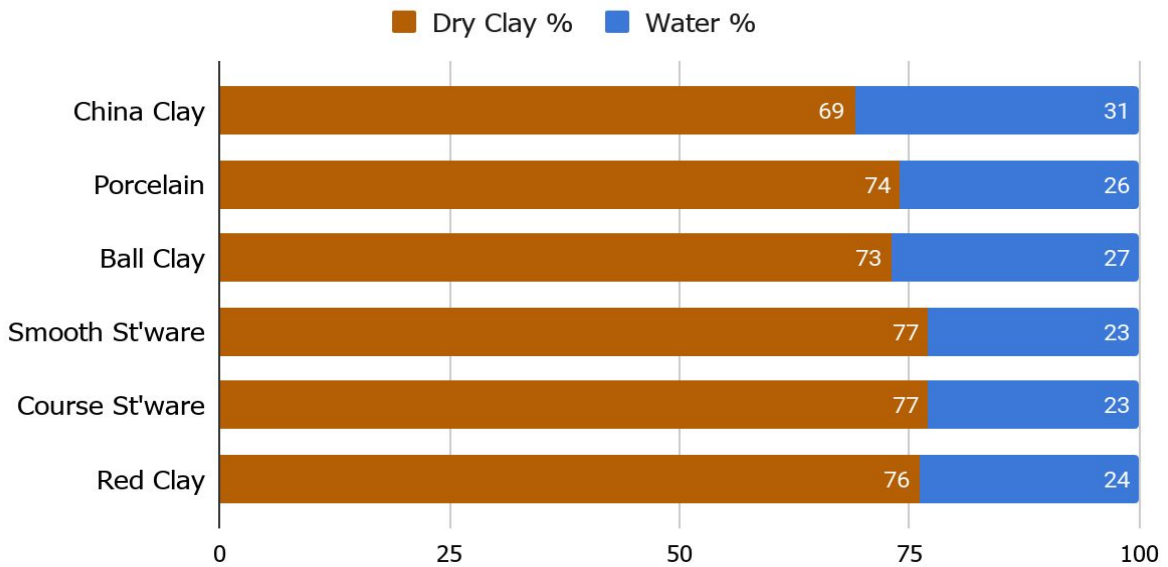
3D Print Quality

A small Delta type printer with a 40cm clay delivery tube was used to make the print samples. A simple 6cm diameter and 6cm high cylinder was selected as a print sample shape. A spiralized gcode was prepared in the Cura slicing software using a 2mm diameter printhead nozzle, a 0.7mm layer height, at a print speed of 25mm per second. The same print file was used for each clay sample and not surprising each print came out very similar. The clay delivery pressure just had to be adjusted in line with the results obtained from the Tube Pressure Flow Rate tests.

Test Results

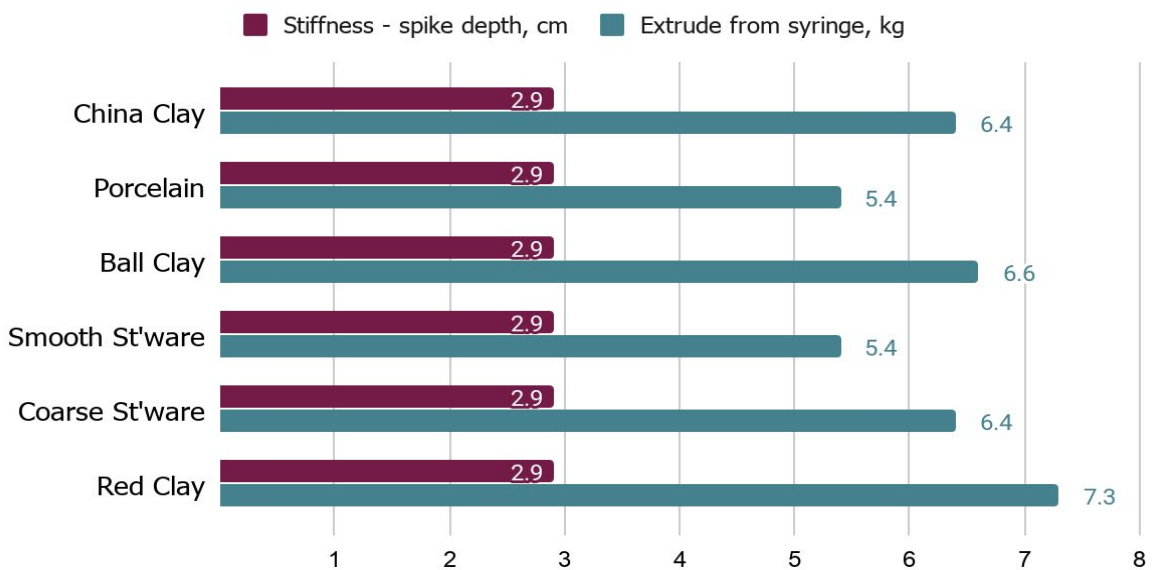
While the composition, character and rheology of clays is renowned for being difficult to pin down and there are no claims for the testing equipment to be highly accurate, in the overall patterns of these results there is useful information to be found for making informed choices. This information gives a sense of what to expect when choosing clays to use for extrusion clay 3D printing.

Clay | Water



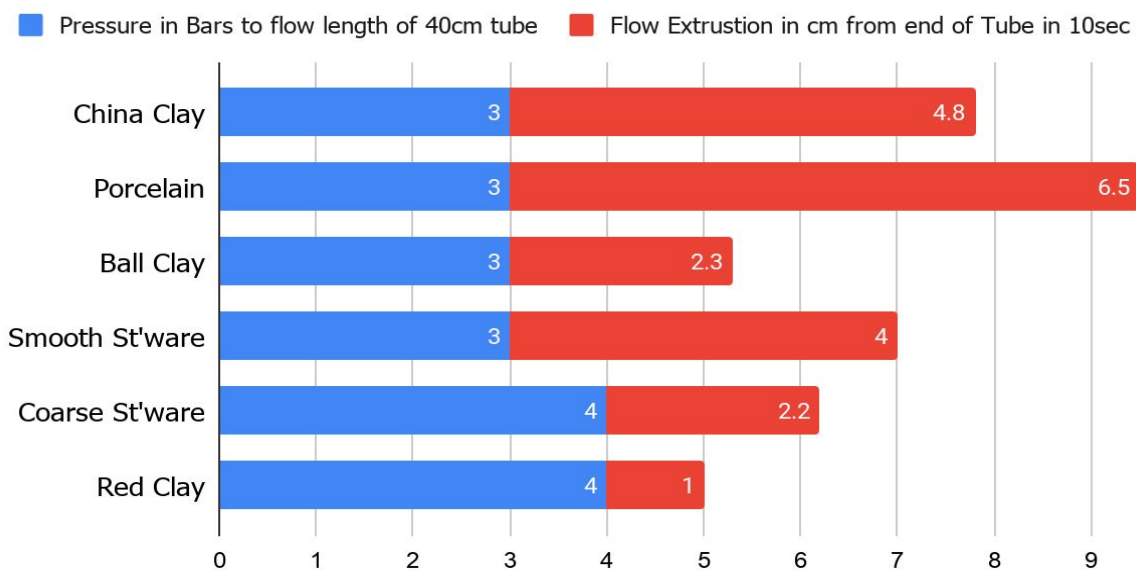
These results clearly show that different clay of the same consistency, measured by feel and eye and confirmed by the spike drop measurements have different ratios of dry material to water. This has relevance to clay extrusion 3D printing, as for the stability of complex shapes with overhangs it could be useful for the clay to dry quickly - the less water the quicker the clay dries. Other printing techniques might require slow drying clay. In the tests the pure clay, China clay and Ball clay required most water. It was expected that the water content of the Red clay would have been higher but it is not known how much non clay material, in the form of fine sand there is in the clay tested. Blended clay bodies such as the Porcelain and the two Stoneware bodies that are made up of a percentage of non clay materials were expected to have less water content. The shape of clay particles are flat or platelet-like, taking up more water between the layers, than the more rounded, non clay particles of grog, that is a crushed fired ceramic material or crushed feldspar or silicate rock.

Syringe Pressure Extrusion



The aim of this test was to obtain measurements illustrating the variation in force required to extrude different clays of the same consistency through a short wide nozzle. Each clay was mixed to have a spike depth measurement of 2.9 cm. Single material, pure clay, homogenous clays (china clay, ball clay) are shown to require more force than blended clay mixes (porcelaine, stoneware mixes). Also as a general observation the darker the natural colour of the clay the more force was required, with the Red Clay requiring the most force. Text books will also show that these are the more plastic clays. Clay bodies with non clay material in the composition, for example Porcelain with 50% non clay (feldspar, flint) and the Smooth stoneware body with 40% non clay (grog) material extruded under the least force.

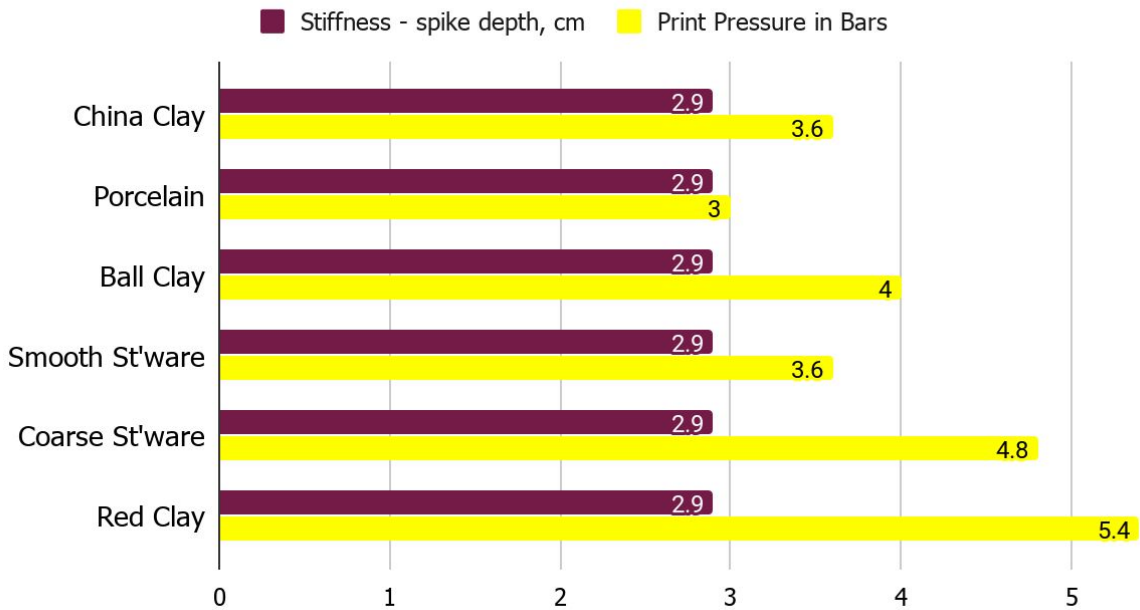
Tube Pressure and Flow Rate



These results make interesting reading alongside the Extrusion Force measurements above. The objective was to gain measurements for the rate of extrusion flow for the different clay samples having traveled through a length of narrow tube. In the table above the last two clays required more pressure, up to 4 bar, from 3 bar of the other four clays to travel the length of the tube. The results of flow for the Course stoneware and Red clay are in fact more restrictive than the graph visualisation indicates. The general pattern of Extrusion Flow is consistent with the Extrusion Force tests. However there are interesting anomalies. For a short extrusion from the syringe, the force required to extrude China clay and the Coarse stoneware were similar. The results in the tube test were very different. China clay flowed out of the 40 cm long tube at 4.8 cm in 10 seconds under a pressure of 3 bar. The Coarse stoneware required 4 bar of pressure to be able to test a flow from the end of the tube and then the flow was only 2.2 cm per 10 seconds. Another interesting comparison is between the Ball clay and Coarse stoneware. The Ball clay needed slightly more force than the Coarse stoneware on the Syringe extrusion test. In the Tube flow test the Coarse stoneware required the 4 bar of pressure to flow the length of the tube and then resulted in a flow speed only slightly less than the Ball clay that was only under 3 bar of pressure. Similarly, comparing the Porcelain and Smooth stoneware clays, where both registered the same Syringe extrusion force. In the Tube test the Porcelain flowed notably faster than the Smooth stoneware under the same pressure. It is clear

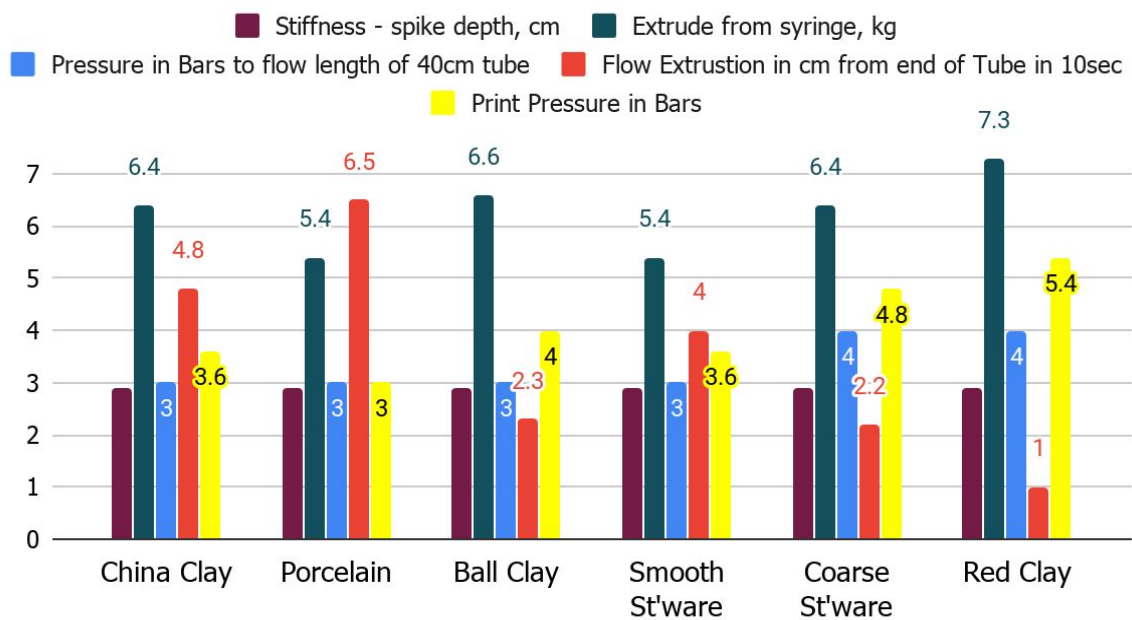
that clay behaves differently when under pressure and extruding a short distance and when being forced down a long tube.

Clay Stiffness and Print Pressure



It must be pointed out that these results are for a Delta type clay printer where the bulk clay is delivered down a 40 cm tube to the printhead. For printer designs where the bulk clay is delivered close to the printhead, then the results would be expected to be more consistent with the Syringe Pressure table. These results are more in line with the Tube Pressure Flow Rate table. With the clay in the printer bulk container all of the same consistency it shows how different clays require different amounts of force to obtain a similar, constant clay feed to the printhead.

Stiffness, Syringe Force, Tube Pressure, Tube Flow, Printing Pressure



Clay Shrinkage

To obtain shrinkage measurements the printed cylinder samples are measured against the dimensions of the original digital model. Measurements were taken once dry, after a bisque firing of 1000°C and again after a low stoneware firing of 1220°C. The horizontal diameter of the inside of the cylinder was measured and the vertical height. The aim was to record the different shrinkage rates of each clay but also the difference in shrinkage of the height and width of the printed samples. While clay shrinks uniformly it has been observed that clay 3D printed objects do not. It is speculated that this is probably due to the vertical pressure of the layered extrusion and the clay memory.



The six clay sample cylinder prints from left to right - China Clay, Porcelaine, Ball Clay, Smooth Stoneware, Coarse Stoneware, Sandy Red Clay. Top row - bone dry. Middle row - fired to 1000° c. Bottom row - refired to 1220° c.

Comparison of the photographic reference from bone dry to bisquet, to a low stoneware firing makes for interesting reading. The china clay that has been shown to have the highest water content at the time of printing did not shrink the most at bone dry. Ball clay with the second highest water content has clearly shrunk the most. It clearly shows that there is more to the properties of shrinkage in clay than the loss of water up to the bone dry state.

The ratio of the shrinkage of the samples at the different states (dry, bisque, high fire) is also not consistent over the range of clays. Looking along the line of tests in each state, it can clearly be seen that in the line of the highest firing there is a distinct pattern to the height shrinkage from left to right, that is not the case when bone dry or bisque fired. China clay has shrunk the most, stepping up towards the Coarse Stoneware that has shrunk the least and then back down to the Sandy Red. The ratio of shrinkage of the ball clay has remained

