Formulating and Testing a Clay Body for Extrusion Clay 3D Printing

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Introduction

While almost any clay can be used for clay extrusion 3D printing it is clear some clays print better than others. This variation can be dependent on the characteristics of the clay but also the type of machine being used and the style of work being produced. The aim of this research was to gain an insight into what considerations there are when formulating a basic clay body recipe from processed powdered raw ingredients. As available ceramic materials will vary from region to region, it is the process of formulating the clay body and the outcome of the tests that are important rather than the actual recipe, although the recipe could act as an initial guide for further development. This initial clay recipe was tested to evaluate its suitability. The effect of clay consistency, in the form of soft, medium and hard clay on the print outcome was tested. The tests developed onto considering what advantage clay additives might offer to this basic recipe and what improvements could be made to the initial recipe.

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

The Clay Recipe

This recipe was formulated for a printer where the clay bulk is situated alongside the machine and the clay is piped to the printhead via a length of tube. It was also designed to be stable at high temperature. As a starting point the recipe was based on a plastic ball clay to offer plasticity and a smooth extrusion. However, plastic clays tend to have higher surface tension so are more difficult to force through narrow tubing. China clay was introduced as tests have shown china clay requires less pressure to be extruded and has a better flow rate through tubing. Fine grog was also included as non clay materials have also been shown to reduce clay body surface tension, thereby increasing flow rate and reducing the extrusion pressure. Further, a proportion of grog in a clay body is known to lower shrinkage, aid in drying and offer a range of particle size that should help with plastic stability. The choice of grog particle size needs to be in keeping with the printer nozzle size to avoid blockages.

Test Mix 1

Ball Clay (Hyplas 71)	44
China Clay (Grolleg)	33
Grog (Fine Molochite)	22

Hyplas 71 Ball Clay	A Devon (UK) ball clay with low iron content, high plasticity. Fires ivory buff colour.
Grolleg China Clay	A blended English china clay, combining moderate plasticity, used in white earthenware, bone china and porcelain bodies. White firing.
Molochite Grog	Manufactured using calcined china clay this is a refractory white grog. A 200 mesh fine grade was used.

While the recipe was given numerical values in percentage by weight a note was made of each material by volume. While proportionally less in weight the china clay in volume was far greater than the ball clay. Considering the idea was to add china clay, for its physical properties to a predominantly plastic ball clay body this turned out not to be the case. In volume this body has more china clay and proved not to be very plastic and 'short' in character - when printing the extrusion broke very easily. On checking the 'formula weight' of Grolleg china clay (276) and that of Hyplas 71 ball clay (541) this difference in weight to volume is explained.

Ball Clay (Hyplas 71)	800 gm	880 ml
China Clay (Groleg)	600 gm	1180 ml
Fine Grog (Molochite)	400 gm	400 ml

Water to Dry Ingredients Proportions

To be able to measure the amount of water in the soft, medium and hard consistency mixes, the tests were prepared from dry ingredients. Left for a day before testing to allow for the water to be absorbed into the clay this short time of 'wetting' of the clay can further account for the 'short' non-plastic character of the clay tests.

A bulk mix of dry ingredients, ball clay, china clay and molochite grog was mixed and dry sieved twice to ensure an even mix. Test samples were prepared from this bulk mix in proportions where dry ingredients and water together total 100%.

	Dry Ingredients %	Water %
Soft Mix	69	31
Medium Mix	72	28
Hard Mix	75	25

Samples were mixed and left to saturate for the 24 hours as mentioned and then further mixed. The hard clay sample could be formed into a ball in the hands with little clay sticking to the hands. Handling the medium sample, sticky clay would progressively build up on the hands but a ball could easily be formed and handled. The soft mix could be formed into a ball in the hands but it was a sticky and messy activity.

Measurements of Clay Consistency

	Soft Mix	Medium Mix	Hard Mix
Dry ingredients: water by weight.	69:31	72:28	75:25
Drop Spike - this tool represents the distance a 38 cm (235gm) sharpened steel rod penetrates into the clay sample when dropped from a constant height of 9 cm.	54 mm	32 mm	22 mm
Syringe Extrusion - this tool consists of an adapted 60ml syringe to have an 8 mm nozzle. The measurement represents the force required to extrude the clay sample through the 8 mm nozzle constriction that is 30 mm in length.	4.1 kg	6.3 kg	10.2 kg

The pressure required to force the clay sample the length of a 40 cm tube with an inside diameter of 8 mm.	2 Bar	2.5 Bar	3 Bar
The pressure used during printing.	2.5 Bar	3 Bar	5 Bar

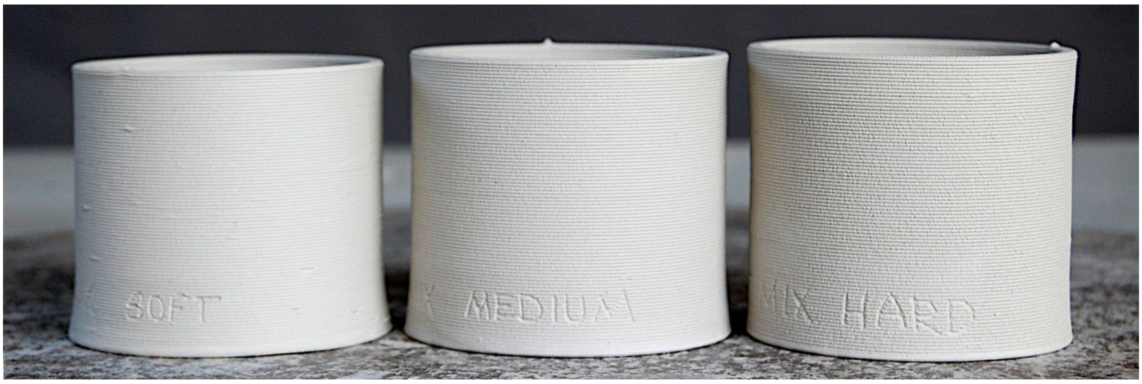
Printing Tests

Two shape print files were prepared to be printed and the tests were run on a small Delta printer (CERAMBOT). One shape file was a standard 6cm high and 6 cm diameter cylinder. The second is an 8 cm height cylinder with a diameter of 6 cm that has three shape tests designed into it. First a vertical corner, second a repeat relief texture and thirdly two 45 degree indentations. In all the following tests the same .gcode file for each of the two shapes was used.

Cylinders

The 6 cm cylinder shape printed much the same for each of the three clay consistencies with more air pressure being required as the clay got stiffer - see table above. A 2 mm nozzle was used throughout and there was little if any noticeable variation in printed wall thickness across all three consistencies. However there are two points of interest worth noting. One is the difference in surface texture over the three tests. The softer the clay the smoother the extrusion. The harder the clay the more fractured or cracked the extrusion surface appears. Significantly it is these fractures that open up more if the form becomes stressed or distorts. Second is the small but noticeable difference in size due to shrinkage of the three tests once bone dry. The greater water content of the soft clay resulting in more shrinkage.

Slight variation of surface texture where the softer the extrusion the smoother the result.



Bone dry variation in shrinkage indicating difference of water content.

Edge, Texture, Overhang Test Shape

The more complex sample shape illustrated just how unsuccessful this clay recipe was for extrusion printing. However it was not totally unsuccessful in that it offered the opportunity to test what improvements could be made to improve the clay mix.

The tests included a three layer base that printed successfully in each consistency of clay. When printing vertically, as with the cylinder tests all three clay samples built up the form as expected. As can be seen from the photographic documentation with this shape no sample printed clean. The soft clay became unstable with the nozzle movement over the repeat texture area and then totally collapsed as it could not hold its own weight, particularly on the indentation overhand. The soft extrusion did not break, it just did not offer enough structural and directional rigidity as the contour of the shape became more complex.

Two views of the soft, medium and hard clay print tests. Left to right - soft, medium, hard clay. Top image illustrates the repeat relief texture side of the test and bottom image the 45° angle indentations test side.

The medium consistency clay was most successful and printed the repeat texture area but broke down at the extreme of the 45° degree angle indentation. The clay was rigid enough to hold its shape overall but did not have enough plasticity or stretch as the printed wall saged in the extreme of the overhang. Once the print broke down it never repaired itself, breaking progressively shorter on each layer.

The hard clay seems to have no elasticity when under stress and breaks easily. The print kept building due to the stiffness of the clay extrusion but not layer by layer in the correct place and was less successful than the medium consistency clay.

It would appear plasticity and elasticity are important qualities in a clay to build more complex shapes than the cylinder. While shapes are vertical as in the cylinder tests and the layers are built up with the support of the previous layer underneath, then extrusion printing is alright. But curved shapes that move off the vertical become more of a challenge. Printed infill could be a solution but the object of these tests were to gage what is possible without infill support. Double wall printing is also more stable but again the objective was to test the material qualities. The print process was kept simple to concentrate on what improvements could be obtained from the clay mix. The exploration of printing techniques was beyond the scope of these tests.

Soft clay is more flexible and less prone to surface cracking but then less capable of supporting its own weight. It would appear an improved clay body would have a stronger surface tension, a good plasticity while also having an inherent self structure to hold its own weight and not fracture under distortion. While printing once a break occurs it is difficult to repair the break and get the structure stable again. The answer is not to get the break in the first place.

Additives to Improve Plasticity and Elasticity

From the unsuccessful print results above it was decided to try and improve the basic test receipt through the introduction of additives. Each additive was tested individually in the original test mix.

Deflocculation

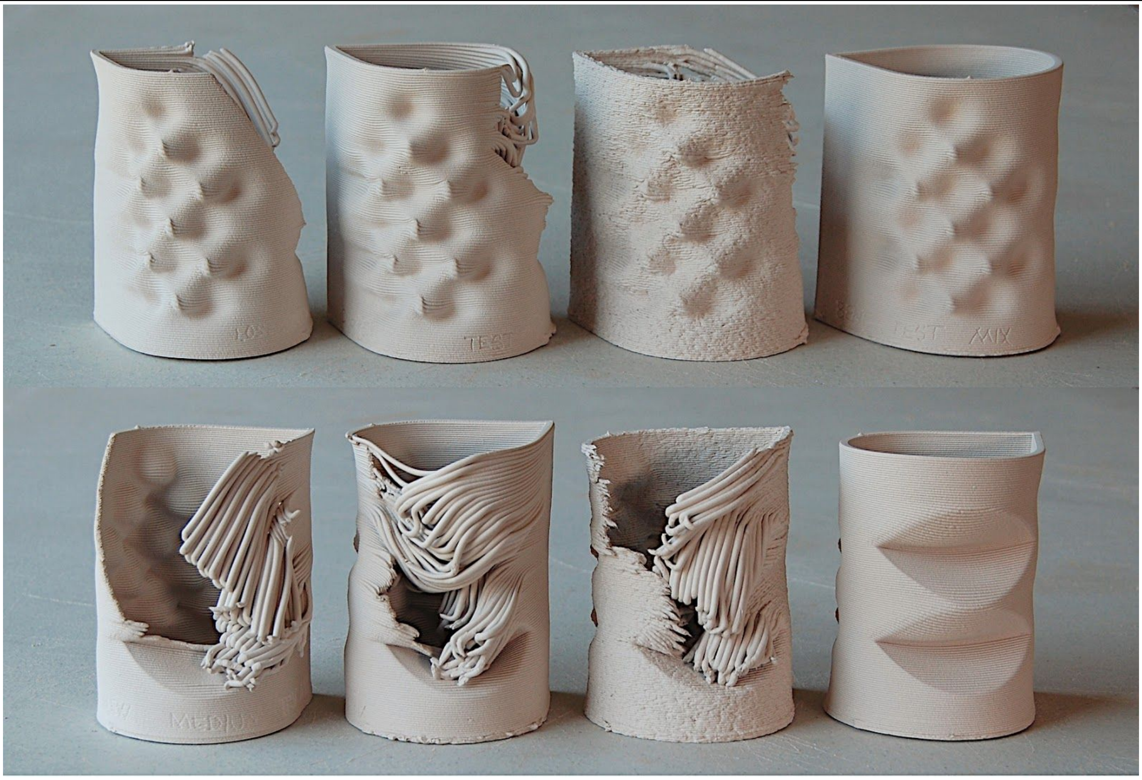
The viscosity of a clay can differ when alkaline, neutral or acid. This is due to electrostatic charged bonds between clay particles. Alkaline additions can result in the dispersal of these bonds resulting in a more fluid clay mix. Sodium Dispex was used in this test. If too much is added it can result in the clay mix taking on a thixotropy character that while desirable for clay slip casting is undesirable for clay printing. A fully deflocculated thixotropic clay does not layer up well when printed and offers no ‘bite’ to the screw in an auger printhead.
The objective of a small amount of alkaline deflocculant was to improve the extrusion surface quality. The smoothness of the extrusion. An inclusion of 0.1% by weight of Sodium Dispex to dry ingredients weight was decided upon with the aim of slightly reducing the surface tension of the clay mix without greatly changing the character of the mix. This proved to also make the clay mix a little more fluid without the addition of any more water. The resultant test print was an improvement on the initial test but still did not produce an unbroken sample.

Paper Fiber

The inclusion of paper fiber into the clay mix was to see if the fibers would help prevent the extrusion breaking. Concern that excessive fiber might create blockages, 1% by weight of toilet paper to the weight of dry clay was calculated. The paper was first broken down in the required amount of water to produce a consistent consistency of clay. It was surprising how much even this small amount of paper altered the texture of the clay mix. The paper mix printed slightly better than without paper but the fiber texture changes the surface look of the test considerably.

Bentonite Plasticiser

Bentonite is a fine highly plastic very sticky clay. As a final additive to be tested, 5% bentonite by dry weight was added to a sample of the initial clay recipe. Finally a complete print was obtained confirming the importance of plasticity in an extrusion 3D printing clay body, if printing curved or overhanging shapes. It was quite a revelation how the addition of 5% of a material can make such a difference.



Test clay body of medium consistency, with no additive.	Test clay body with the addition of 0.1% Sodium Dispex.	Test clay body with the addition of 1% paper fiber.	Test clay body with the addition of 5% bentonite.

Reformulated Receipt: Test Mix 2

From the additive results and the observation that Test Mix 1 had a high amount by volume of china clay to ball clay in it, a reformulated Test Mix 2 was prepared. For this mix the added paper was reduced to 0.1% of dry weight. The china clay to ball clay ratio was balanced to be equal by volume and the grog, half the volume of any one clay or one quarter of the combined clay volume. This new clay mix was prepared by weight. Water was added in the proportion of 74% dry weight to 26% water, mixed and left overnight.

Test Mix 2

Ball Clay (Hyplas 71)	52
China Clay (Grolleg)	24
Grog (Fine Molochite)	24
Bentonite	5
Sodium Dispex	0.1
Paper	0.1

This new mix produced an adequate print but there are other commercially available clay bodies on the market that produce better results on these test shapes and using this equipment. In fairness to this mix it will improve hugely with ageing and may well prove to be the basis of a successful extrusion printing clay body in time.

Sample printed with Test Mix 2

Test Clay Mix Comparisons

	Test Mix 1	Test Mix 2
Dry ingredient to water	72% : 28%	74% : 26%
Spike Test	32 mm	30 mm
Syringe extrusion	6.3 kg	7.2 kg
Print Pressure	3 Bar	6 Bar