NAZARBAYEV UNIVERSITY

School of Engineering and Digital Sciences

Bachelor of Engineering in

Mechanical and Aerospace Engineering

THE RHEOLOGICAL ANALYSIS OF BUCKWHEAT DOUGH FOR 3D PRINTING

(Final Report for Capstone Project)

by

Adib Yermagambet
Farida Ospanova
Temirlan Sadykov

Principal Supervisor: Professor Didier Talamona
Co-Supervisor: Professor Konstantinos Kostas
Course Instructor: Professor Altay Zhakatayev

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Declaration

We hereby declare that this report entitled “The Rheological Analysis of Buckwheat dough for 3D printing” is the result of our own project work, except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

Names: Adib Yermagambet, Farida Ospanova, Temirlan Sadykov

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Abstract

This research examines buckwheat dough rheological properties aiming to enhance their printability for 3D food manufacturing due to expanding market interest in gluten-free and sustainable clean-label products. Rheological characterization using oscillatory and steady shear rheometry examined the viscoelastic properties as well as flow behavior of buckwheat doughs with different water content levels combined with hydrocolloids including guar and xanthan gums. The Herschel–Bulkley model fitted the formulated doughs before printer tests were conducted on the Foodini 3D device to evaluate printability. Doughs containing 1% weight mass of guar gum and xanthan gum exhibited ideal elastic moduli ranges from 3 to 4.5 x 10^4 Pa and yield stresses of 2 kPa which resulted in optimal shape retention together with stability properties. However, increased water content along with xanthan gum dosage impaired the structural properties. The tested doughs maintained print heights above 96% which validated their printing capabilities. Research findings present usable criteria to make printable gluten-free doughs which will help expand the functionality of 3D printing in food creation.

1 Introduction and Problem Statement

3D food printing technology enhances modern food production by creating functional food products which also have appealing appearance while offering personalized designs. 3D printing techniques deliver exact regulation of food structures for compiling textures and materials which becomes indispensable for people with dietary restrictions.

The main benefit of 3D food printing enables precise food production catering to patients with distinct dietary needs particularly for those avoiding gluten in their diet. Current research shows that gastrointestinal disorders affecting people with Crohn's disease and irritable bowel syndrome (IBS) exist extensively throughout the world's population. Three diseases mainly affect 60 to 70 million people in the United States [1]. Due to its widespread popularity gluten-free foods now serve both medical and general health purposes in widening markets.

Buckwheat, as a pseudo-cereal, offers a promising candidate for gluten-free 3D printing, making it of interest to researchers because of its nutritional benefits. Buckwheat-derived flour contains a high level of fiber as well as phenolic compounds, linked to favorable consequences on human health [2]. However, although its nutritional benefits are highly desirable, dough from buckwheat has been found to pose challenges in 3D printing, particularly in its rheological properties. Absence of gluten leads to defective viscoelastic properties which affects shape stability before and after printing occurs. Furthermore, a high level of fiber can negatively affect flow properties of dough. Such problems can be solved through the utilization of hydrocolloids, e.g., xanthan gum. These additives function as gluten replacements in gluten-free dough products to create viscoelastic characteristics and maintain moisture retention and improve the overall shape quality. Even when present in small levels below 1% of weight, xanthan gum plays a significant role in enhancing rheological properties of gluten-free dough [2]. Additionally, buckwheat dough has a relatively high level of water-absorbing capacity, a factor by which baking time can be reduced through amplification of water enthalpy versus temperature [3].

The objective of the present work was to address these problems by characterizing rheological properties of buckwheat dough and fine-tuning its formulation to make it 3D printable. The function of these additives in gluten-free dough includes restoring the viscoelastic properties while improving water retention and enhancing shaping stability. The work focuses on dough formulation from buckwheat flour and xanthan gum tailored to be 3D printable through extrusion technology. Finally, this project makes a meaningful contribution to creating a green as well as healthy food source to meet dietary needs of subjects having dietary restrictions.

Limitations of study

The Rosand RH10 capillary rheometer performed rheological tests throughout this research to measure flow properties by assessing shear stress against viscosity changes at different shear rates during steady-state flow conditions. The research team established that evaluation of extrudability served as a vital printability parameter based on this technical method. Various technical problems emerged to disrupt the project development process continuously from start to finish. The Rosand RH10 apparatus lacked the capability to detect dynamic rheological characteristics including shear modulus (G) and storage modulus (G′) and loss modulus (G″) which are fundamental to understand viscoelastic dough properties. The analysis demanded oscillatory rheometry due to which the university maintained only a single dynamic rheometer which researchers could not use effectively throughout the project timeline. Experimental guidance for adequate results became possible after the midpoint of Semester 2 even though the instruments operated during the initial weeks of Semester 1. The experimental work faced multiple drawbacks caused by restricted access and very long test periods because each assessment took multiple hours.

One significant limitation was introduced by the change from brown to green buckwheat flour, triggered by electron microscopy analysis identifying inconsistencies in grain size between buckwheat types. This required a complete re-running of all Semester 1 experiments to determine optimum water content to flour ratios using the new buckwheat, hence severely hampering progress. The late arrival of equipment, such as the dough mixer and oven, around mid-November also contributed to the loss of considerable test time to ensure consistency in methodology. Extra weeks were also needed to adjust to working with new equipment, as well as to settle on a standardized approach to testing. The proposed research study evaluated the temperature-dependent dough rheology properties by performing experiments at three temperatures: 25°C, 55°C and 85°C. However, this design was later abandoned. Initial tests revealed temperature to have little influence on dough rheology and printability. Additionally, equipment restrictions—namely, the inability of the

Foodini printer to warm dough internally, as well as higher evaporation rates when higher temperature levels were used—made temperature regulation more difficult. Bringing the sample temperatures up to 85°C would take up to 40 minutes, making this practice inefficient and unfeasible considering time constraints on this project. As a result, all conclusive tests were conducted at room temperature. In spite of equipment issues above as well as a change in material direction, along with time constraints, much data was still accumulated in regards to green buckwheat dough properties as a function of 3D printing.

2 Literature Review

2.1 The development of dough requires gluten to form its structure

Traditional doughs need gluten for their elastic behavior because it adds cohesion and enables the dough to trap fermentation gases. The necessary textural qualities of doughs depend on all these capacities. The review of 3D printing indicates structural and extrusion problems resulting from gluten-free doughs because these doughs lack necessary viscoelastic properties needed to achieve smooth extrusion and adequate structural stability. The regular functional and structural attributes of gluten can be simulated through Xanthan gum (XG) and Guar gum (GG) hydrocolloids [5, 6]. Studies in rheology enable the comprehension of unusual materials including buckwheat flour while developing 3D printing practices. The literature review investigates how buckwheat-based dough affects rheological measures which determine its suitability for 3D printing.

2.2 Rheological properties hold essential value during the process of 3D printing operations

Different material 3D printability depends on their rheological properties. Shear-thinning behavior is essential for dough because it enables easy material flow through nozzles and preserves printed structure [7]. The viscoelastic properties of starch gels improve through the addition of hydrocolloids including locust bean gum and XG since they enhance the capability to stack layer-by-layer [5]. According to [6] ground GER has been characterized as a substance that enhances layer-layer bond formation by thickening the starch gel networks within egg yolk granules. Shear-thinning behavior alongside viscosity and elasticity control both the printable characteristics and structural stability of materials while printing and determine the selection of appropriate materials to achieve proper layer adhesion according to [4].

2.3 Challenges in Gluten-Free and Alternative Doughs

The lack of gluten in doughs including buckwheat-based doughs creates substantial obstacles when attempting 3D printing. The absence of viscoelastic network in gluten-free doughs results in poor structural and textural qualities because these doughs lack cohesiveness and gas retention capabilities. The use of hydrocolloids represents a key solution to compensate for gluten deficiencies as established by [2] and previously confirmed by [8] through work that showed xanthan gum improved sensory and physical quality of buckwheat-based gluten-free biscuits.

2.3 Challenges in Gluten-Free and Alternative Doughs

The production of 3D printed dough faces major obstacles when gluten is eliminated from the system including buckwheat-based formulations. The absence of gluten within doughs leads to poor structural qualities along with deficient textural properties because gluten-free doughs do not develop viscoelastic networks that retain gases. Research findings reported in [2] confirmed that hydrocolloids play a key role in resolving gluten deficiencies as previously shown in [8] when xanthan gum was used to improve both sensory characteristics and physical properties of gluten-free buckwheat-based biscuits.

2.4 Buckwheat's Potential in Food Applications

Agro-industries recognize buckwheat because of its nutritional value alongside its potential to serve as a base ingredient for developing gluten-free food products. The research presented in [3] studied dough composed of wheat and buckwheat flour mixtures where the authors discovered extended dough development times coupled with elevated water uptake. A stability reduction was observed by their team because this reduced the feasibility of buckwheat dough for 3D printing applications. Studies prove the necessity of creating specialized buckwheat dough formulations that meet requirements for additive manufacturing success.

2.5 Hydrocolloids and Additives for Rheological Optimization

Research indicates hydrocolloids consisting of guar gum and xanthan gum strengthen the rheological behavior of doughs suitable for 3D printing processes. The research conducted by Team in [10] showed that xanthan gum boosts pork paste self-supporting properties and shear-thinning properties which led to new development opportunities for plant-based and alternative doughs. Research results published in [6] established how guar gum added both gel modulus and cohesiveness which provide critical components for maintaining structuring integrity during printing sessions. Hydrocolloids maintain essential roles through improving the printability together with the structural stability of gluten-free doughs. Scientific research has extensively investigated the role of XG and GG as ingredients which simulate gluten properties through elastic attachment and cohesive behavior. Research by [2] and [5] demonstrates that dough additive elements improve overall viscosity measurement along with storage and loss modulus which results in smooth extrusion followed by better printed shape retention.

2.6 Impact of Finer Particle Size on 3D Printability of Dough

The printability of dough improves through enhaced water absorption and stable cohesive structure which results from using finer flour particles. The rhelogical characteristics of wheat-based flour and its shape retention remained consistent when using smaller flour particle sizes. The 3D food printing process benefits from finer buckwheat particles since they create smooth extrusion while improving layer stability which leads to printing success [9].

2.7 3D Printing with Alternative Flours

The authors in [1] conducted research which studied how different food matrices including alternative flour types affect the functioning of 3D printing technologies. The research established that the use of additive manufacturing provides the ability to create customized food items with buckwheat and other wellness ingredients. Research paper [10] demonstrated that dough formulation optimization requires lower sugar content to maintain printing stability. The study found in [5] established that Xanthan gum strengthens starch gel hydrogen bonds to result in better mechanical properties. The research work from [6] used SEM to verify GG creates strong gel structures in starch-based systems that enhances printing self-support capabilities.

2.8 Gap in the current research

The research community needs to further explore the application of buckwheat flour in 3D food printing despite recent significant advances. Scientific research primarily studies individual hydrocolloids together with starch systems while lacking information about buckwheat behaviors when printed through extrusion methods. The researchers have focused minimal efforts on developing optimized formulations which cater to the dietary requirements of people with digestive problems.

3 Methodology

It is important to mention the methodology of the research to show the credibility and reliability of results and the scope of research being done. Also, the methodology in research papers help to guide the research enthusiasts and overall readers on further research or just understand how data can be gathered. The following section shows transparency of the work, enabling peer review and thinking of any improvements.

3.1 Materials

Flour: Green buckwheat flour was used as the raw material (Fit Parad, ‘Мука из зеленой гречки без глютена’), whose nutritional composition per 100 g of: protein – 12.6 g, fat – 3.3 g, carbohydrates – 57 g.

Additives: Two hydrocolloid food-grade polymers, XG (xanthan gum) and GG (guar gum), in each case 1% by flour weight, were used.

Water: Drinking water was used to hydrate additives and flour, with three different ranges of water content being tested: 75%, 85%, and 120% by weight.

Equipment:

- Dynamic Rheometer: TA Instruments DHR1 with 40 mm parallel plate geometry was used to measure viscoelastic and flow behavior.
- 3D Food Printer: Foodini 3D food printer with 4 mm nozzle and printing rate of 800 mm/min.
- Mixing Equipment: Stand mixer with dough hook, mixing at low speed (3–5 min of mixing).
- Measurement Tools: Accuracy scale with 0.01 g precision for weighing of ingredients.
- Scanning Electron Microscope (SEM) to examine and compare grain size and surface morphology of green vs. brown buckwheat flour before formulation

3.2 Dough preparation

Three dough preparations were prepared:

- Control Group: Hydrocolloid-free dough (simple green buckwheat flour and water).
- Experimental Groups: Dough with the incorporation of either 1 wt.% xanthan gum (XG) or 1 wt.% guar gum (GG) into the flour.

For each formulation, water level ranges was altered (75%, 85%, and 120% by weight). Ingredients were mixed at low speed using a stand mixer for 3–5 minutes. After mixing, the dough can be used immediately, as the gluten-free dough does not require resting time prior to rheological testing and 3D printing.

3.3 Dynamic Rheological Analysis

Dynamic rheology was recorded using a TA Instruments DHR1 rheometer, 40-mm parallel-plate configuration, at ambient temperature, as a substitute for earlier temperature-dependent assessments in an attempt to measure viscoelastic, as well as flow, properties of dough.

Tests Conducted:

1) Amplitude Sweep: Conducted at a frequency of 1 Hz over a 0.1–100% range of strain to locate Linear Viscoelastic Region (LVR).
2) Frequency Sweep: Conducted in LVR across an angular frequency range of 0.1 to 100 rad/s to measure frequency-dependent viscoelastic response.
3) Flow Sweep: Conducted at rates of 0-100 s^{-1} to observe shear-thinning phenomena as well as compute flow parameters.

Parameters Measured:

- Storage modulus (G′), loss modulus (G″)
- Yield stress (τ)
- Flow index (n) and consistency index (K)
- LVR boundaries (critical strain)

3.4 3D Printing Protocol

3D printing was carried out using the Foodini 3D printer at room temperature. The setup configuration was determined as follows:

- Nozzle diameter: 4 millimeters
- Layer thickness: 3.2 millimeters
- Printing speed: 800 mm/min
- Printed geometry: A hexagonal-shaped cookie was used to test its form stability as well as its structural integrity.

Assessment Standards:

1) Dimensional Stability (%) = $\frac{Height\ after\ 1\ hour}{Height\ immediately\ after\ printing} \times 100$
2) Printability (%)= $\frac{Achieved\ height\ of\ printed\ object}{Target\ height} \times 100$
3) Extrusion Quality: Qualitative observations on layer adhesion, smoothness, and absence of cracking.

3.5 Data Analysis

Rheological measurements were performed to identify how the viscoelastic properties of buckwheat dough, in particular, storage modulus (G′), loss modulus (G″), and shear stress (τ), correlate with its performance in 3D printing applications. Steady shear tests and dynamic oscillatory tests were used to describe flow properties as well as structural stability.

Flow Behavior Analysis

To describe flow characteristics of dough, Herschel-Bulkley model was used, considering its applicability to non-Newtonian materials that possess a yield stress, e.g., doughs and pastes. The correlation between shear stress (τ) and shear rate ($\dot{\gamma}$) can be written as:

$$\tau = \tau_y + K\dot{\gamma}^n$$

Where:

- τ= shear stress (Pa)
- τ_y = yield stress (Pa)
- K = consistency index ($Pa \cdot s^n$)
- $\dot{\gamma}$ = shear rate (s^{-1})
- n = flow behavior index

It both covers the yield stress required to start flow as well as the shear-thinning properties commonly found in doughs.

Apparent viscosity

The dough viscosity was quantified using flow curves, which were then correlated using the power-law segment of Herschel-Bulkley model, specifically after establishing that the yield stress was small:

$$\eta = K\dot{\gamma}^{n-1}$$

This allowed the characterization of shear-thinning properties, along with their influences on extrudability and shape preservation during printing.

Dynamic Rheology Oscillatory shearing tests were performed in the domain of linear viscoelasticity to determine:

G′ (Storage Modulus): represents the elastic behavior.

G″ (Loss Modulus): representing a viscosity characteristic.

These moduli were used to analyze the dough composition as well as its ability to preserve its structure after the extrusion process.

3.6 Project Plan Table

Table 1. The Plan for the Semester 1 and Semester 2 with task descriptions

Semester 1		
Week	**Task**	**Description**
1	Project Planning	Define objectives, scope, and deliverables; conduct an initial literature review; develop a detailed methodology outline.

2	Literature Review and Materials Sourcing	Finalize literature review; procure necessary materials and equipment (e.g., buckwheat flour, rheometer, Foodini 3D printer).
3	Experiment Design	Design testing variables (ratios, temperatures, additives); schedule experimental trials
4	Preliminary Setup	Calibrate RH10 Rosand rheometer and Foodini 3D printer; conduct trial runs.
5-6	Control Group Testing (Without Xanthan Gum)	Prepare dough samples (1:2 to 1:4, step size: 0.33); test rheological properties at 25°C, 55°C, and 85°C; record data.
7-8	Experimental Group Testing (With Xanthan Gum)	Prepare samples with 1% xanthan gum; repeat tests at all temperatures; systematically document data.
9	Data Analysis (Preliminary)	Analyze data from control and experimental groups to identify suitable ratios and temperature ranges.
10	Printing Trials (Initial Testing)	Test dough samples for 3D printability; adjust printer settings and extrusion parameters.
11	Refined Testing Design	Narrow dough ratios; reduce step size to 0.167; plan refined rheological and printing tests.
12-13	Refined Rheological Testing	Conduct tests on refined samples; evaluate shear stress, yield stress, and viscosity.
14	Refined Printing Trials	Print refined dough samples; capture photographs and assess print quality.
15	Semester Summary and Report	Summarize findings; write a preliminary report covering methodology, initial results, and insights.
Semester 2		
Week	**Task**	**Description**

1	Review and Feedback	Review preliminary report; incorporate feedback from supervisor.
2-3	Grain Size Analysis via SEM	Use electron microscopy to compare grain structure of brown vs. green buckwheat; determine flour suitability.
4	Switch to Green Buckwheat	Based on SEM results, switch flour type; prepare for full experimental repeat.
5	Redo Control Group Experiments	Repeat all rheological and printability tests using green buckwheat, no xanthan and guar gum.
6-7	Redo Experimental Group	Repeat experiments with green buckwheat + 1% additives; evaluate print quality and dough consistency.
8	Final Printing Trials (Green Buckwheat)	Finalize best formulations; perform 3D prints and document quality.
9-11	Dynamic Rheology Testing	Conduct oscillatory tests (frequency and strain sweep) on selected green buckwheat doughs.
12	Comparative & Statistical Analysis	Compare doughs in different condicitons; perform statistical validation.
13	Final Report Drafting	Draft sections: updated methodology, SEM findings, dynamic testing, discussion.
14	Final Report Submission	Submit the final written report for evaluation.
15	Final Presentation	Deliver final presentation to the evaluation committee.

4 Results

Results and summary of analysis from last semester

During the first semester we set out to establish whether buckwheat dough—naturally gluten-free and therefore rheologically fragile—could be tuned for extrusion-based 3-D printing by manipulating water content, temperature and hydrocolloid type. We used brown buckwheat flour as the initial model system and tested two series of formulations: a control group that contained only flour and water at ratios between 1 : 2 and 1 : 4 by weight, and an experimental group in which every flour-to-water ratio was supplemented with one per-cent xanthan gum. All samples were printed using a Foodini FDM food printer and tested at 25 °C, 55 °C and 85 °C; rheological flow curves were then measured on a Rosand RH-10 capillary rheometer so that apparent viscosity, shear stress and the parameters of the power-law model:

$$\tau = K(\frac{du}{dy})^n$$

Printability testing revealed narrow "sweet spots" that were very temperature-dependent. At ambient temperature, doughs of 2 .33 : 1 to 3 .33 : 1 water-to-flour printed with clean strand definition in the presence of one per-cent xanthan, while the gum-free control needed marginally drier mixes (around 2 .83 : 1 to 3 .5 : 1) to give similar shape retention. At 55 °C, the optimum ratio for both series was between 2.33:1 and 3.33:1. The finding implies that moderate heat decreased some of the loss in viscosity observed in gum-free dough, whereas the gum formula sustained cohesion by promoting moisture retention. At 85 °C successful printing continued only for gum‑reinforced mixtures between 2 .67 : 1 and 3 : 1; greater water content resulted in extreme slumping as evaporation took over, and leaner mixtures were too stiff to extrude. Prints were all rated on extrusion smoothness, layer adhesion, surface finish and the capability to retain ≥ 90 % of their height for an hour. Those scores provided a rapid pass-fail filter before deeper rheology was performed.

Rheological characterisation attested that all printable doughs exhibited shear-thinning. Flow-curve fitting using the power-law equation gave flow indices n less than unity for all samples; the most successful at any temperature ranged between $n \approx 0.3$ and $n \approx 0.5$, a range that provides a balance between nozzle flow and post-extrusion stability. Consistency indices K decreased as water was added, but the inclusion of xanthan gum increased K at a specified ratio by about one order of magnitude, showing its effect in reinforcing the transient network of hydrated starch and proteins. Apparent viscosity profiles also demonstrated this interaction: low-water dough had an order of magnitude greater viscosity than high-water dough at 0.1 s^{-1}, but the two were identical near 100 s^{-1}—the range of shear-rates experienced within the nozzle—thus accounting for the fact that rigid low-water dough could still be extruded within the 300 kPa pressure capacity of the printer.

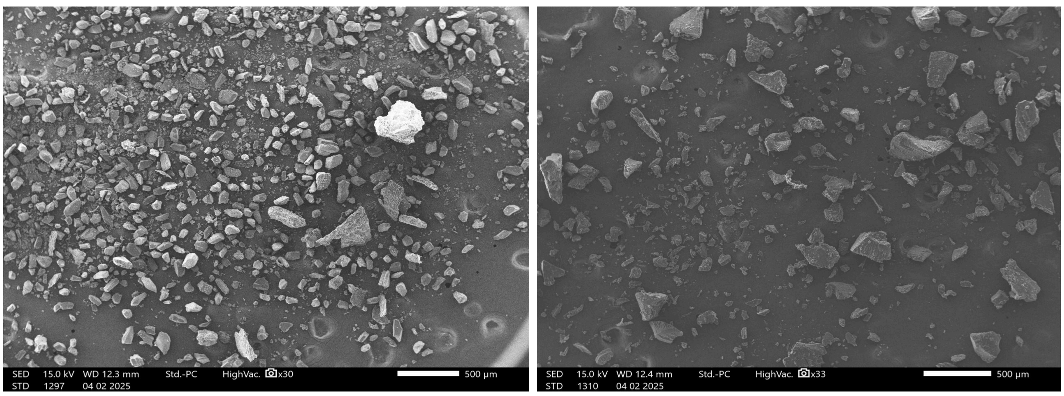
Gum-free dough at 70 % water produced τ_0 circa nine-hundred pascals, whereas the same ratio at 83 % water dropped to about six-hundred pascals. Adding one per-cent gum pushed τ_0 into the 2 kPa region, and subsequent rheological ageing showed that τ_0 doubled after twenty-four hours in the fridge and tripled at room temperature because of ongoing starch retrogradation and gum–starch junctioning.

These values establish the "shape-retaining window" that we have found for alternative printed doughs (between fifty and several hundred pascals) and rationalize our next decision of substituting roasted flour with raw green flour, as its smaller particle size needed less water content and inherently raised τ_0 into the desired range.

At about 55 °C, pasting of brown-buckwheat starch commenced, thickening the continuous phase and extending the linear-viscoelastic region such that critical strain γ_c roughly doubled from 0.05 % to 0.1 % in the xanthan series. Above 85 °C, however, evaporation lowered surface moisture and created brittle shells; layer adhesion suffered and prints cracked unless additional water or steam compensation was provided.

Hence 55 °C was determined to be the most tolerant temperature for brown-flour inks, giving the best compromise between ease of extrusion and dimension stability. Hydrocolloid comparison during the semester targeted xanthan. The methodological limitations were acknowledged. Our rheometer could not perform oscillatory sweeps; therefore, the moduli G' and G'' were indirectly inferred from capillary data. A rheological device with the capability of oscillatory measurements, which is currently under repair, will be incorporated in the next stage to derive true viscoelastic spectra. Equipment delays also limited the number of replicate trials at high temperatures, and the heating sleeve of the Foodini printer could only maintain, not increase, filament temperature; pre-heating in an oven brought in some moisture loss that needed to be reduced with foil covers. Nutrition and sustainability remained ongoing incentives throughout the semester.

Green and Brown Buckwheat Flour Comparison



a) b)

Figure 1. a) Green Buckwheat Flour; b) Brown Buckweat Flour

Green flour (left) is noted for having small, angular particles—deteriorated starch granules and protein bodies that have preserved their original, glassy structure. High background of fines occupying areas between large pieces. Compact general packing with minimal inter-particle porosity.

Brown flour (right) contains very few fines and plenty of large, flaky shards. Those flakes are composed of fragments of the roasted seed coat together with partially gelatinised starch plates formed when the groats are parboiled and dry-roasted. Void space between such coarse particles is much higher.

More compact particle packing prevents clogging of print-head and results in smoother layer surface. Natural starch limits gelatinisation process to within printer: once baked or steam-cooked, the printed item, in-situ gelatinisation locks final structure into the exact printed shape. Less contaminated flavour profile—no charred flavours—makes product an innocent vehicle for sweet or savory mixtures.

The Scanning electron microscopy reveals native (raw) buckwheat starch granules as polygonal, intact, and tightly packed, while thermal roasting generates granule breakages and conglomerates that expand void spaces among fragments [17]. Research shows that the swelling power and water-absorption index of roasted buckwheat flour are considerably higher than those of raw flour, which verifies that pre-gelatinised starch and denatured proteins within brown flour take up 20–40 % more water before suspension printing [18].

If we compared the same 95 %-guar buckwheat dough immediately after mixing, after 24 h in the refrigerator (4 °C) and after 24 h at room temperature (≈ 22 °C), three different patterns were seen.

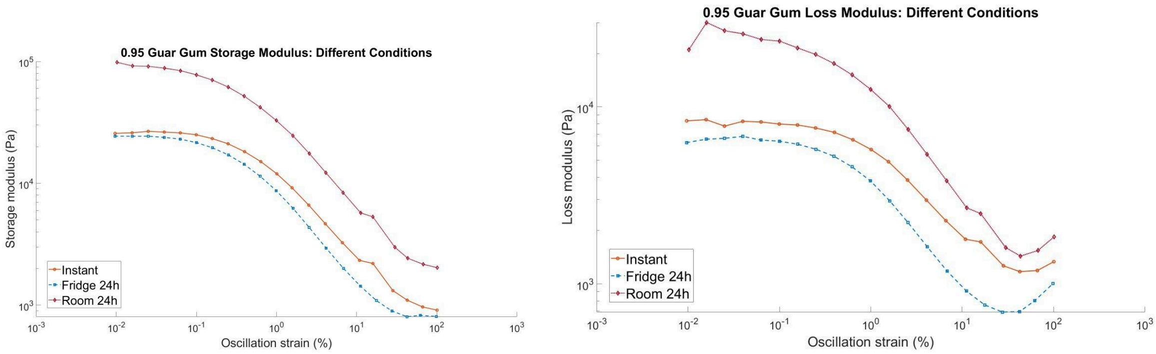


Figure 2. Moduli vs. Strain for different storage conditions

Fresh dough (tested within 30 min) already possesses the character of a weak gel suitable for printing: storage and loss moduli plateau at around 2×10^4 Pa, yield stress is around 2 kPa, and the linear-viscoelastic window cuts off at around 0.05 % strain. This "as-mixed" state is our baseline for jobs that go straight from mixer to syringe.

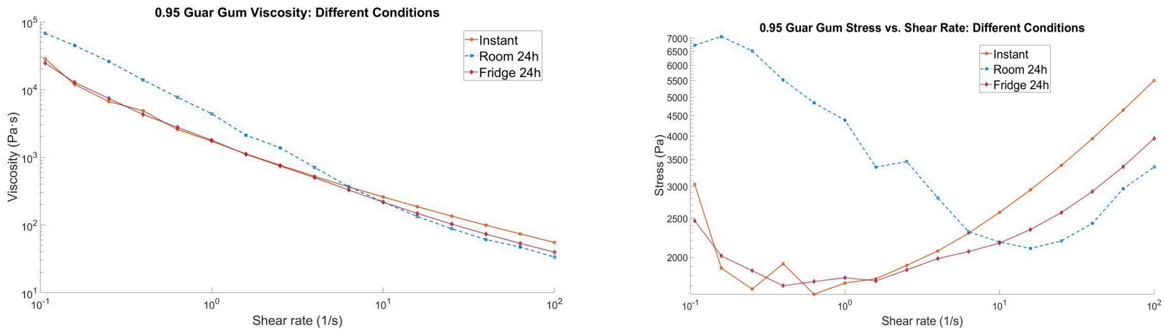


Figure 3. Viscosity and Stress vs. Shear rate for different storage conditions

Fridge-aged dough (24 h at 4 °C) shows a moderate softening of the network—both moduli fall by around 10–15 %—but, interestingly, the critical strain approximately doubles to ~0.1 %. Cold hydration enables guar chains to finish their swelling and starch granules to equilibrate gradually, so the gel becomes slightly more ductile while its yield stress increases to ~4 kPa. Extrusion is actually easier at shear rates above 1 s^{-1} because the whole viscosity curve shifts down. These graphs simulate what happens when a kitchen stores cartridges in a refrigerator overnight.

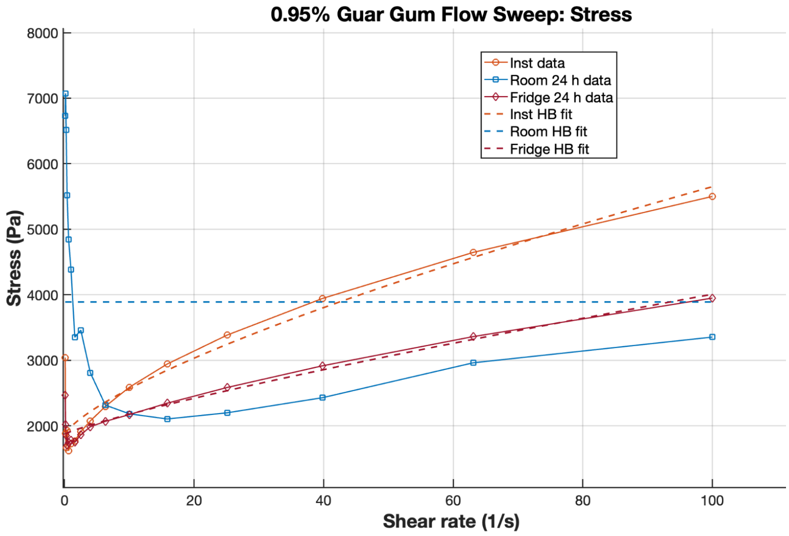


Figure 4. HB model fitting for different storage conditions

Room-aged dough (24 h at 22 °C) exhibits the opposite behavior: prolonged warm rest triples the storage modulus to around 9×10^4 Pa, but the critical strain drops to ~0.03 %, reflecting a stiffer but more brittle structure. Viscosity below 1 s^{-1} and the entire stress curve rise steeply (≈ +2 kPa), and the Herschel–Bulkley fit shows the yield stress has roughly tripled relative to the fresh state. The cause is enhanced starch retrogradation and closer guar–starch junctioning at ambient temperature. This dough is highly resistant to slumping but needs higher nozzle pressure and is more prone to surging.

Therefore, it can be seen that overall the fridge-aged dough could be used to observe the properties close to the fresh dough.

Pure Buckwheat without Additives

70% wt% shows clear yield stress, demonstrating solid-like behavior up to critical stress. At higher stresses (up to ~10^3 Pa), the implication is one of greater structural resistance to flow. 83% wt% has lower yield stress compared to 70% wt%, implying easier initiation of flow at lower stress. Stress values plateau at lower magnitudes (~10^2 Pa).

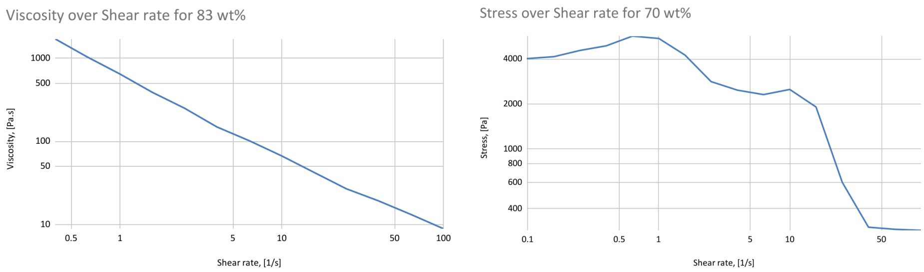


Figure 5. Stress vs. Shear rate for 70% and 83% water content for pure buckwheat flour

70% wt% shows dominant elastic behavior (G' > G") at low strain (0.01–1%), with G' around 40,000 Pa. Moduli are invariant up to high strain (>10%), indicating robust network integrity. 83% wt% has weaker viscoelastic structure. G' is at a maximum of ~10,000 Pa, with the crossover to liquid-like behavior (G" > G') at lower strain (~1–10%).

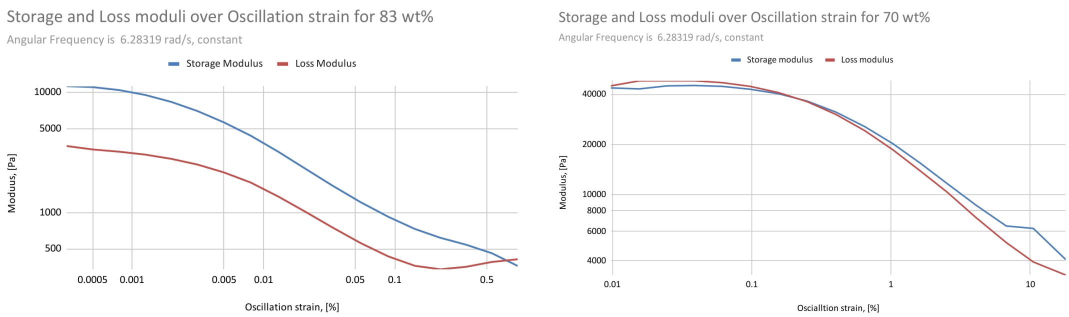


Figure 6. Moduli vs. Strain for 70% and 83% water content for pure buckwheat flour

70% wt% G' and G" rise with frequency (0.1–100 rad/s), with G' > G" throughout. Elastic dominance implies firm structure under deformation. 83% wt% has lower moduli values (G' ~6,000 Pa at 0.1 rad/s) are less frequency dependent. Reduction in G' is faster at higher frequencies.

Figure 7. Moduli vs. Angular frequency for 70% and 83% water content for pure buckwheat flour

For 70% wt% viscosity reduces quickly (10^4–10^1 Pa·s) with increased shear rate (0.1–50 1/s). Shape retention is maintained by high initial viscosity (~10^4 Pa·s). Stress rises quickly with shear rate (up to ~10^4 Pa) with high resistance to flow. For 83% wt% viscosity drops from ~10^3 to 10^1 Pa·s at similar shear rates. Reduced stress values (~10^3 Pa) point toward less internal structure.

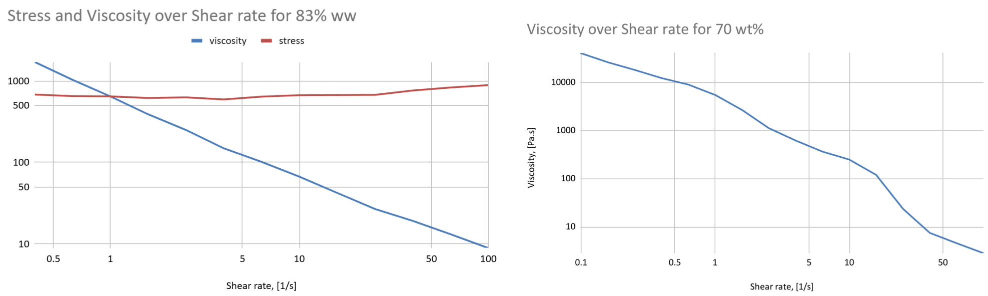


Figure 8. Viscosity vs. Shear rate for 70% and 83% water content for pure buckwheat flour

70% wt% has higher G', G", and yield stress, which are most critical for print stability. Additives can reinforce 83% wt%'s poor network. Shear response for both samples shear-thin, but 70% wt%'s larger reduction in viscosity and greater stress are a sign of better extrusion control. Additives can regulate this behavior. Strain sensitivity 70% wt% is more flexible over broader strain ranges, with reduced risk of collapse. Additives can increase strain tolerance of 83% wt%.

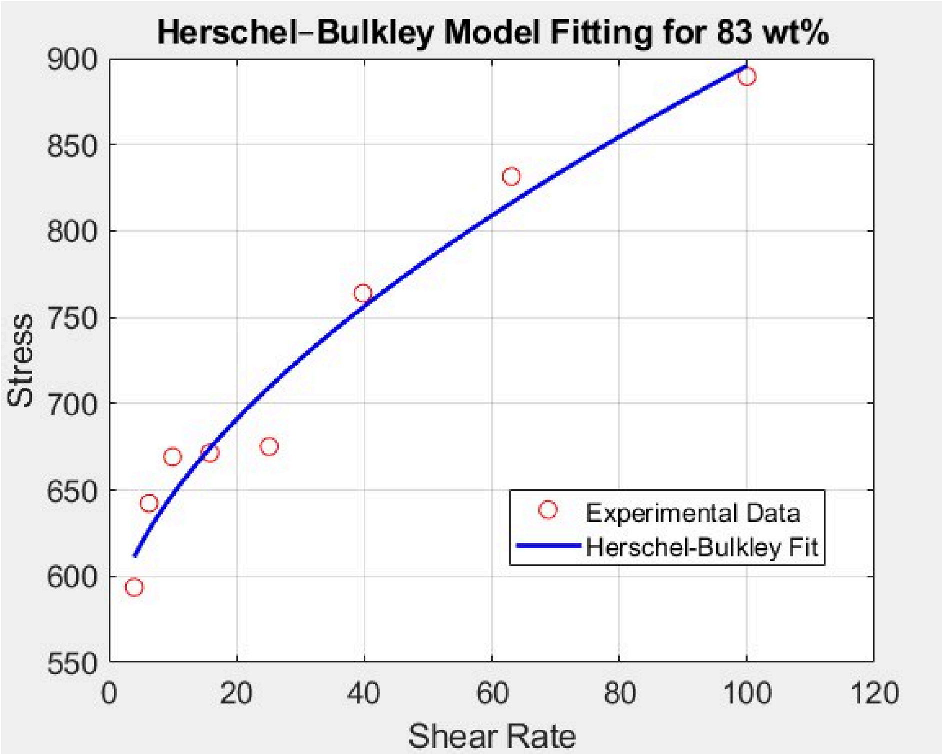


Figure 9. HB Fitting for Pure Buckwheat Dough at 83% ratio

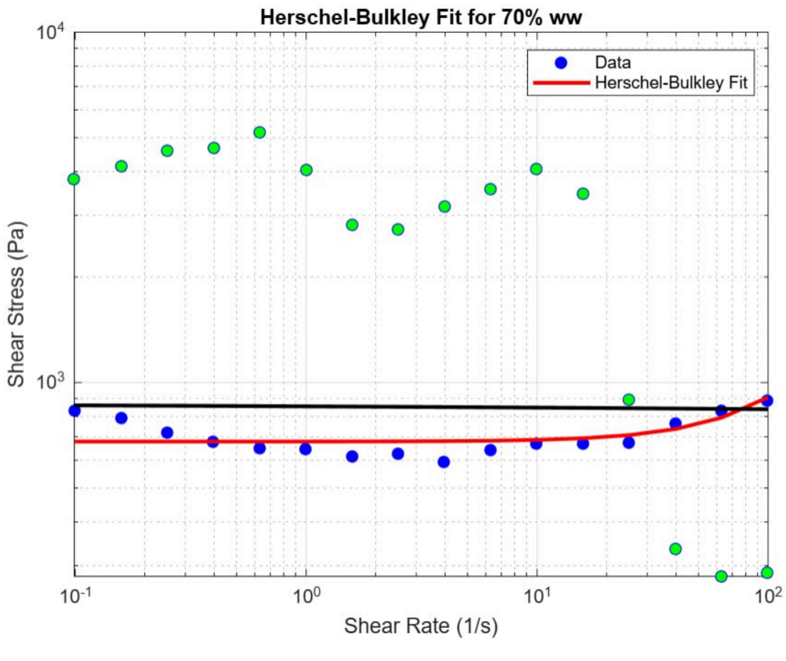


Figure 10. HB Fitting for Pure Buckwheat Dough at 70% ratio (green dots are data points and green line iss model fitting; blue is the second trial)

Table 2. Summary of results for 70% Pure Buckwheat

Amplitude sweep (G′ & G″ vs strain)	•Plateau 0.01 – 0.1 % strain: G′ ≈ 4.2 × 10^4 Pa, G″ slightly higher. •The initial significant degradation begins at a strain of approximately 0.2%. • At 10 % strain both moduli have fallen ≥ 85 %.
Frequency sweep (0.1 – 100 rad s^{-1})	• G′ peaks ≈ 6 × 10^4 Pa at 0.1 rad s^{-1} → minimum ≈ 3 × 10^4 Pa near 1 rad s^{-1} → rises again to ≈ 4.3 × 10^4 Pa at 100 rad s^{-1}. • G″ < G′ throughout.
Flow properties (stress and viscosity as functions of shear rate)	• Shear stress quasi-plateau 4 – 6 kPa up to 1 s^{-1} → gradual decline to ≈ 1 kPa at 50 s^{-1}. • Observed η decreases ~2 log units (≈ 2 × 10^4 → 2 × 10^2 Pa·s).
Herschel–Bulkley fit	• Yield stress τ_0 ≈ 9 × 10^2 Pa. • n < 1 flow index (high shear-thinning). • Fit accurate ≤ 20 s^{-1}, diverges above.

Table 3. Summary of results for 83% Pure Buckwheat

Amplitude sweep	• Plateau to ≈ 0.005 % strain: G′ ≈ 1.1 × 10^4 Pa, G″ ≈ 2.8 × 10^3 Pa. • Reduction of > 95 % in both moduli by 0.5 % strain; G′ is still greater than G″.
Frequency sweep	• G′ starts at 6.5 kPa (0.1 rad s^{-1}) and

	then decreases to 4.1 kPa (about 2 rad s^{-1}), before increasing to 5.3 kPa (about 60 rad s^{-1}). • G″ minimum ≈ 0.7 kPa; always < G′.
Flow sweep	• Shear stress approximately flat 0.6 – 0.7 kPa (0.5 – 10 s^{-1}) → rises to ≈ 0.9 kPa at 100 s^{-1}. • Observed η falls consistently from ≈ 1.2×10^3 → ≈ 10 Pa·s (≈ 2.5 log-unit drop).
Herschel–Bulkley fit	• Yield stress $\tau_0 \approx 6.5 \times 10^2$ Pa. • n < 1, slightly larger than 70 % sample (milder shear-thinning). • Fit follows full range.

Green Buckwheat Flour with Guar Gum

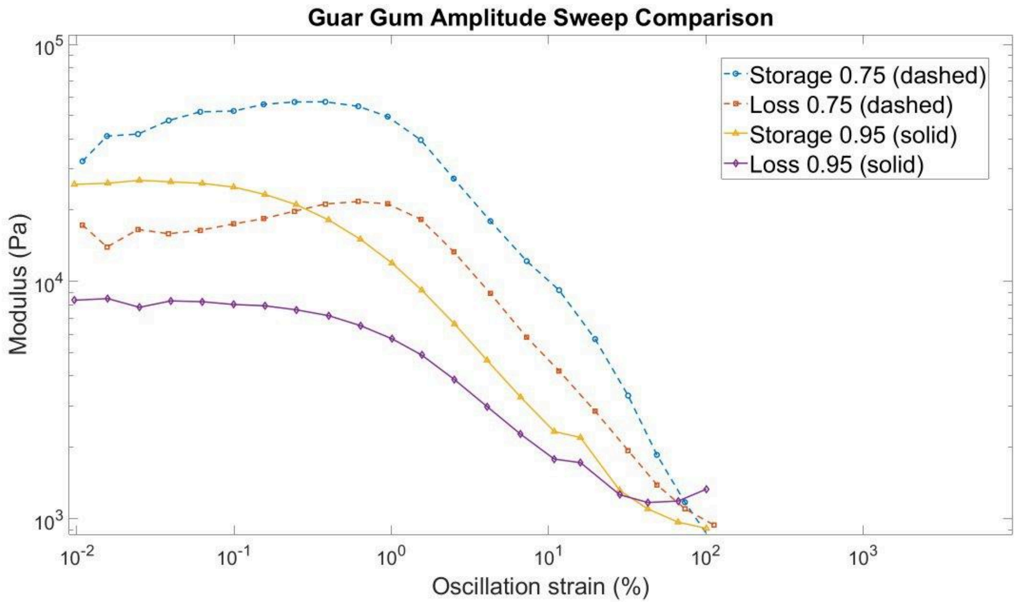


Figure 11. Amplitude Sweep for Flour with Guar Gum Additives

Guar gum in buckwheat green dough leads to a Herschel–Bulkley viscoplastic fluid ($\tau = \tau_0 + K\cdot\dot{\gamma}^n$, $n < 1$) with complex modulus $G^* = G' + iG''$ and loss tangent $\tan\delta = G''/G'$.

For the 0.75 % wt% sample, the linear-viscoelastic regime is found between 0.01–0.3 % strain ($G' \approx 4.5\times10^4$ Pa, $\gamma\_c \approx 0.3$ %), and for 0.95 %, only up to 0.05 % strain ($\gamma\_c \approx 0.05$ %). The two suspensions break down >90 % of G′ to ~15 % (0.75 %) or ~8 % strain (0.95 %), which is indicative of network fracture due to bond breakage.

Frequency sweeps from 0.1 to 10 rad·s^{-1} show the 0.75 % sample as $G' \propto \omega^{-0.4}$ with a high-ω upturn from hydrodynamic stiffening, while the 0.95 % formulation is an order of magnitude more at low ω and has $\tan\delta < 0.4$ (0.75 %) or < 0.3 (0.95 %), indicating increased elastic dominance.

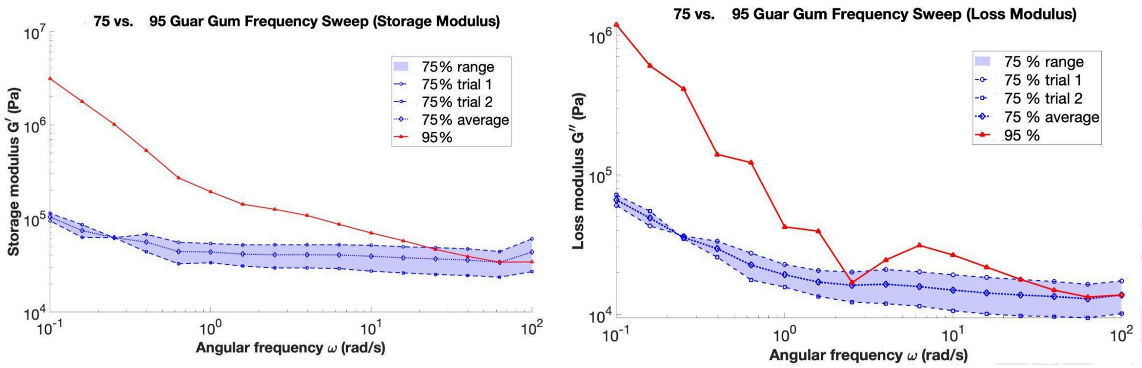


Figure 12. Moduli vs. Angular frequency for Guar Gum Dough

Under steady shear, viscosity scales $\eta \propto \dot{\gamma}^{-0.8}$; at 100 s^{-1} the 95 % system is roughly 120 Pa·s—about 50 % more viscous than the 75 % sample. Herschel–Bulkley fits yield $\tau_0 \approx$ 2.3 kPa (0.75 %) versus ≈ 2.0 kPa (0.95 %), K rising from 1.7×10^3 to 3.5×10^3 Pa·s^n, and n increasing from 0.42 to 0.65 (with transient shear-thickening, $n > 1$ above 30 s^{-1})

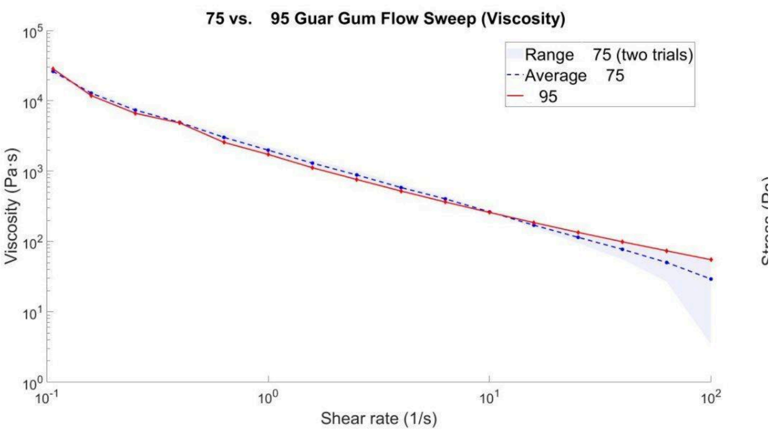


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Figure 13. Viscocity vs. Shear rate for Guar Gum Dough

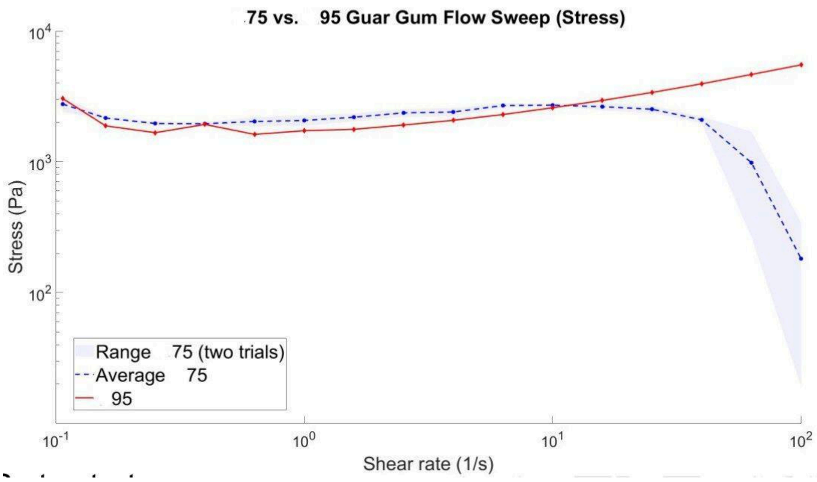

Figure 14. Shear Stress vs. Shear rate for Guar Gum Dough

Thus, increasing guar between 0.75 % and 0.95 % lowers the LVR, improves low‑frequency stiffness and high‑shear viscosity, but at a cost of ductility—key quantitative metrics for optimizing gum level, hydration, and nozzle dynamics for cereal‑free 3D printing.

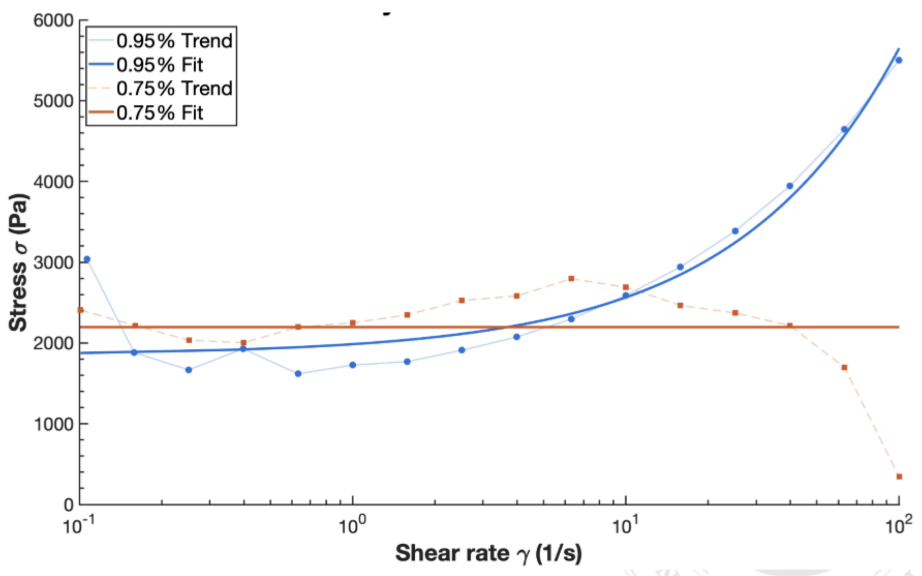

Figure 15. HB model fitting for Guar Gum Dough

Table 4. Summary of results for 75% wt% 1% Guar Gum

Amplitude Sweep	• Plateau G′ ≈ (4–5) × 10^4 Pa between

	0.01 % and ≈ 0.3 % strain. • G″ ≈ (1.8–2.4) × 10^4 Pa in the same region. • Initial 50 % reduction in G′ at ≈ 1 % strain; 90 % reduction by ≈ 15 %.
Frequency Sweep	• G′ band 5 × 10^4 → 3 × 10^4 Pa (minimum near 3 rad s^{-1}) → slight rise to 4 × 10^4 Pa at 100 rad s^{-1}. • G″ band 6 × 10^4 → 1.0 × 10^4 Pa over same range. • Tan δ is 0.2 – 0.4.
Flow Sweep	• η falls off from 4 × 10^4 Pa·s (0.1 s^{-1}) to 4 × 10^2 Pa·s (10 s^{-1}) to ≈ 40 Pa·s (100 s^{-1}). • Stress plateau 3.5–2.5 kPa (0.1 – 2 s^{-1}) → gentle increase to 4 kPa (≈ 20 s^{-1}) → fall below 80 s^{-1}.
Herschel–Bulkley fit	• τ_0 ≈ 2.3 kPa (from fit intercept). • n < 1; fitted curve approximately flat to 5 s^{-1}, then moderate up-turn.

Table 5. Summary of results for 95% wt% 1% Guar Gum

Amplitude Sweep	• Plateau G′ ≈ 3 × 10^4 Pa up to ≈ 0.05 % strain. • G″ ≈ 8 × 10^3 Pa in plateau. • 50 % decrease in G′ at ≈ 0.5 % strain; 90 % decrease by ≈ 8 %.
Frequency Sweep	• G′ starts ≈ 4 × 10^6 Pa at 0.1 rad s^{-1}, falls to ≈ 5 × 10^5 Pa (1 rad s^{-1}), and further to ≈ 6 ×

	10^4 Pa at 100 rad s^{-1}. • G″ follows $1 \times 10^6 \rightarrow 1 \times 10^5 \rightarrow 2 \times 10^4$ Pa. • Cross over with "0.75" G′ at ≈ 80 rad s^{-1}.
Flow Sweep	• η track close to 0.75 up to 30 s^{-1}; remains ≈ 60 Pa·s at 100 s^{-1} (≈ 50 % above 0.75). The 0.95 curve remains superior to the 0.75 curve at frequencies exceeding 5 s^{-1}, attaining approximately 7 kPa at 50 s^{-1} and roughly 9 kPa at 100 s^{-1}.
Herschel–Bulkley fit	• τ_0 ≈ 2.0 kPa. • Steep up-turn: stress rises > 6 kPa by 100 s^{-1}; fit indicates super-linear rise (n > 1).

Green Buckwheat Flour with Xantham Gum

Two inks with different water content, xanthan‑enriched buckwheat inks with 114 % and 120 %, were investigated with frequency sweeps and steady‑shear flow matched to the Herschel–Bulkley law.

114 % water ink gives p ≈ –0.45, G′≈0.02 Pa at 0.4 rad/s, with a G′=G″ crossover at ~15 rad/s, indicating slow increase in viscous response. The 120 % water ink gives p ≈ –0.65, G′≈0.13 Pa at 0.4 rad/s, with no crossover within the investigated range, hence making elasticity common for extrusion frequencies.

The loss tangent tan δ = G″/G′ is below 0.5 for both inks at low ω, placing them in the spring-dominated regime best for resisting sag when flowing through a nozzle.

Herschel–Bulkley models fit yield τ_0 ≈ 282 Pa, K ≈ 9.1 Pa·s^n, n ≈ 0.68 for the 114 % ink; and τ_0 ≈ 334 Pa, K ≈ 44.5 Pa·s^n, n ≈ 0.40 for the 120 % ink. Both exceed the 50–100 Pa limit for supporting printed pillars. The moderate τ_0 increase is a sign that xanthan's native viscosity compensates for extra water, while the five‑fold increase in K is a sign of significantly higher zero‑shear viscosity. A lower n at 120 % allows for a more precipitous drop in viscosity after yield, making pumping easier, while 114 % ink retains more structure.

Xanthan's rigid, charged double‑helix chains take up space. A rise in water from 114 % to 120 % swells coils, increasing junction density (and therefore τ_0 and G'_0), packing molecules (K), and making power‑law decay more negative (p more negative), but in the crowded regime rather than the dilute regime.

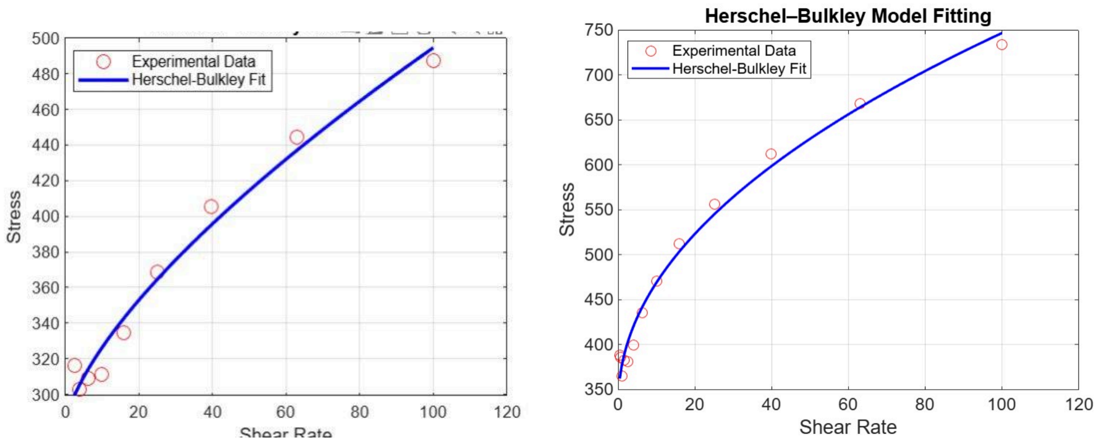

Figure 16. HB model fitting for Xantham Gum Dough

Water augmentation from 114 % to 120 % elevates low-frequency stiffness six-fold, raises yield stress by ~18 %, quintuples consistency index, and enhances shear-thinning. Both inks satisfy $\tau_0 \approx 0.1–1$ kPa, $\tan\delta < 0.5$, and Bo < 1, with the 120 % formulation exhibiting a more rigid, more dense viscoelastic window and the 114 % formulation an enlarged LVE range.

Table 6. Summary of results for 114% wt% 1% Xantham Gum

Frequency sweep	• G' decreases from ≈ 2×10^{-2} Pa at 0.4 rad s^{-1} to ≈ 7×10^{-3} Pa at 40 rad s^{-1} (≈ 0.45-decade drop per decade ω). • $G'' \approx 4 \times 10^{-3}$ Pa → 2×10^{-3} Pa over the same range. • Crossover $G' = G''$ is around 15 rad s^{-1}.
Herschel-Bulkley fit	• Yield stress $\tau_0 = 282$ Pa • Consistency index K = 9.1 Pa·s^n • Flow index n = 0.68

Table 7. Summary of results for 120% wt% 1% Xantham Gum

Frequency sweep	• G′ starts ≈ 1.3×10^{-1} Pa at 0.4 rad s^{-1}, falling to ≈ 3×10^{-2} Pa at 40 rad s^{-1} (≈ 0.65-decade drop per decade ω). • G″ traces ≈ 6×10^{-2} Pa → 1×10^{-2} Pa. • G″ surpasses G′ throughout entire range; no crossover.
Herschel–Bulkley fit	• Yield stress τ_0 = 334 Pa • Consistency index K = 44.5 Pa·s^n • Flow index n = 0.40

Analysis and Discussions

The water content of 70 for pure buckwheat (W-70) sample at 0.63 rad s^{-1} has a plateau storage modulus of 4.2×10^4 Pa, γ_c of 0.20%, and tan δ of 0.30. The increase in moisture content to 83% (W-83) decreases the value of G′ to 1.1×10^4 Pa and γ_c to 0.005%, while tan δ increases to 0.47.

The incorporation of 75% guar (GG-75) results in the rise of G' to 4.5×10^4 Pa and raises γ_c to 0.30%, with tan δ of 0.25. When the guar concentration is raised to 95% (GG-95), G' is still high at 3.0×10^4 Pa; however, γ_c decreases to 0.05%, while tan δ is found to be 0.28.

In xanthan systems, the 114 %-water ink (XG-114 %) demonstrates significantly lower properties, with G′ approximating 2×10^{-2} Pa and an undetectable γ_c (< 0.05 % strain, beneath the noise level), while tan δ is around 0.20. Conversely, the 120 %-water ink (XG-120 %) exhibits a marginally greater stiffness at 1.3×10^{-1} Pa, yet similarly lacks a distinguishable plateau, with tan δ measuring approximately 0.15.

Herschel–Bulkley fits provide for W-70 a yield stress τ_0 ≈ 900 Pa, consistency index K ≈ 2.4×10^3 Pa·s^n, flow index n ≈ 0.38, and apparent viscosity about 200 Pa·s at 50 s^{-1}.

The W-83 ink is τ_0 ≈ 650 Pa, K ≈ 6.0×10^2 Pa·s^n, n ≈ 0.52, and η_{50} ≈ 30 Pa·s.

Guar at 75 % raises τ_0 considerably to ≈ 2.3 kPa with K ≈ 1.7 × 10^3 Pa·s^n, n ≈ 0.42, η_{50} ≈ 90 Pa·s. At 95 % guar the ink continues to flow at ≈ 2.0 kPa but K rises to ≈ 3.5 × 10^3 Pa·s^n; shear-thickening is obvious as n ≈ 0.65 below 30 s^{-1} then > 1 above; η_{50} ≈ 120 Pa·s. Xanthan inks have considerably smaller stresses: XG-114 % yields at only ≈ 282 Pa with K ≈ 9.1 Pa·s^n, n ≈ 0.68, η_{50} ≈ 6 Pa·s; XG-120 % yields at ≈ 334 Pa but has K ≈ 44.5 Pa·s^n, n ≈ 0.40, η_{50} ≈ 9 Pa·s. In study by Jeon and Min, they reported in their high-quality-printing compositions (A6–A8, olive-oil–water base) G' between 7 165–12 590 Pa and G" between 4 161–8 297 Pa, ranges which were conducive to smooth extrusion and good shape reproduction [3]. These ranges overlap nicely with our desired elastic moduli (3–6 × 10^4 Pa for guar-strengthened buckwheat), emphasizing that a mid-10^4 Pa G' is reliably printable.

Merely increasing water from 70 % to 83 % moisture reduces G′ four-fold and shrinks γ_c forty-fold, showing that water primarily dilutes starch-granule contacts. In the presence of gums, additional water first swells polymer coils but, beyond a point—as in the > 110 %-water xanthan inks—decreases overlap density and collapses the elastic backbone. Thus water and hydrocolloid dosage need to be adjusted.

Low apparent viscosity (η_{50}) in xanthan inks promotes faster wetting but the danger of over-spread; guar inks provide mid-range viscosities with firmer bonding, and W-70 falls between them. Elastic Bond numbers for 5-mm columns computed are ~0.04 for GG-75, 0.07 for GG-95, 0.09 for W-70, 0.30 for W-83, and many orders of magnitude above unity for both xanthan inks—the latter thus fail the 90 % height requirement.

Recent research quantified G′, τ_0, and flow indices for buckwheat doughs containing no gum, 0.5 %–1 % guar, and xanthan; the formulations of all conformed to the Herschel–Bulkley model with n = 0.52–0.87 and τ_0 = 4.8–85.9 Pa [19]. In cookie-dough FDM, τ_0 = 50–73 Pa and $\eta_{10 s^{-1}}$ = 181–230 Pa·s enabled extrusion through 0.5–1 mm smooth nozzles [20]. High-fidelity prints required gels with $G' = 7–12 \times 10^3$ Pa and $\tan \delta < 0.5$ that self-supported strands without slumping [21]

As the formulations of dough, which were partially theoretically chosen as optimal for 3D printing, the testing in Foodini was carried out to prove experimentally. The following images are the results obtained with 83 wt% dough without any additives:

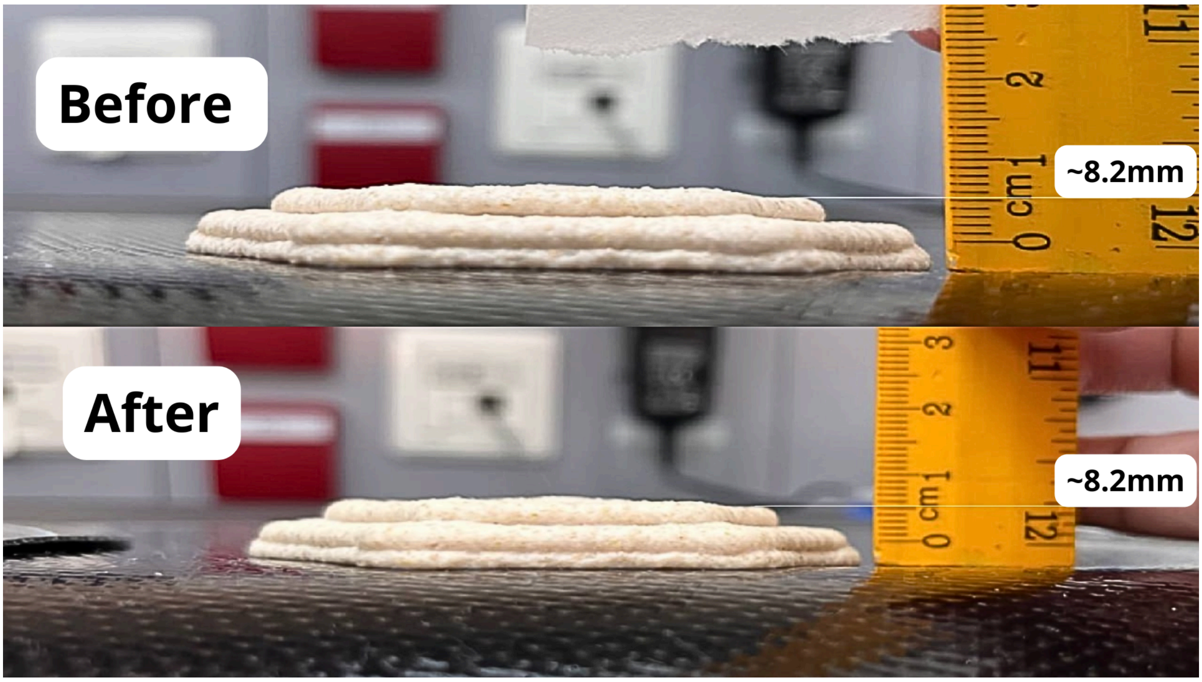

Figure 17. 3D printed result of 83 wt% dough without any additives, freshly printed, and 1 hour after.

All 6 formulations depicted the structural stability of 96% or higher, meeting our expectations and leading to the achievement of the project aim.

Challenges and Limitations

Several challenges were encountered during the study, including the dough slippage during the experiment in the dynamic rheometer and the water evaporation during the 3D printing process. The dough was slipping from the surface of the smooth testing plates, and they were replaced by other plates with a rough surface. Overall, the work with the dynamic rheometer required a very careful approach due to the vulnerability of the accuracy of inner mechanisms, and therefore several lessons and tutorials were learnt before practicing to avoid the risk of breaking the components of the rheometer. As discussed before, the dough is an organic thing, and it was important to conduct many experiments with varying temperatures and resting times, as well as the conditions it and the flour are being stored at, because all tested doughs of one formulation must be the same. During 3D printing, water evaporation was observed at higher temperatures, and the Foodini 3D printer was limited in maintaining consistent filament temperatures. Future studies should focus on the study of the influence of forces and stresses during the dough-making process, like mixing, and explore alternative solutions to avoid water loss during printing at high temperatures.

Role of Rheological Analysis of Buckwheat Dough in Sustainable and Functional Food Development

Effective printing requires knowledge of rheological analysis, and the current clean-label and eco-friendly, gluten-free trends, and medical care needs require the integration of 3D food printing into making buckwheat products. Examining the rheology of such unusual material will enable us to modify the formulations, advance in 3D printing processes, and widen the range of organic and healthy products for customers.

5 Conclusion

The research evaluated buckwheat dough rheology that included studies of different water concentrations and hydrocolloid combinations (guar and xanthan gums) in order to optimize printed food output from an extruder. A successful identification of optimal formulation zones by applyingideoscopic and steady shear tests following Herschel–Bulkley modeling together with Foodini printer print trials for balancing device performance with structural integrity and environmental sustainability was achieved.

The study established water content as the primary factor which influenced dough rheological behavior. Adding more solution water from 70% to 83% rendered the dough stiff with diminution of the storage modulus to 1.1×10^4 Pa from 4.2×10^4 Pa and yield strain dropped from 0.20% to 0.005%. This shows water reduced intergranular bond strength. The over-hydrated formulations (114–120%) that contained xanthan gum demonstrated extremely low stiffness values ($G' < 1$ Pa), negligible yield strain and were incapable of retaining any shape due to the dilution failure of polymer networks.

The addition of guar gum at concentrations between 75 to 95% improved both dough elasticity and strength properties. The rheological properties of GG-75 included a G′ value of 4.5×10^4 Pa together with yield stress at 2.3 kPa which guaranteed shape integrity during and after printing. The greater viscosity of GG-95 exhibited shear-thickening properties even though it required caution in high flow rate settings because it still fulfilled printing requirements. The Elastic Bond measurements on guar-enriched doughs came out at less than 0.1 which confirmed their capability to sustain vertical alignment without collapsing.

The Herschel–Bulkley model adequately described the flow behavior of all dough samples including original and gum-enriched dough batches through their spanning flow indices of 0.38 to 0.68 and their corresponding apparent viscosities that ranged between 6–200 Pa·s at 50 s^{-1}. The rheological measurements demonstrated equivalent results to printable doughs and gels documented in published studies thus validating our dough development.

During the printing process several technological issues emerged because dough slipped off the plates while being measured and the machine evaporated water as it printed. The researcher addressed the initial issue through plate surface modifications and further development of methods to confront the second problem is needed particularly when printing items with thermal sensitivities or lengthy durations. The evaluation of rheological evolution requires future research to study mechanical processing forces that affect mixing intensity levels. New printing moisture retention techniques need investigation because researchers should test both humidified chambers and encapsulated printing environments. A continued investigation involving multicomponent doughs with fiber, protein and oil addition should analyze how their presence affects rheological changes. An investigation of printed structure longevity under different storage and cooking environments must be conducted to determine their durability.

This study adds knowledge to clean-label gluten-free sustainable food technologies while benefiting contexts that require medical nutrition for aging populations with individual dietary needs. The study establishes fundamental knowledge about buckwheat dough rheology to develop flexible and visually pleasing natural-food products that can be printed through three-dimensional processes.

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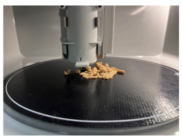
Appendix

1. Experimental results from the Fall semester, printing with varying temperature and water content.

Buckwheat-to-Water Ratio	*Gum percentage(%)*	*Temperature(°C)*	*Outcome*	*Observation*
1:1	*0*	*25*		*bad*
2:1	*0*	*25*		*not good*

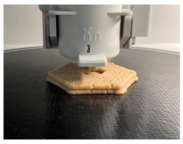
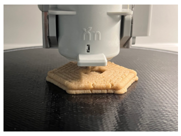
2.5:1	0	25		good
3:1	0	25		good
4:1	0	25		average
2:1	1 GG	25		not good
3:1	1 GG	25		average
3.5:1	1 XG	25		good

Table 3. *The printing results at 55°C*

Buckwheat-to-Water Ratio	Gum percentage(%)	Temperature(°C)	Outcome	Observation
2.5:1	1	55		not good
3:1	1	55		average
3.33:1	1	55		good

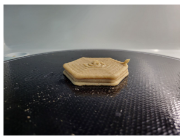
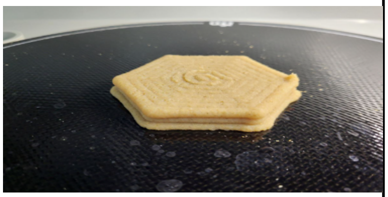
3.33:1	*10 XG*	*55*		*good*
3.67:1	*1 XG*	*55*		*not good*

Table 4. *The printing results at 85°C*

Buckwheat-to-Water Ratio	*Gum percentage(%)*	*Temperature(°C)*	*Outcome*	*Observation*
2:1	*1 XG*	*85*		*average*
2.33:1	*1 XG*	*85*		*good*
2.5:1	*1 XG*	*85*		*average*
3:1	*1 XG*	*85*		*average*
3.33:1	*1 XG*	*85*		*not good*
3.67:1	*1 XG*	*85*		*not good*
4:1	*1 XG*	*85*		*bad*

Table 1. *The most suitable outcomes of printing with corresponding ratios from semester 1*

25°C	*55°C*	*85°C*
		
2.33:1 to 3.33:1	*2.33:1 to 3.33:1*	*2.67 to 3:1*

2. Capillary rheometer results from Fall semester

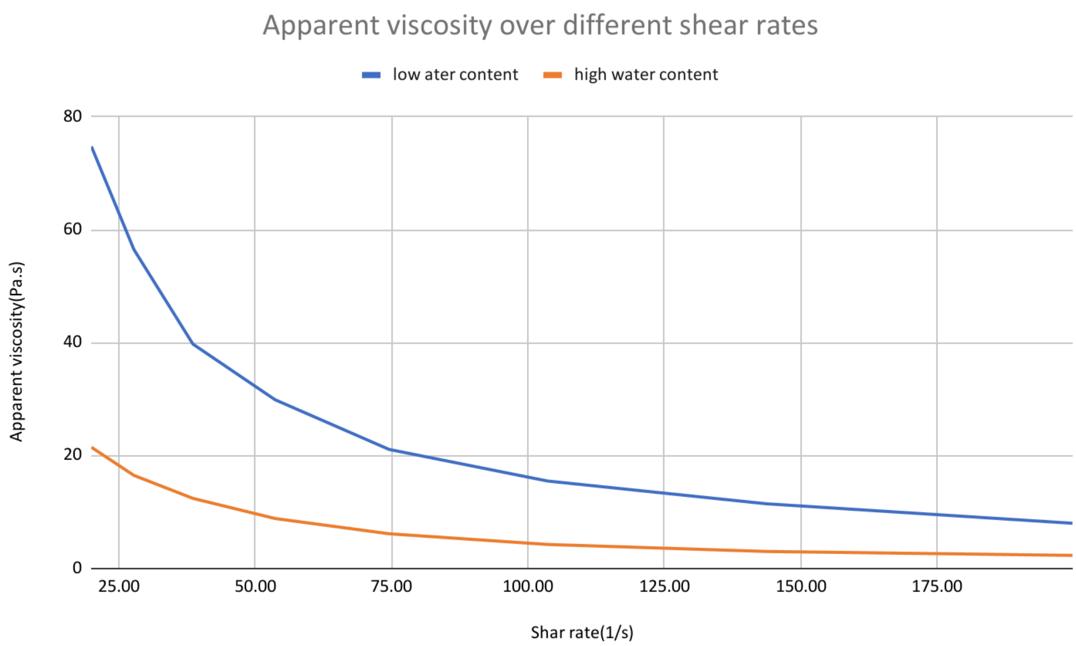


Figure 1. *Apparent viscosity over shear rate giving printability*

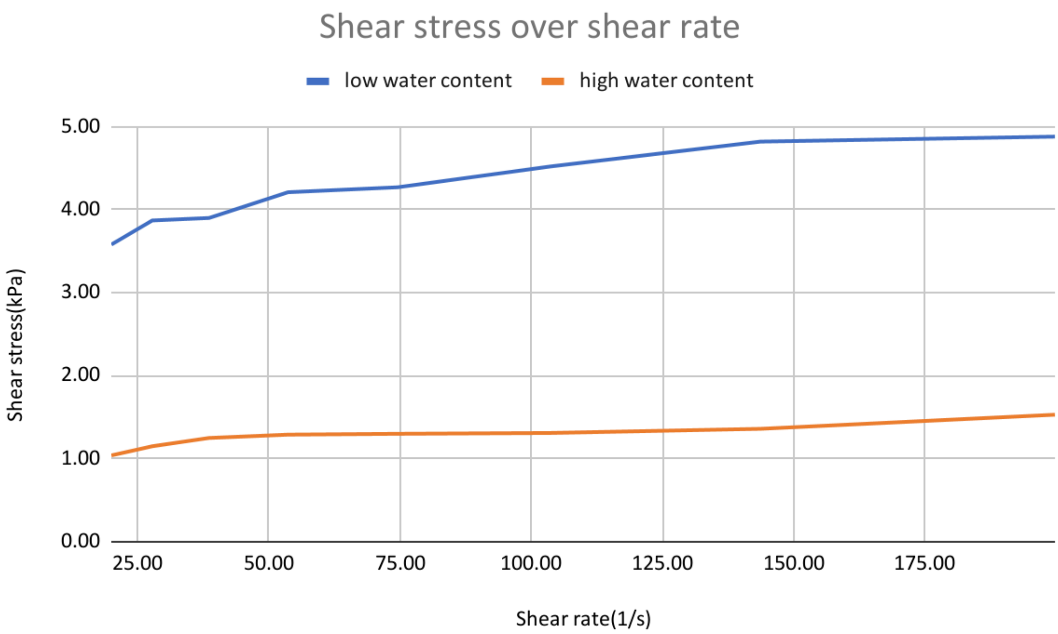


Figure 2. *The dependance of shear stress over a shear rate*

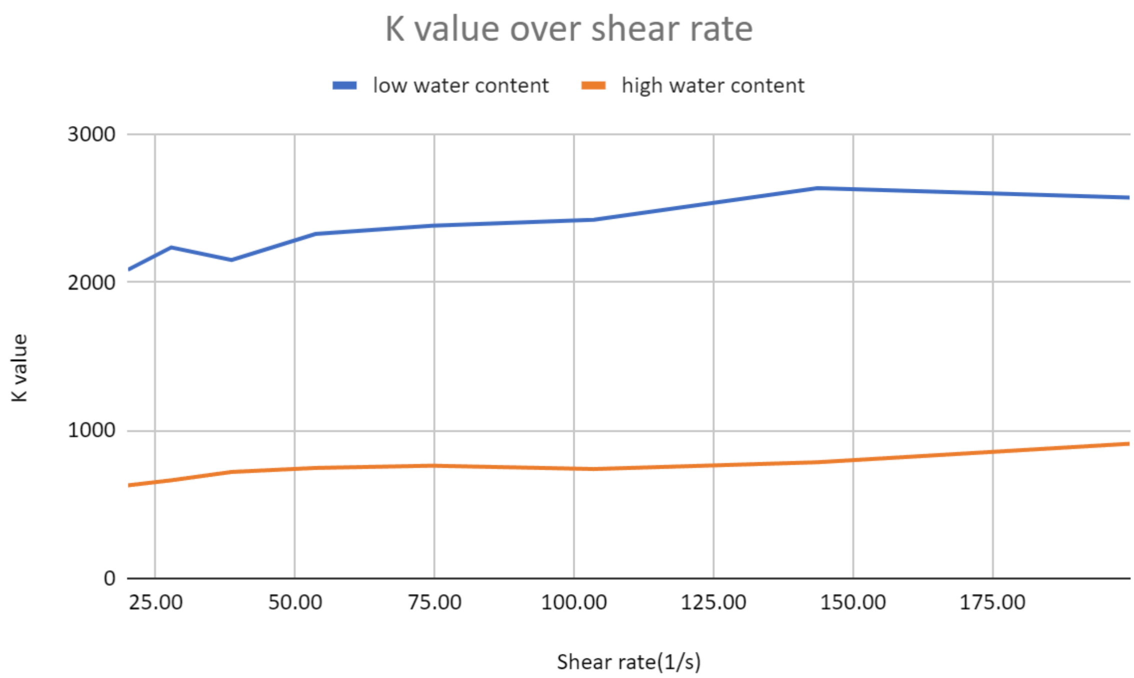


Figure 3. *K value over shear rate*