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DEVELOPMENT OF A PROCESS TO CONVERT PAPER TOWEL FIBRE WASTE DESTINED FOR LANDFILL INTO VIABLE CONSTRUCTION MATERIALS.

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Abstract

This thesis covers the continued development of a Precycle NZ product made from paper towel waste fibre. The initial product by Precycle NZ was a rigid board made from paper towels destined for landfill, with the idea of using it as a building product. This Master's project covered the development of this board, which included the literature review where manufacturing methods, similar products, and standards and certifications like the Building Code were researched. Development was done on the manufacturing methods outlined by Precycle NZ through fine-tuning, optimising, and trialling adhesives from the literature. This development resulted in various panels, such as starch glue panels, casein panels, and regular panels of different sizes, before filtering some out based on structural failings internally, while others continued for testing.

The tests included measuring the moisture content and observing the mould growth under different humidity, which was important to the Building Code's internal moisture requirements, its insulative properties, which was vital as it had the potential to be used as an insulative panel, and mechanical properties where the compressive strength, bending strength, and impact resistance were tested, as structure and durability were outlined in the Building Code.

The testing found that the tapioca starch glue–pulp panel was the best overall compared to the other manufactured pulp panels. However, this was not durable enough to justify using this as a structural panel compared to industry standards. It was found to have good insulative properties, though insufficient to replace industry insulation products or meet roof insulation requirements, and comparable mould growth to wood products like MDF. The panel should be considered non-load-bearing for future development and placement but can be paired with a load-bearing material. It can provide insulative properties as part of a prefabricated wall system and be converted into alternative uses like furniture or some other use case.

Future development should cover other tests that still need to be performed, such as acoustic testing and breathability, to determine airflow. This will also involve scaling to larger panels by determining their cost-effectiveness and researching new manufacturing methods before scaling to a pilot plant.

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1.0 Introduction

Paper towels are a helpful product for mopping up spills, drying hands, and covering food, and are primarily sent to landfills. This is an untapped fibre resource that can be reused for other purposes.

This Master's project aims to continue the development of a Precycle NZ product involving reusing the paper towels destined for landfills as a fibre source for building material. This will reduce waste by providing an alternate use case for the paper towels. Also, the construction and demolition industry use many unsustainable materials that are landfilled at the end of their lives. A building material made from waste fibre and sustainable materials will allow the product to have better end-of-life options.

At the start of this project, the paper towels were reused by being pressed into a panel-like structure by Precycle NZ to place this somewhere in the building industry as a construction material.

The project involves further developing their panel at bench scale by improving the formulation, optimising processes, and identifying potential use cases. The formulation will be improved by researching and implementing adhesives and other additives to improve performance. The regular panels (no additives) and additive panels will be tested against each other and existing products using standards outlined by research into the Building Code and similar products in New Zealand and overseas. Research into fibres and composites will also be done to see manufacturing methods and gain a greater understanding of the process that will be implemented into the panel. Understanding the manufacturing process of paper towels and their disposal methods are also of interest as that is the primary feedstock used.

The manufacturing methods section will discuss the process for making the panels and outline their development, such as how glues were added, improvements to the manufacturing phases, moulds, and mixtures.

The testing methods section will review how each test was performed and the standard each test will follow. Results will discuss the performance of the various panels and compare these to tested industry products for comparison. A use case for the panels will be justified from this data and outlined in the future development section. The future development section will also discuss how the panel will be further improved following this Master's, such as scaling up. The Appendix section will show the complete raw data in table form for each test performed and extraneous information to the main talking points discussed in this thesis.

Therefore, this thesis aims to research, develop, and test the fibre insulation panels from the initial benchtop concept to a viable panel that meets the specifications outlined by the building code and relevant standards. Key research questions and objectives that aim to be answered in this thesis include:

- What manufacturing methods and binders are used for similar products in the industry that could be incorporated into the panel-making process?
- What certifications and standards need to be met to be viable for New Zealand homes?
- What tests must be done to meet these certifications and standards, and how will they be performed?
- What can be done to improve these panels further after the scope of this research is finished?

2.0 Literature Review

The literature review will cover the scale of paper towel waste in New Zealand to gauge the market potential and show its abundance. General background information on the manufacturing process of paper towels will also be investigated to understand better the material being worked with and its composition. As the intention is to place this panel in the New Zealand building industry, the New Zealand building code and relevant standards should also be researched and applied to the testing done on the panels to determine their viability. Other areas of research include the background on fibre and composite materials to see their manufacturing processes and use, similar products used to assess competitor products and gain ideas for where to place the product, and finally, research into binders and adhesives to bond with the panels to improve its properties.

2.1 Paper towels as a non-recyclable fibre waste stream

Paper towels are used for many applications from cleaning up spillages, holding foods as an alternative to plates, drying hands, and cleaning surfaces. Essity, a significant supplier of tissue and hygiene equipment, comprises branches such as Handee, Sorbent, Purex, and Tork, which sell toilet tissue and paper towel products (Essity, n.d.). To provide an insight into the potential feedstock of paper towels, Essity's Kawerau branch provided through personal communication that they manufacture an estimated 10,000 tonnes/year of paper towels to be sold in both New Zealand and Australia (Shepherd & Sherman, 2022). An estimated $271,130 USD of paper towels and other sanitary products were imported from Singapore and sold in NZ (Trading Economics, 2023).

In Essity's Environmental Product Declaration (EPD), they identify waste quantities from their products in the Australasian region. In 1000 kg of Tork Xpress® Multifold Hand Towel / Slimline H2 Advanced (one of their products) plus 27 kg of packaging, there is a global warming potential (GWP) total of 2,910 kg CO_2e (equivalent) from transport and landfill, and 1,470 kg CO_2e from transport and compost (Asaleo Care, 2019). This shows that a significant portion of waste material ends up in landfills that could be put to other use.

Essity has a system in other countries to recycle these paper towels, called the Tork PaperCircle® (Essity, 2021). The Tork PaperCircle® process involves having a separate bin in washrooms for paper towels set up with signs to notify the user before taking the paper towels and repurposing these into new paper towels or other tissue products. This system is not in use in New Zealand due to Essity's lack of deinking equipment to separate out usable fibres from waste in recycled paper towels. Also, the population density around the paper mills is insufficient to warrant investment in the equipment (Shepherd & Sherman, 2022).

Composting paper towels also has some issues that prevent it from being used to give paper towels viable end-of-life at scale in New Zealand. A lack of kerbside green waste collection services in New Zealand means the infrastructure needs to be improved to manage all the waste. While some regions, such as Auckland (Waste Management, 2021) and South Taranaki (South Taranaki District Council, 2023), do have green waste collections, others, such as Wellington (Wellington City Council, n.d.) and Palmerston North (Palmerston North

City Council, 2023) rely on residents home composting or dropping off their green waste at landfills. Another issue with composting paper towels is that as they break down into natural wood pulp, contaminants from cleaning, such as greases, oils, fats, and other chemicals, can destroy the compost by forcing oxygen out, creating an environment great for anaerobic bacteria (INSINC Products Ltd, 2022). Table 1 shows the emissions from landfills vs composting.

Table 1: Comparisons between biogenic carbon emissions of paper from landfill vs. composting (Asaleo Care, 2019).

Landfill emissions (per kg of carbon converted to landfill gas)	**Composting emissions**
28.8% CH_4 (methane) 71.2% CO_2	9 kg CH_4 released per tonne of paper Rest as CO_2

2.2 Manufacturing process of paper towels

The manufacturing of paper towels involves many stages before reaching the finished product. Paper towels and paper follow similar manufacturing steps, except with a few additives including a wet strength agent.

The first stage is processing the wood into cellulose fibres, which are used for paper. This is done by operations such as debarking, chipping, screening and storing (Bajpai, 2017). Uniform chip sizes of approximately 10 – 30 mm in length and 2 – 5 mm in thickness are taken to be used in the following stages, while oversized chips are sent to be rechipped. In Kraft pulping, the chips are mixed into sodium hydroxide and sodium sulphide solution to break down the lignin, leaving behind the cellulose fibre for pulp. Kraft pulp can be made from either softwood or hardwood fibres (Paper Excellence, n.d.). Other pulping methods, such as CTMP (chemi-thermomechancial pulp), involve mechanical operations such as washing, preheating, refining under temperature and pressure, and impregnating the wood chips with alkaline chemicals such as sodium sulphide or alkaline peroxide (Bajpai, 2017). If recycled paper is to be used in the process, the paper must be rewetted and repulped. If contaminants such as ink or adhesives are mixed in with recycled paper, chemical deinking and mechanical separation processes are required to process this.

Bleaching is another process that chemically increases the brightness, softness, and absorption of the pulp for applications in writing, printing, and tissue paper (Bajpai, 2017). Unbleached pulp is usually used for cardboard and other similar products. Chemicals used for bleaching in paper making include:

- oxygen
- ozone
- chlorine dioxide
- sodium hydroxide
- hydrogen peroxide

A tour was undertaken at Essity's Kawerau site, where they manufacture their tissue and paper towel products, to understand the paper-making process better. During the visit, (Shepherd & Sherman, 2022) discussed the paper towel production process and gave details on its manufacture.

Kymene, a wet strength agent, is mixed in at the start of the process to attach to fibres (Shepherd & Sherman, 2022). Wet strength agents improve the wet strength properties of paper towels, which is vital as they are often used to mop up liquids. Kymene is a water-soluble additive made from polyamide-epichlorohydrin (PAE) resin (Solenis, 2022). Once the additive cures, the Kymene creates a cross-linked structure with the cellulose, forming a covalent bond with the cellulose fibre, giving it wet-strength properties.

The general process for paper making is as follows:

Kraft or CTMP pulp is mixed into the headbox at a ratio of approximately 99.7% water and 0.3% pulp through a 12 mm gap to sieve pulp (Shepherd & Sherman, 2022). Kraft pulp is made from Softwood pine with a thick fibre size of 3 x 0.03 mm and Hardwood (Eucalypt) with a thin fibre size of 1 x 0.015 mm. Lignin is an organic polymer that holds cellulose fibres together (Gas IR Paper Drying Technologies, 2015). Kraft pulp has its lignin removed. CTMP is made by softening and mechanically separating the fibres. Lignin is not removed from this, so the pulp turns yellow in the sunlight. After mixing into the headbox, water is drained through the fourdrinier (Gas IR Paper Drying Technologies, 2015). The fourdrinier comprises a wet, dry, and calendar section. The wet section consists of a conveyor belt for the pulp with rollers and drains for removing water content. After drainage, the pulp is dried through a yankee dryer, an 18 – 25 ft diameter rotating press with hot air for drying (Gas IR Paper Drying Technologies, 2015; Shepherd & Sherman, 2022). A creping blade is used at a set angle to separate the pulp from the yankee dryer (Shepherd & Sherman, 2022). The calendar section is the final fourdrinier step and has metal rollers to compress the paper to a uniform thickness (Gas IR Paper Drying Technologies, 2015). Patterns are also pressed onto the paper in this step if required. Finally, the paper is then wound onto a reel. The entire process is shown in Figure 1.

This is similar to the process for paper towels, except for a few variations. The force applied when being compressed is decreased to create paper towels with a softer texture than paper (Lacoma, 2017). Two layers of this soft paper are then bonded and embossed to create air pockets that allow the paper towels to absorb water better. Bonding two layers together forms a single sheet – a one-ply, while a two-ply paper towel involves bonding two sheets together. Paper towels are made primarily from softwood fibres, these are longer and more robust than hardwood fibres and gives the paper towel the required strength and provides good absorbency (de Assis et al., 2018; Kumar Jain, Dutt, & Jain, 2022).

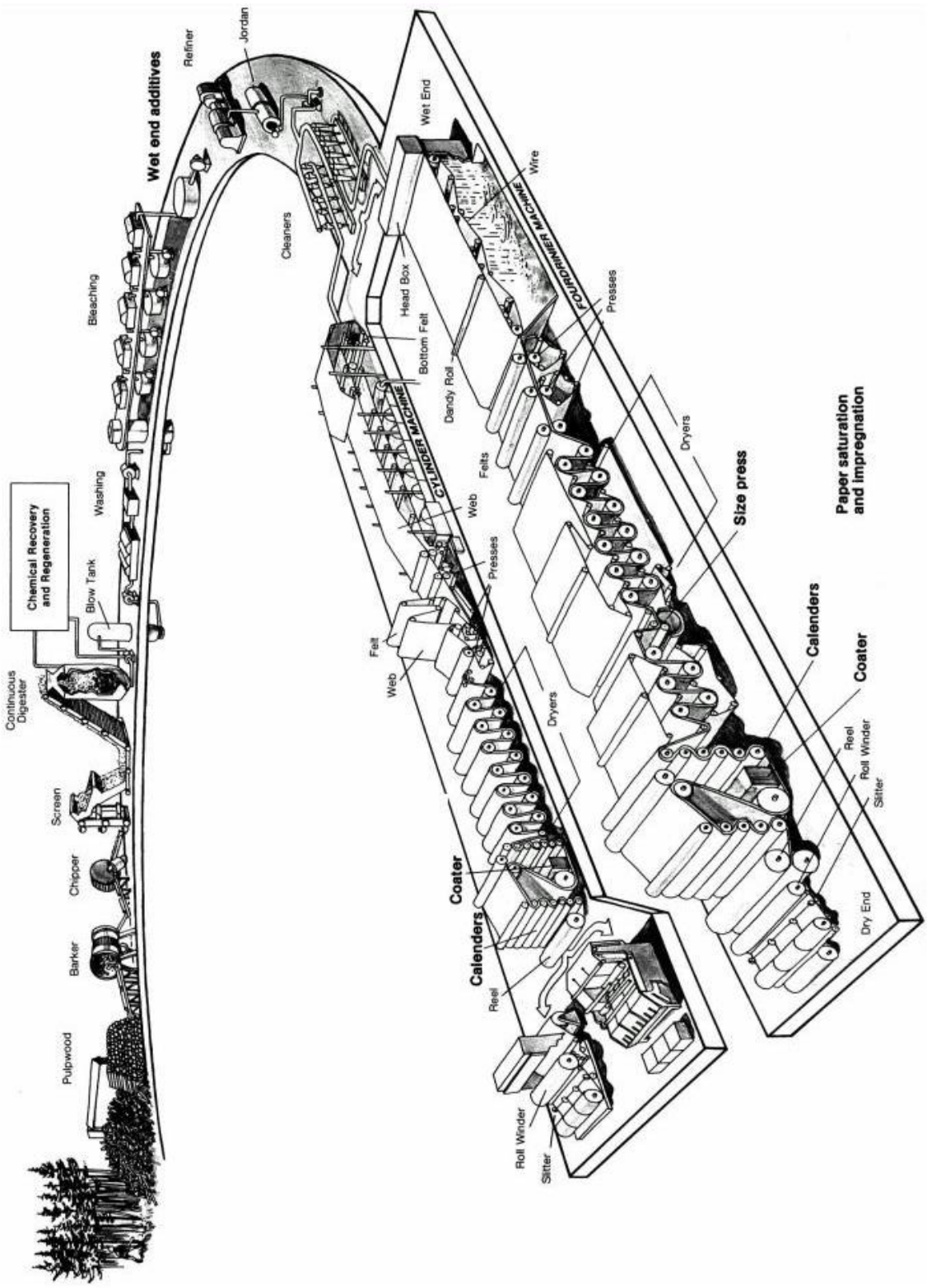

Figure 1: Paper manufacturing process (Gas IR Paper Drying Technologies, 2015).

2.3 Fibres and Composites

2.3.1 Fibre Usage and Disposal

Fibres can be used to improve materials' physical and mechanical properties (Mohajerani et al., 2019). A diverse range of natural and synthetic fibres are available, each with associated advantages, disadvantages, and environmental impacts.

There is an extensive range of natural fibres, such as soft and hard wood fibres, cereal straw fibres, and leaf fibres (Mohajerani et al., 2019). Natural fibres are relatively low-cost and have good thermal insulation, adhesion, and biodegradability properties. Bast fibre types like flax and hemp have high tensile strength properties. Palm fibres have high water absorption properties but low tensile strength. Coir fibres are extracted from coconut and have high strength, fire resistance, and fungi growth resistance. Also, coir fibre breaks down slowly due to the high lignin content. Synthetic fibres such as steel, glass, and plastic are manufactured. The purpose of these fibres is typically as reinforcements to improve the structure of materials. Fibres are disposed of by either recycling or repurposing them for other uses (such as reusing steel or rubber and extracting the fibre or using it in concrete) or sent to landfill which is the most common end of life outcome. There is ongoing research into sustainable alternatives to synthetic-based composites by replacing them with natural fibres in applications such as biopolymers and textiles (Kurien, Maria Anil, Sharan Mohan, & Anna Thomas, 2023). Other uses include automotive linings, construction materials, furniture, and packaging (Thyavihalli Girijappa, Mavinkere Rangappa, Parameswaranpillai, & Siengchin, 2019) (Peças, Carvalho, Salman, & Leite, 2018). According to (Bartl, Hackl, Mihalyi, Wistuba, & Marini, 2005), fibres may be recycled and used in asphalt mixtures or other concrete reinforcements. The pavement asphalt mixture contains fibre additives such as Arbocel ground cellulose, which increases the mixture's temperature resistance and load capacity. The fibres from waste tyres may be used as an alternative.

Some examples of New Zealand fibres include KiwiFibre, which utilises Harakeke fibres (KiwiFibre, 2023), Hemprino which makes clothing products from hemp and merino wool blends (Hemprino, 2023), and Hemptastic which uses hemp for plastic applications and composites (Hemptastic, 2016).

A table provided by (Mohajerani et al., 2019), compares properties of different fibre types, including cellulose, bast, hemp, hair, wood, leaf, and more. Of the natural fibres, the one with the highest tensile strength was hemp fibre, with a tensile strength of 900-1077MPa. The table also shows the properties of cellulose fibres, which will be of great importance to this project. These cellulose fibres include lignocellulose, and lignin fibres. Lignocellulose fibres have a tensile strength of 475 MPa, a length of 0.21 mm, and a melting temperature of 160 °C. Lignin fibre is said to have an average length of 1.1 mm, a diameter of 0.045 mm, and a melting temperature of 200 °C. The tensile strength properties of lignin fibre are not listed in the table.

Other fibres, such as synthetics, have a higher upper limit for tensile strength (Yurtseven, 2004). While there are lower performers like acrylic at a tensile strength of 210-420 MPa,

there are much stronger fibres such as glass at 1050-3850 MPa, carbon at 1800-2600 MPa, and steel at 280-2800 MPa.

2.3.2 Composites Usage and Disposal

One of the most commonly found composite materials similar to the panels is MDF, a wood product used for many applications, including buildings and furniture. A general outline of the manufacturing process of MDF is as follows (United States Environmental Protection Agency, 2002): preparing wood by debarking, chipping, and washing, mechanical pulping, multiple stages of drying, blending with resins such as urea-formaldehyde and other additives (sometimes other resins are blended like phenolic, melamine, and isocyanates), hot pressing, and finally, cutting to its final dimension specifications.

A common method overseas for disposing of composite materials, such as carbon fibre from wind turbine blades, involves pyrolysis to recover the fibre source for reuse (Mason, 2021). Other more sustainable methods that reduce the costs, regain more of the original fibre, or lower the carbon footprint are being investigated. One such method in the Netherlands is to recycle thermoset composites by shredding the composite parts with a waterjet before running through a specialised pultrusion process. The traditional pultrusion process involves pulling the fibres through a resin bath before into a die to be moulded. This specialised pultrusion method adds another step at the entrance of the die. The reused composite flakes from the shredding are extruded into the hollow centre of the part. This results in a virgin outer shell to make up the shape of the part, with the insides being composed of reused composite material. The carbon footprint is lower by reusing composite material in the part as opposed to all virgin material.

2.4 New Zealand Certifications and Standards

This section will cover relevant New Zealand Building Code sections to outline what key requirements are needed for building materials. Relevant standards will also be discussed to provide guidance for testing panels to determine viability and performance.

2.4.1 New Zealand Building Code Requirements

Potential use cases of the materials made from waste fibre as either panelling or an insulative product mean they likely need to be fire-safe, durable, and perform to insulation requirements, so these will be looked into in the building code.

Manufacturer or Supplier Requirements

Sections from the Building Regulations 1992 (Parliamentary Counsel Office, 2021b) discuss building material requirements in New Zealand. Relevant sections of importance to this project are the product manufacturer or supplier responsibilities outlined in the Building Act 2004 (Parliamentary Counsel Office, 2021a) section 14G. If installed to specification, this section says products should comply with relevant sections of the building code. Also, building products should be supplied with product information and requirements covering installation, warnings, contact, etc.

Structure and Durability Requirements

The Building Regulations 1992 (Parliamentary Counsel Office, 2021b), section B1, says that building materials should withstand loads they are likely to undergo throughout their lifetime without failure. Section B2.3.1 covers the durability of the building materials across their lifespan. The durability of walls or flooring is dependent on the intended lifespan of the building. This means that if the building is intended for a lifespan greater than 50 years, the building materials must comply with the building code for its intended lifespan if they are structural, hidden, hard to access, or hard to maintain. This requirement is not as strict for 15-year or 5-year buildings as they only must last the building's lifespan if they are moderately difficult to maintain and see or easy to maintain and see, respectively.

Mechanical tests (found in the standards shown below in 2.4.3) can be performed on the panels to gauge how durable they are and how they perform against destructive tests.

Moisture Requirements

The Building Regulations 1992 (Parliamentary Counsel Office, 2021b) discusses moisture requirements for buildings. Section E3 addresses internal moisture requirements. Fungal growth must be prevented, and areas with a high potential for moisture to develop should provide adequate thermal resistance and proper ventilation. Floor and wall surfaces must not allow water to pass through and be capable of being cleaned with ease.

The behaviour and performance of the panels produced in this project could be assessed through a series of experiments by exposing them to different moisture levels in a controlled manner.

Insulation Requirements

A table provided by (South Peak Homes, 2022), identifies the requirements for different parts of the household for the six climate zones in New Zealand following H1 of the Building Code. The reproduced table of R-values is shown below:

Table 2: R-value requirements for building elements in New Zealand climate zones - table remade from (South Peak Homes, 2022).

Building element	Climate Zone 1	Climate Zone 2	Climate Zone 3	Climate Zone 4	Climate Zone 5	Climate Zone 6
Roof	R6.6	R6.6	R6.6	R6.6	R6.6	R6.6
Wall	R2.0	R2.0	R2.0	R2.0	R2.0	R2.0
Floor (Slab-on ground flooring)	R1.5	R1.5	R1.5	R1.5	R1.6	R1.7
All other Flooring	R2.5	R2.5	R2.5	R2.8	R3.0	R3.0
Windows and Doors	R0.46	R0.46	R0.46	R0.46	R0.50	R0.50
Skylights	R0.46	R0.46	R0.54	R0.54	R0.62	R0.62

The climate zones of New Zealand are shown in figure 2 from (South Peak Homes, 2022).

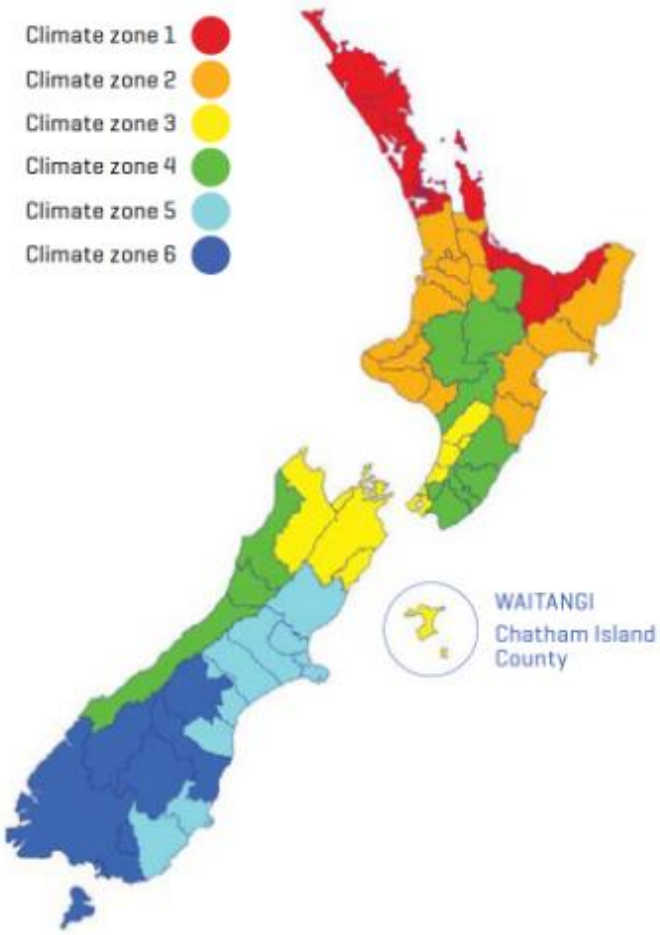

Figure 2: Climate zones obtained from (South Peak Homes, 2022).

This shows that the South Island has slightly higher requirements due to its colder climate. These R-values will be compared against in the testing to determine how the panels perform.

Fire Prevention Requirements

Building Regulations 1992 (Parliamentary Counsel Office, 2021b) section C2 discusses the requirements around the prevention of fire occurring. An important performance requirement for building products is that combustible building materials must not have a maximum surface temperature greater than 90°C when subject to controlled combustion.

Building Regulations 1992 (Parliamentary Counsel Office, 2021b) section C3.4 identifies fire safety criteria for internal surface linings such as walls and ceilings and the criteria for flooring. This is shown in Tables 3 and 4 from (Department of Building and Housing, 2012) below.

Table 3: Internal wall and ceiling surface material fire requirements – table remade from (Department of Building and Housing, 2012).

Area of the building	**Performance determined under conditions in ISO 9705: 1993**	
	No automatic fire sprinkler system	**Automatic fire sprinkler system**
Wall/ceiling materials in sleeping areas with care or detention	Material Group Number (MGN) 1-S	MGN 1 OR 2
Wall/ceiling materials in exits	MGN 1-S	MGN 1 OR 2
Wall/ceiling materials in occupied areas in importance level 4 buildings	MGN 1-S	MGN 1 OR 2
Internal surfaces of ducts for HVAC systems	MGN 1-S	MGN 1 OR 2
Ceiling materials in crowd and sleeping units except household units, care, or detention areas	MGN 1-S OR 2-S	MGN 1 OR 2
Wall materials in crowd and sleeping units except household units, care, or detention areas	MGN 1-S OR 2-S	MGN 1,2, OR 3
Wall/ceiling materials in occupied spaces in all other areas in buildings and household units	MGN 1,2, OR 3	MGN 1,2, OR 3
External surfaces of ducts for HVAC systems	MGN 1,2, OR 3	MGN 1,2, OR 3
Acoustic treatment and pipe insulation within airhandling plenums in sleeping uses	MGN 1,2, OR 3	MGN 1,2, OR 3

Table 4: Floor surface material fire requirements – table remade from (Department of Building and Housing, 2012).

Area of building	**Minimum critical radiant flux when tested to ISO 9239-1: 2010**	
	No automatic fire sprinkler system	**Automatic fire sprinkler system**
Sleeping areas and exits in buildings with care or detention	4.5 kW/m^2	2.2 kW/m^2
Exit ways in all other buildings	2.2 kW/m^2	2.2 kW/m^2
Firecells accommodating more than 50 people	2.2 kW/m^2	1.2 kW/m^2
All other occupied spaces except household units	1.2 kW/m^2	1.2 kW/m^2

The Material Group Number in Table 3 refers to the combustibility of the material. Group Number 1 has the lowest combustibility, and Group Number 4 has the highest (Goode, 2015). The "S" refers to the criteria that the smoke growth rate index does not exceed 100 (Building Performance, 2015). The methods for determining the Material Group Number is done by either an ISO 9705 full-scale room corner fire test or an ISO 5660 bench fire cone calorimeter test (Building Performance, 2015).

In Table 4, the critical radiant flux refers to the minimum radiant energy for a fire to sustain its spread across the floor (Armstrong Flooring, 2019). This is tested by measuring the distance the floor burns until extinguishment and is converted into W/cm^2. A higher W/cm^2 value occurs for a more flame-resistant floor and vice versa.

Due to the scale of equipment required for fire related testing, this will not be performed at this stage of development. These tests will have to be outsourced, so it makes more sense practically and economically to wait until the later stages of product development and certification.

2.4.2 BRANZ Certification

BRANZ CodeMark certification (BRANZ, 2022b) lets people know that a certified product meets the New Zealand Building Code or Building Code of Australia requirements.

CodeMark certifications are most beneficial to new and/or innovative products and products that are potentially hazardous under failure. The CodeMark certification provides registration for compliant products and enables them to use the CodeMark brand for advertising purposes to increase marketability.

According to (Building Performance, 2016a), the NZ CodeMark scheme was derived from the Building Act 2004 and the Building (Product Certification) Regulations 2008. The CodeMark certification requires evidence and technical information regarding the product's compliance with the Building Code and annual inspections and audits.

To apply for CodeMark, specific requirements need to be met. These include details about the product, such as its name, technical literature, specifications, the product uses, the quality control plan, and the Building clauses being met (BRANZ, 2022c).

Other BRANZ-related schemes include appraisals, which are more technical opinions based on performance that can be used for partial evidence of compliance, though not for legal standing (Building Performance, 2016b), and testing reports. These are way more common than full CodeMark certification, as shown by the number of products on their website (BRANZ, 2023) listed under these alternate methods. It is worth noting that the first CodeMark listed was in 2019, so it is a relatively new scheme compared to other methods, which were 2005 for the first Appraisal and 2011 for the first testing report, respectively. CodeMark had merely 18 listings, whereas Appraisals had 507, and testing reports had 407. Products like GIB opted to do testing reports on their products, as shown when filtering under Winstone Wallboards Ltd.

A phone conversation with BRANZ indicated tests that may be of interest for the panels. (BRANZ, 2022a) supported the requirements found in the New Zealand Building Code and identified other tests that could be valuable, such as R-value for insulation, impact resistance, P21 bracing primarily for earthquakes, and moisture resistance.

BRANZ testing for fire resistance and other requirements is done at their Judgeford site near Wellington (Reed, 2018). The standards that are tested here include material reaction to fire (they have both the cone calorimeter test and room corner test for finding the rate of heat

released and smoke generation rate) and accelerated ageing and exposure tests (moisture, ultraviolent, high temperatures, chemicals, and others).

2.4.3 Testing and Standards

As there is no direct “paper towel panel” standard due to this being a novel product, the standards that testing will be based on will loosely follow testing methods for wood and other panel-based products. To indicate structure and durability performance to act in accordance with the Building Regulations 1992 (Parliamentary Counsel Office, 2021b) sections B1 and B2, various mechanical testing standards were researched to provide a combination of load types to the panels and comparative building products. These include compressive strength testing, three-point bending test, tensile strength, and impact resistance. These tests cover forces the panels might undergo when placed in different applications, such as walking on the panel, bracing the panel, or throwing hard objects at the panel.

The key mechanical tests performed on wood to determine its strength properties, which are vital for supporting loads without failure are as follows (University of Minnesota, 2018): The tests include compressive tests on faces perpendicular and parallel to the grain to test the load the beam can carry, static bending tests, shear tests for both perpendicular and parallel to the grain, impact resistance to measure shock absorption, and hardness testing.

According to (Page, 2008), common building materials found from a BRANZ survey of interest include timber, fibreglass insulation, plasterboard, and particleboard. This will provide a basis for some existing materials to test against. Common insulation materials in New Zealand homes include wool, fibreglass, polystyrene, polyester, and paper-based (Ministry Of Business, n.d.).

BRANZ discusses a method for testing the bracing of panels against wind and earthquakes (BRANZ, 2010). This is important for meeting the structural and durability requirements in the building code. As this test involves using a full-scale panel for the test, this is outside the scope of the project, though if the panel performs well at bench scale against mechanical tests, this will be performed in the future scale-up of the panel.

Moisture content and fungal testing are also important in Building Regulations 1992 (Parliamentary Counsel Office, 2021b) section E3, as this should ideally be minimalised within the panels to prevent growth and failure over time. Relevant standards covering how to determine the moisture content of materials were looked into.

As insulation is outlined in the H1 section of the Building Code, a method for testing the insulative properties of the panel was investigated. Massey University provided a method of test to do this, which is discussed in the Methods section.

Looking into the acoustic properties of panels will provide a bonus to existing properties as it is a point discussed by similar products (see section 2.5 of this thesis). This was decided to be worked on for future work as setting up the testing rig required for standards was more extensive than other tests.

A list of read standards are provided below which cover all of these sections:

AS/NZS 4266.1:2017 Reconstituted wood-based panels – Methods of testing Part 1: Base panels

ISO 13061-5 Physical and mechanical properties for wood – Test methods for small clear wood specimens – Part 5: Determination of strength in compression perpendicular to grain

ISO 13061-12 Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 12: Determination of static hardness

ASTM D256-10 (2018) Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics

2.5 Similar Products

Research into similar products in the building industry will provide insight into their properties and usage.

2.5.1 Overseas Products

There are a few boards that are made from sustainable materials currently in the market. Enviroboard is an overseas product made from agricultural waste such as sugarcane, wheat straw, rice straw, and elephant grass (Enviro Board Corporation, 2015). The manufacturing process for their product involves using a patented milling process on their fibre wastes to convert them into boards. Their boards are used in ceilings and walls for insulative and acoustic purposes. Their Strawboard is made by loading a straw bail into a hydraulic press and pressing it into a die (Siemens, 2013). A similar one to this is the Durra Panel for walls and ceilings made using heat, pressure, a natural binding agent from their straw fibre, and coated with recycled Kraft liner paper with water-based PVA (Durra Panel, n.d.).

Other fibre-based building products, such as low-density fibreboard (LDF) (Maines, 2019), are found in Germany. This wood-fibre-based insulation product is made from softwood chips and comes in batt, board, or blown form. The stated benefits of this product are that it is made from renewable feedstock, is water resistant, allows easy vapour diffusion (breathability), and has zero volatile organic compounds (VOCs). Due to its low density, it is referred to as (LDF). This product performs well against and is price-competitive with extruded polystyrene (EPS) insulation. This product is made using either a wet or dry method, and both are described as similar to the MDF manufacturing process. The wet method involves mixing wood chips and shavings with water and binders before compressing and drying. Wastewater extruded from the process can be reused for the next batch of fibreboards. This wet method creates boards ¾ inches thick and can undergo a lamination stage with water-based adhesives to thicken further. The dry method uses a similar process, except the fibres are dried before mixing with polyurethane binders and paraffin wax to improve water-resistant properties. Like the other method, this is then

pressed and dried, though the drying process involves using steam and pressure to cure the binders. While these additives are unsustainable, the process uses 40% less energy than the wet method. The ratios of mixtures are stated in table 5 below:

Table 5: Composition of wood fibre products and their uses according to (Maines, 2019)

Product Type	**Composition**	**Uses**	**Additional information**
Gutex Multitherm (dry-method board)	95% wood fibre, 4% resin binder, 1% paraffin wax	Rigid insulation under flooring, over structural sheathing, exterior insulation, interior insulation in walls and/or roofs	Boards can be fitted to slot together by using tongue-and-groove joints. Variations in thickness for different R-value needs, and levels of paraffin wax for water resistance are possible. Some products can be plastered over when used for internal insulation.
GO Lab (batt)	85% wood fibre, polyester binder, ammonium polyphosphate (flame retardant)	Insulation between framing members	
Blown	Wood fibres, borate (flame retardant)	Loose-blowing for attics, dense-packing	

Hemp is also used as a fibre source for insulative products overseas (Greenfield, 2020). Hemp insulation comprises 92% hemp and almost 8% polyester fibres. The remaining >1% is used for fire retardants and non-toxic binders. This product comes in batt form between 3.5” and 5.5” thick. The hemp insulation is used for replacing fibreglass and foam products. It is used for its insulative, breathability, and water absorption properties. Water absorption means removing condensation from the household without severely affecting the product structure due to water damage.

2.5.2 New Zealand based products

Some examples of similar products found in New Zealand are discussed below.

SaveBOARD is a product composed of 100% upcycled materials (saveBOARD, n.d.). It primarily comprises plastics, wood fibres, and packaging undergoing shredding and compression steps. Their boards are used for ceilings, walls, and other applications.

Ecopanel is a New Zealand company that sells insulated wall systems (Ecopanel, 2022). Their panels are composed of a structural framing filled with insulation like Terra Lana – a New Zealand wool insulation (Terra Lana, n.d.), or Knauf Earthwool – a New Zealand glass wool insulation (Knauf Insulation, 2023a). Exterior layers of the Ecopanel system include a weather-resistant membrane and battens for cladding.

Terra Lana insulation is of interest as well, as it is used for insulation and is manufactured in Christchurch, New Zealand (Terra Lana, 2023). Terra Lana is certified by BRANZ with its Appraisal 682:2010 (Terra Lana, n.d.) and has a 50-year warranty. In addition to its high insulative properties (R-rating range of R1.2 to R3.6), the product has other desirable attributes. It absorbs moisture, has acoustic properties, has insect resistance, and maintains its rated durability for the building's lifetime (50 years).

Woodtex Panels (Woodtex Panels, n.d.-a) are manufactured in Ngaruawahia, New Zealand (Woodtex Panels, n.d.-b) and are made from woodwool, cement following a woodwool standard BS 1105:1981. This product comes in three sizes: 1200 x 600, 1800 x 600, and 2400 x 600 (mm). Other specifications, such as the thickness, average density, and thermal resistance, are shown in Table 6 below.

Table 6: Woodtex Additional Specifications (Woodtex Panels, n.d.-a)

Thickness (mm)	**Average Mass/Area (kg/m^2)**	**Thermal Resistance (R-value) (m^2°K/W)**
25	15	0.31
38	21	0.47
50	26	0.63

The fire testing performed on these products was the *"Applied Physics Laboratory Test Report No 9483 (1994) A.S. 1530 Part 3 1989 Simultaneous Determination of Ignitability, Flame Propagation, Heat and Smoke Release"* (Woodtex Panels, n.d.-a) which involved them blasting the test samples with approximately 600°C from their heating torch for over two minutes to see the ignitability of the panels. They found that while the product was singed, it did not catch fire. Other tests include acoustic testing to determine the sound absorption properties of the material. This was done with the Impedance Tube Method (similar to ASTM E1050-19, though their testing was done on an older standard from 2001). The product is also resistant to fungi and rodents. The product is not, however, resistant to moisture as it is not to be used in permanently wet environments.

Table 7: A list of insulation materials used in New Zealand homes (Ministry Of Business, n.d.-a).

Insulative Material	**Form**	**Usage**
Glass and mineral wool	Blanket, loose fill, segment	Ceilings, walls, under-flooring
Polyester	Blend	Ceilings, walls, under-flooring
Wool	Blanket, loose fill, segment	Ceilings, walls, under-flooring
Polystyrene	Rigid sheet or plank. Also mixed with fire retardant in manufacture.	Under-flooring, walls, ceilings, cladding
Paper-based	Paper or cardboard loose fill. Mixed with fire retardant in manufacture (up to 35% of the insulation mixture.	Ceilings where blanket insulation is hard to install

In Table 7, similar products show that it is worth looking into insulation, durability, fire resistance, and acoustics.

2.5.3 Plasterboards

Manufacturing Process

Plasterboards are a common building material used for internal walls and ceilings. These products help create partitions, wall linings, and provide smooth finishes. Also, they help meet fire, acoustic, moisture, and thermal regulations (Siniat, 2024). Common overseas plasterboards include Siniat and Gyproc.

A New Zealand plasterboard manufacturer is Winstone Wallboards, which manufactures the plasterboard GIB® and has a large product range of different thicknesses and applications. Some of their products include Fyreline (Winstone Wallboards Limited, 2024b), which provides ½ hr to 4 hours of fire protection, or Aqualine (Winstone Wallboards Limited, 2024a), which resists moisture and prevents steam and moisture penetration.

Most plasterboards are primarily composed of gypsum which is sandwiched between two layers of paper. Gypsum occurs naturally and is a mineral composed of calcium sulphate dihydrate with the chemical formula $CaSO_4.2H_20$. Other internal components of gypsum plasterboards include vermiculite, fibreglass and other materials, depending on te manufacturer (Thomas, 2002).

According to (Jiménez Rivero, Sathre, & García Navarro, 2016), following the mining and extraction processes, the gypsum is heated (calcined) to partially dehydrate the compound. Water and additives are added to create a gypsum slurry. Paper is added to both sides of the gypsum slurry by uniformly spreading the mixture on the bottom layer before applying the top. This paper provides the majority of the tensile strength support to the plasterboard. Primarily recycled paper is used for the linings, along with the following additives (Jiménez Rivero et al., 2016):

- Starch,
- Lignin,
- Perlite,
- Vermiculite,
- Soap foam,
- Retarders,
- Accelerators,
- And Shredded Paper.

The mixture rehydrates and solidifies into the hardened final product before post-processing which involves cutting to the required dimensions and drying in a kiln. This process suggests that the additives should be applied in the slurry/pulp stage of the manufacturing process before spreading and drying.

Plasterboard Testing

According to (Erbs et al., 2021), the tests done to determine the properties of plasterboards include axial compressive strength, splitting tensile strength, surface hardness, longitudinal and transversal flexural strength tests, and adhesion resistance. This shows the tests on plasterboards are very similar to those of wood products shown in 2.4.3.

Some Types of Plasterboards and General Pros and Cons

- GIB/Winstone Wallboards
- Elephant Plasterboard
- ProRoc
- USG Corporation/Knauf
- Gyproc
- Georgia Pacific Gypsum

The bulleted list shows some different plasterboard brands for different applications such as internal cladding. Plasterboards also provide good fire resistance due to their non-combustible gypsum and have other favourable properties including water resistance, ease of use, a good finish, durability, and competitive pricing (All Dry USA, 2024; Erbs et al., 2021). An example of their good durability is in ceilings; GIB can support loads up to 3.0 kg/m^2.

Some disadvantages of plasterboards include mould growth and water damage after heavy exposure to moisture, poor durability when installed in areas with curves or where the plasterboards are made to bend, can be dented after impact, and have poor end-of-life outcomes (All Dry USA, 2024).

Other problems in the plasterboard industry are primarily around the market. Winstone Wallboards, the manufacturer of GIB, holds a 95% market share in New Zealand. This resulted in supply issues when demand increased (Mandow, 2022).

2.6 Binders and Adhesives

To improve the properties of the paper towel panels, binders and additives were researched to gain an understanding of existing synthetic and natural adhesives. As adhesives are used in the manufacturing of building products such as MDF, literature was studied to identify common adhesives and their uses.

2.6.1 Formaldehydes and VOCs

An important adhesive consideration is minimising formaldehyde and VOC (volatile organic compound) levels. These gasses can be emitted from chemicals in buildings and can cause potential health concerns (United States Environmental Protection Agency, 2023). VOCs are typically caused by paint thinners, adhesives, cleaning products, and other chemicals. The adhesives that commonly emit VOCs include (Kim, 2009):

- Urea Formaldehyde – Used to glue plywood layers together
- Melamine Formaldehyde – Hot press adhesives
- Other formaldehyde-based adhesives

Adhesives containing formaldehyde or VOCs will be avoided in this project as their use conflicts the aim of producing a sustainable product.

2.6.2 Types of Binders and Adhesives

There are many different types of adhesives found in the construction industry. The different types of adhesive from (Constro Facilitator, 2020) are shown in Table 8 below with their properties. Table 9 identifies other common adhesives (Designing Buildings, 2022).

Table 8: Adhesive Types and their performance (Constro Facilitator, 2020) (LD Davis, 2019) (Adhesive Specialities, 2021) (Besley, 2024a) (Besley, 2024b) (TWI Limited, 2024).

Adhesive Class	Type/Properties	Advantages	Disadvantages	Usage
Polymer Adhesives	Thermoset – cures and can't be remoulded Or Thermoplastic – can be remoulded above threshold temperature.	Strong, flexible, good impact resistance. Many are dispersed into water.	Long cure time, difficult to work with	Automotive, construction, electrical, aviation
Hot Melt Adhesives (HMA)	Thermoplastic	No need for VOCs (volatile organic compounds), no drying or curing required, long shelf life, easily disposable	High temperatures decrease bond strength and can even remelt the adhesive	Hot glue guns

Adhesive Class	Type/Properties	Advantages	Disadvantages	Usage
Acrylic Adhesives	Thermoplastic or Thermoset	High strength, inexpensive, fast cure time	Can shrink due to exothermic reactions, odours	Joins acrylics, structural
Resin Adhesives	Powdered, emulsion (blended), liquid, spray	Prevents bacteria microleakage, improves composite and compomer retention	Not water-resistant	Wood, glass, metal
Anaerobic Adhesives	Dimethacrylate monomer adhesive that cures when there is no air	Doesn't corrode metals. Resistance to weathering, water, organic solvents, temperatures not exceeding 200°C	Requires no air to cure	Structural, metals, glass, and some woods and plastics
Epoxy Adhesives	1-component heat curing or 2-component room temperature curing	High strength, versatile, resists chemicals and environments, resists creep under load	1-component heat curing requires temperatures between 250-300°F	Structural, metals and a large variety of other materials
Pressure Adhesives	Viscous, made from polyacrylates or rubbers such as natural or synthetic	Can be applied easily by hand	Bond failure and bubbles form if pressure applied or temperature is too low, creeps under load, wets surface	Tape, temporary adhesion
Electrically Conductive Adhesives	Composed of 80% conductive particles in a sticky substance. Sticky substance can be 2-component epoxy, acrylate, or polyester. Conductive component is a metal such as	Cure quickly in less than two minutes, conductivity	Long term performance less well known than solder	Instead of solder

	iron, copper, or silver			
Adhesive Class	**Type/Properties**	**Advantages**	**Disadvantages**	**Usage**
Phenolic Resin Adhesives	Produced through the condensation of phenol and formaldehyde.	Cheap. Thermoset type is resistant to high temperatures, creep, and deformation. Good thermal, mechanical and chemically resistant properties.	Requires high heat and pressure	Organic and inorganic reinforcements and fillers. Cellulose filler, boards, plywood
Plastisol Adhesives	A paste of PVC particles mixed with a plasticiser.	Flexible or rigid, good peel resistance, low flammability, cheap		Oiled metals and plastics
Reactive Adhesives	1-component or 2-component	High strength, increases strength quickly		Two surfaces together
Thermoset Adhesives	Crosslinked polymeric resin, cures with heat and/or pressure. 1-component or 2-component resin and hardener	High strength, resistance to moisture and heat	Cannot be reversed due to cross-linking changing the material's structure	Structural
UV Curing Adhesives	Cures under UV in minutes at room temperature	Quick to cure, clear finish	Can be more expensive	Glass, plastics
Water-based Adhesives (including starch and casein glues)	Polymers - natural or soluble synthetic	Low VOCs, consistent	Object being glued must be permeable	Paper and cardboard production, labelling, laminating, wood
Polyurethane Adhesives	1-component or 2-component	Strong, flexible, low odour	Long cure time, requires a clean surface for applying	Woods, metals, polymers

Adhesive Class	Type/Properties	Advantages	Disadvantages	Usage
Melamine Adhesives	Thermoset	Durable, heat resistant, chemical resistant, moisture resistant	Can't be remoulded	Particleboard binder, plastics

Table 9: Common adhesives and their properties (Designing Buildings, 2022).

Adhesive	Properties
PVA	Woodwork glue, water resistant
Synthetic Resin	Woodwork glue, water resistant
Epoxy Resin	Used for plastic and metal
Acrylic Cement	Used for acrylic and plastic
Casein	Cold setting adhesive made from sour milk
Urea Formaldehyde	Cold setting resin adhesive used for timber. Weakens after prolonged exposure to heat and water.
Resorcinol Formaldehyde	Cold setting adhesive used for timber. Remains strong at high temperatures.
Phenol Formaldehyde	Warm setting adhesive. Temperature needs to be above 86°C to set.

Natural glues and their uses are outlined by (LD Davis, 2019). These natural glues include starch, which is used as an adhesive for paper and cardboard production or as a thickening agent for cooking; dextrin, which is used for labelling, laminating, etc.; protein glue, which is used for paper and wood applications and is completely biodegradable.

According to (Hot Melt, 2022), there are four main kinds of water-based adhesives. These include vegetable glues such as starch (dextrin) adhesives; casein (created from animal organs or milk); resin or polymer acetate adhesives such as PVA or EVA mixed with water; latex-based made from rubbers and elastomers.

As starch is used for paper and cardboard, and due to its ready availability, this will be trialled as a potential adhesive. It is also a water-based adhesive used for cellulose insulation, so it will be trialled. Polymer adhesives will also be trialled as they have good mechanical properties, such as high impact resistance. Epoxy adhesives can also be tested due to their mechanical strength properties and environmental resistance. PVA is a water-resistant woodwork glue, so it will also be trialled. Other adhesives that will be tried including other water-based adhesives such as casein to try a cold setting adhesive.

Further research into starch glue

According to (Institute of Food Science and Technology, 2017), starch thickens when heated due to gelatinisation, which is how starch glue is made. While being cooked in liquid at 60°C, starch granules expand and take in moisture before releasing starch into the liquid at 85°C.

At 96°C, the gelatinisation phase has been completed, and as the mixture cools, it thickens before becoming a gel at 38°C.

One method for making cornstarch glue, according to (Burch, 2014), is by mixing cornstarch with ¼ cup of water and stirring before adding a further 2 ¾ cups of water to the mixture. This is placed into a pan and cooked while continuously stirring until the mixture boils. The heat is removed at this point, and as the mixture cools, it will thicken. A similar method to this shall be used in trials for starch glues.

Further research into casein glue

According to (P., 2023), low or non-fat milk should be used when making casein, as higher fat content prevents the casein from undergoing polymerisation. As for its moisture resistance, while casein is water resistant, the microorganisms in the water can eventually break down the glue.

Other methods for making casein glue are discussed by (Zinski, n.d.), which will be followed for testing. The method is discussed in section 3.2.3. Another method for making casein glue is by (Forest Products Laboratory & U. S. Department of Agriculture, 1961). Similarly, this will be followed, tested, and discussed in the same section.

3.0 Manufacturing Methods

An overview of the completed process flow is shown in figure 3.

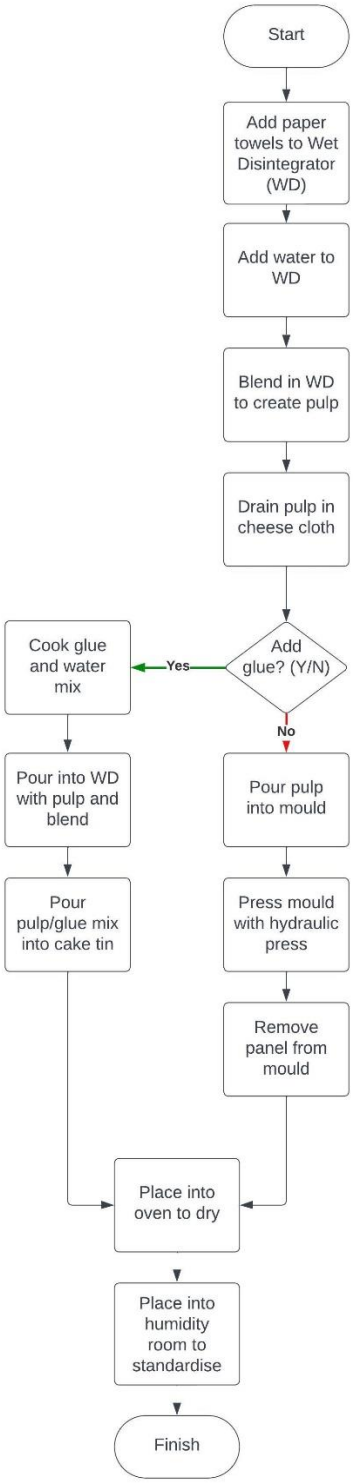

Figure 3: Process Flow Diagram of Manufacturing Process.

The development of the process is documented below.

3.1 Regular Panels

Before this master's project commenced, some benchtop prototype panels had been produced by Precycle NZ as a proof of concept. It had been demonstrated that paper towels could go through a repulping process, be manually pressed into a panel, and then dried. For this master's project, following the literature review, the next stage was to develop a procedure for making these panels and demonstrate that they could be produced with consistent properties.

3.1.1 First Prototype Panels

The first prototype panels, following the proof of concept panel, used waste paper towels from the Massey University Recreation Centre that were placed in a plastic bag for collection. They were then taken and run through an autoclave for sterilisation. The paper towels were then repulped by using a wet disintegrator (Wet Disintegrator from Jeffco Bros. Ltd), which was used to shred the paper towels and churn them into pulp. In this initial test of the manufacturing process, the exact ratio of paper towels to water was not measured. However, this was quickly standardised for the second prototype, which is discussed in 3.1.2. Paper towels were added to the wet disintegrator bucket (figures 4 and 5) until it was three-quarters full. Room temperature water was added to submerge the paper towels (figure 6). The machine was turned on and run for one minute, successfully converting the paper towels into pulp (figure 7). The figures shown below show the wet disintegrator used, the stage where the bucket is filled, and finally, the end of pulping.

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Figure 4: Wet disintegrator make and model.

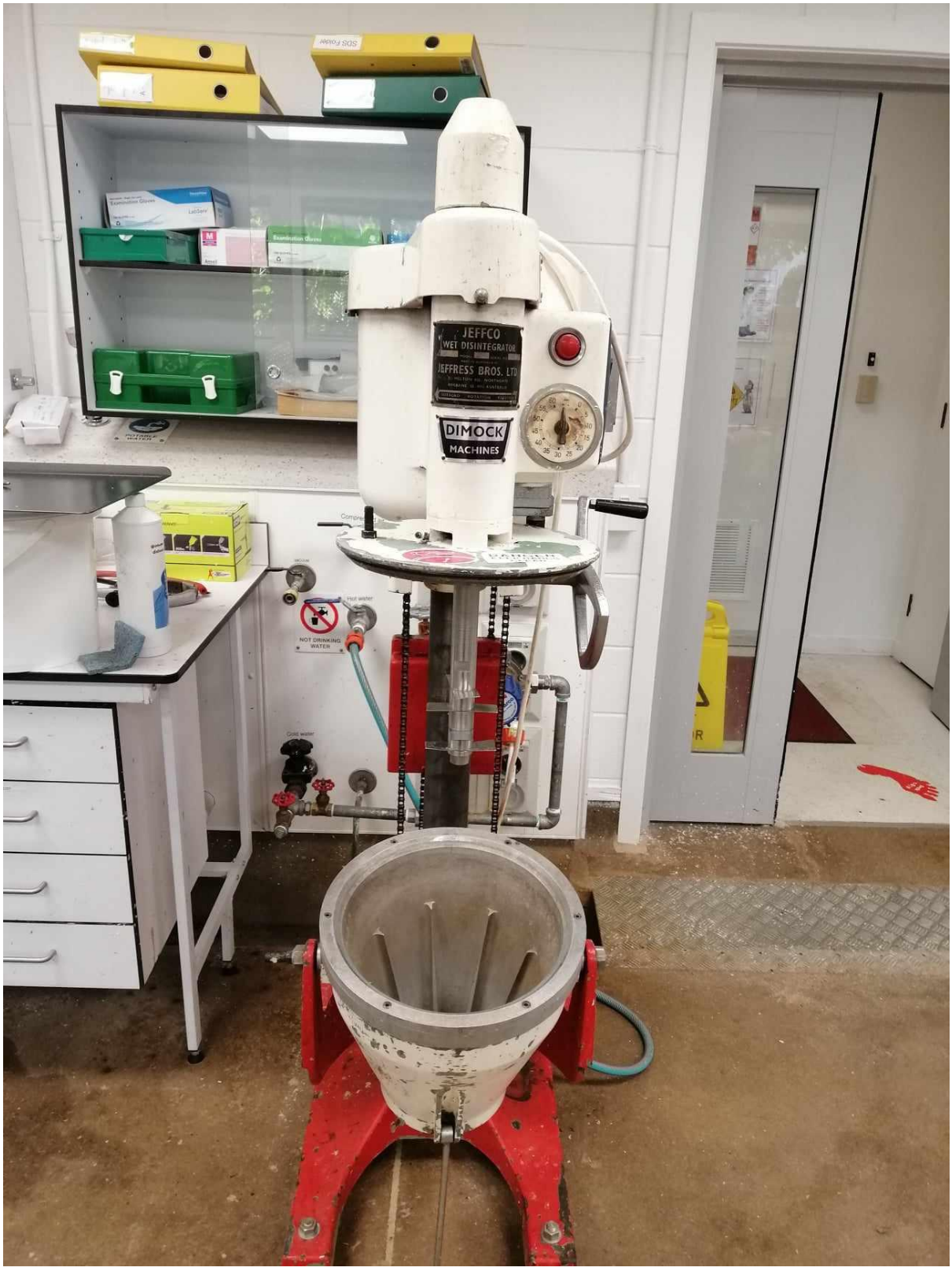

Figure 5: Wet disintegrator (before putting paper towels in)

Figure 6: Filled wet disintegrator bucket before pulping.

Figure 7: End of pulping in wet disintegrator.

The pulp was then drained through a cheesecloth to remove excess water. The cheesecloth was squeezed manually to remove further water. The average pulp yield and moisture content after squeezing with the cheesecloth were determined in the second prototype, so this is discussed in 3.1.2. This process was repeated twice so there was enough pulp to fill the 181 mm x 150 mm x 55 mm mould (small mould). The pulp was pressed by hand into the mould, as shown in Figure 8.

Figure 8: Inserting pulp into small mould manually.

The mould was put in a hydraulic press (manufactured by Hansen Engineering Co. Ltd.), and 19.6 kN of force (two tons of mass) was applied to the mould to compress the pulp and remove more water. This process produced homogeneous boards 38 mm thick that were stable enough to be held by hand, even while still wet. Figure 9 shows the panels after being pressed.

Figure 9: Panel formed after press.

Finally, the panels were placed into an oven at 60°C for 48 hours until dry (figure 10). Figure 11 shows the first prototype finished.

Figure 10: Panels drying in the oven.

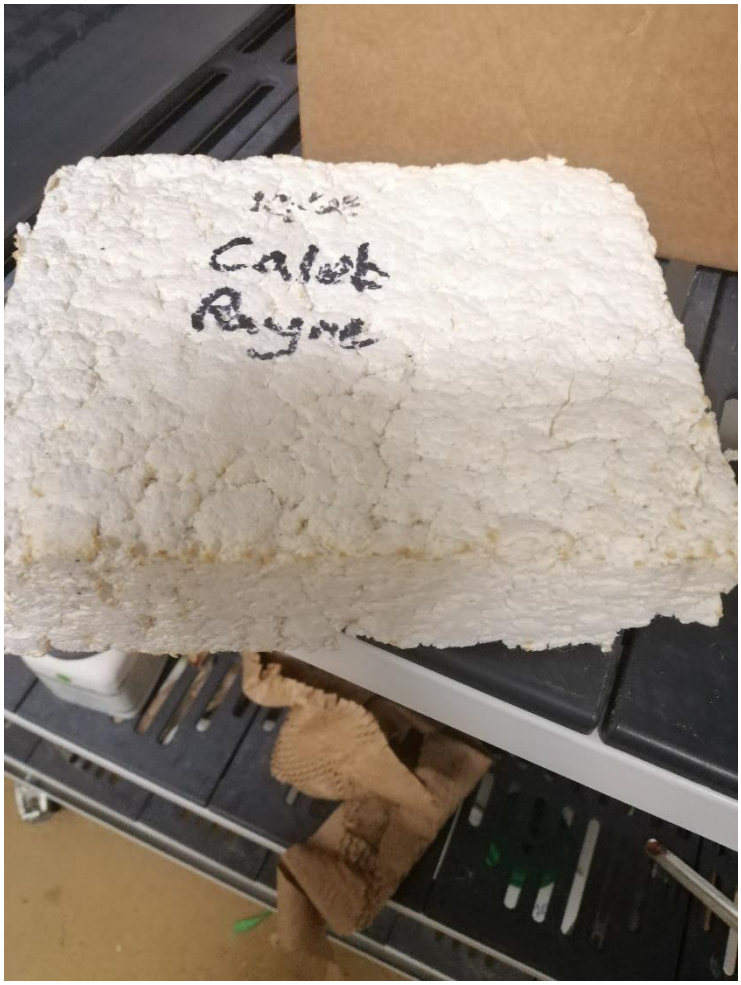

Figure 11: First prototype panel completed after oven drying.

3.1.2 Standardising the Regular Panels

Following the success of the first prototype, the process used to create it was standardised to ensure future panels would have similar properties to each other. This standardised process is as follows:

- 230 g of paper towels that were autoclaved in bags, and 3.62 kg of water are placed into the wet disintegrator.
- The wet disintegrator is run for 45 s to convert into pulp.
- The pulp is then filtered through a cheesecloth and hand-squeezed to remove excess water. Filtering and squeezing resulted in an average of 1134.5 ± 180.8 g of pulp with an average moisture content of 70.6 ± 4.3%. This is shown in Appendix 7.1.
- 1500 g to 2000 g of pulp are placed into the small mould.
- The mould lid is placed onto pulp in the mould base and aligned to be centred for the hydraulic press ram.
- The hydraulic press is pumped until 19.6 kN of force (2 tons of mass) is applied and held on the gauge.

- The panel is removed from the mould and carefully weighed before being placed in the oven at 60°C (later 103°C).
- Daily weighing is performed until it reaches constant mass.
- Panels are moved to the humidity room at 20°C at 65% relative humidity and weighed until they reach constant mass or have been there for a minimum of 7 days before being used for testing.

Discussion of Standardisation Process

The quantity of paper towels placed into the wet disintegrator was 230 g, as this filled up the wet disintegrator's bucket approximately three-quarters full while leaving room for water and did not stall the wet disintegrator motor due to overloading. 3.62 kg of water was used to fill the remaining volume in the bucket. This amount of water was set by measuring the quantity required to submerge the paper towels completely while not overfilling the wet disintegrator bucket. Rather than weighing the water for each batch, a line was marked on the bucket, corresponding to 3.62 kg of water, which would be used for filling and pouring purposes going forward.

Table 10: Measuring water lost through cheese cloth process

	Paper Towels in Wet Disintegrator (g)	**Water in Wet Disintegrator (g)**	**Water drained out of cheese cloth (g)**	**Water remaining in pulp after draining (g)**	**Mass of pulp after draining (g)**	**Moisture content after cheese cloth draining (%)**	**Solid content after draining (%)**
	232.1	3725	2430	1295	1527.1	84.8	15.2
	231.8	3710	2645	1065	1296.8	82.1	17.9
	232.8	3685	2715	970	1202.8	80.6	19.4
	231.5	3595	2715	880	1111.5	79.2	20.8
	230.2	3680	2710	970	1200.2	80.8	19.2
	230.8	3510	2640	870	1100.8	79	21
	229.9	3515	2730	785	1014.9	77.4	22.6
	230.0	3455	2710	745	975.0	76.4	23.6
	230.4	3640	2890	750	980.4	76.5	23.5
	230.7	3745	3040	705	935.7	75.3	24.7
Average (g)	231.0	3626	2723	904	1134.5	79.2	20.8
Std Deviation	1.0	102	159	180	180.8	2.9	2.9

As shown in Table 10, there is some variation in the amount of water added and water loss from the wet disintegrator process and drainage through the cheesecloth. For example, there is ± 159 g of water removed from squeezing the cheesecloth. To test whether this variation significantly affected the moisture content of the dried panels, samples were taken and dried in the oven to constant mass and compared to the measured moisture content of

the dried panels. After measuring the moisture content, the panels were found to be very similar in moisture content to both each other and the samples, with minimal variation. This is shown by their moisture content percentages from the pulp stage to oven dry in the range of 82.9 ± 1.6% to 85.9 ± 1.2% (note that this moisture content measures from wet pulp in the mould to oven dry whereas the cheesecloth moisture content listed above was from paper towels to wet pulp). This is discussed in section 5.1 of the thesis and Appendix 8.2. This shows that the variation in the moisture content of the panels is minor, so it can be determined that the regular panels are consistent with each other. The variation in test results will be caused due to additives and other factors.

It was found that the difference in pulp fibre when running the wet disintegrator at forty-five seconds versus one minute or two minutes was minor based on appearance and texture, so the run time was set at forty-five seconds for all boards from this point onwards. Less than this time could result in unblended paper towels in the wet disintegrator.

The amount of compression on the hydraulic press was initially done to constant depth to keep panels relatively the same height. However, this was changed to be compressed to 19.6 kN of force (unless otherwise stated as a different amount) to keep panels consistent. The constant force was easier to keep consistent due to the gauge, while constant height required using a ruler to check the compression depth and was not as accurate.

To ensure complete drying and consistency of the panels, panels in the 60°C oven were weighed every 24 hrs until a constant mass was reached (<1% change in mass after 24 hrs).

3.1.3 Other Developments of Regular Panels

A larger mould plate (figure 12) of the dimensions 290 mm x 290 mm x 24 mm was made to create larger panels, using more pulp (figure 13). These panels were better for cutting more test samples per panel and seeing how a larger-scale panel would perform. It was found that when compressed with 19.6 kN of force (2 tons of mass), it created a uniform, thick panel (figures 14 and 15). With 98.1 kN of force (10 tons of mass), the resulting thinner panel was less uniform as the panel flexed when drying. This could have been mitigated by drying in a mould, as done with the glue panels (see section 3.2).

Figure 12: Large mould used for making big panels (before painting).

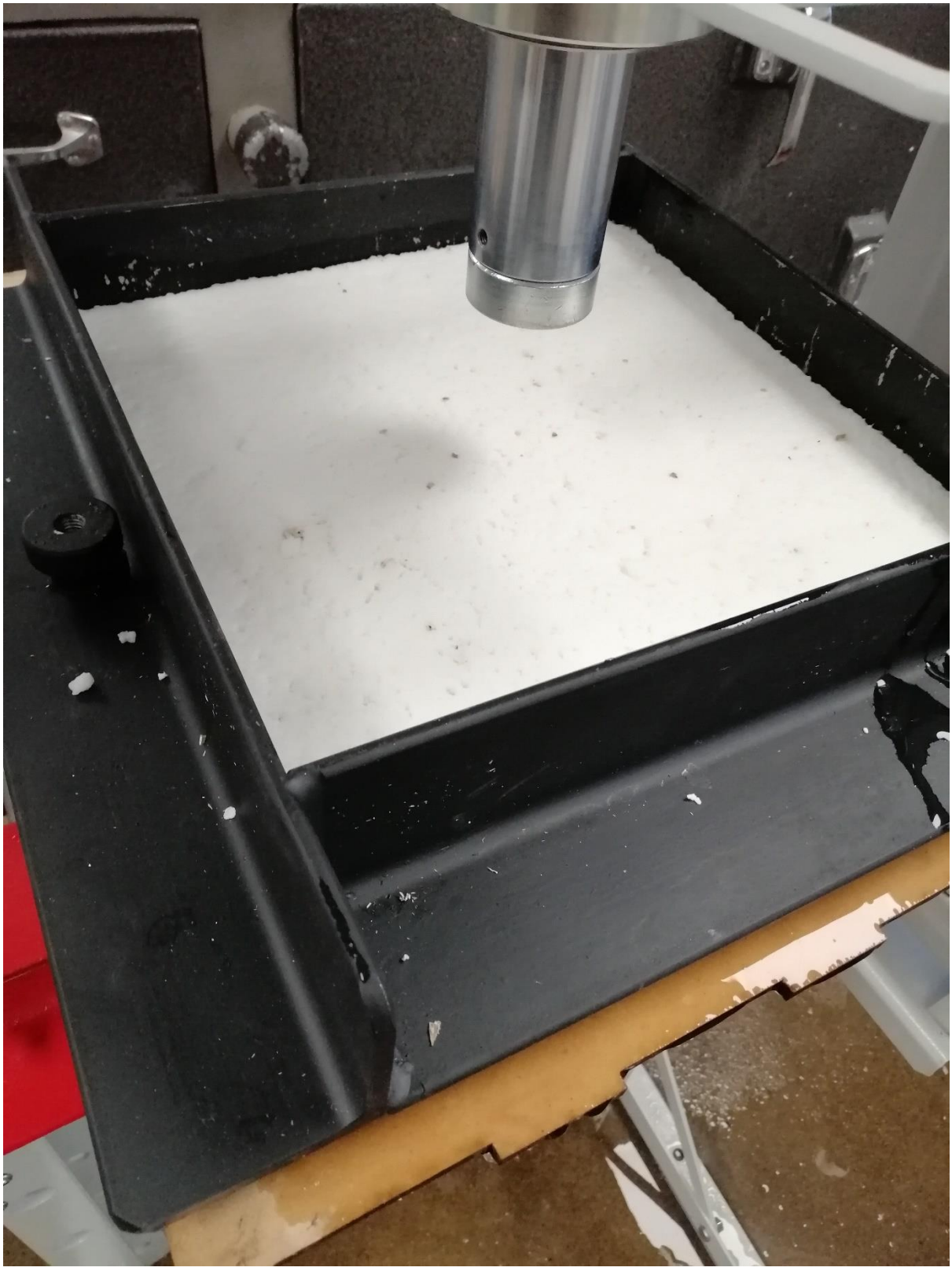

Figure 13: Large panel formed after press.

Figure 14: Removing large panel from mould, ready for drying.

Figure 15: Drying large panel.

The oven temperature for drying was changed from 60°C to 103°C to follow standards for testing wood products which tests were modelled after. Panels were then placed into humidity rooms at 20°C and 65% relative humidity following the oven dry stage to bring

them to room conditions at constant mass, as per standards. This is discussed in section 4.1 of this thesis.

3.2 Adhesive Panels

Pulp made using the standardised process outlined in 3.1.2 was mixed with adhesives to see how the properties were improved (figure 16). Initially, small trial batches of pulp were mixed with some common adhesives used in the construction industry, outlined in section 2.6. Also, water-based glues were trialled due to their use with cellulose products and their usage in similar products, as discussed in section 2.5. The trial blends included pulp with the following:

- epoxy
- gorilla glue (polyurethane-based)
- tapioca starch
- potato starch
- corn starch

Figure 16: Epoxy mixed with pulp (black sample), and Gorilla Glue mixed with pulp (light-coloured sample).

3.2.1 Synthetic Glue Samples

The epoxy glue (black sample) took up a large portion of the pulp/glue mixture, so the resulting sample was more glue mixed with pulp than vice versa. The mechanical properties from manually feeling its strength were quite strong, though the amount of glue was the primary cause, not the pulp. Less glue could have been tried in a mix, but epoxy was found to be quite expensive anyway, which was not desirable. Also, its synthetic nature defeated a significant benefit of having organic panels.

The gorilla glue was used in a better pulp/glue ratio and had good mechanical strength, though, like the epoxy, the inorganic nature and cost were undesirable.

3.2.2 Starch Adhesives

Starch glues were made using recipes from various sources such as (Burch, 2014), and (Uys, 2012).

Tapioca, potato, and corn starch were all used as an adhesive. To make the starch glue, 40 g of one of the starch variants was put in 200 g of water and cooked for approximately 15 minutes at 300°C until boiling (figure 17). While cooking, constant stirring was performed to remove lumps. After boiling, this was removed from the heat and allowed to cool (figure 18).

It was observed that the starch was hard to mix due to its non-Newtonian fluid nature. As the mixture boiled, the starch became lumpy and thick as it gelatinised. After removing from the heat, the glue remained in a hot, sticky, liquid form for about 30 mins before solidifying. This method was followed for the other starch glues. All acted similarly while boiling, though the appearance of the glues was different, as shown in the figures 19, 20, and 21 below.

Figure 17: Potato starch and water after being boiled.

Figure 18: Potato starch glue cooling and beginning to set.

Figure 19: Potato starch after cooling formed into a solid gel.

Figure 20: Solidified corn starch glue.

Figure 21: Solidified potato starch (left) and solidified tapioca starch (right).

All starch glues showed promise by forming a sticky, solid gel after being allowed to set. The corn and potato starches were particularly interesting as they formed slimy, rock-like structures, whereas tapioca maintained a similar form while it was boiling, though still hardened, and remained sticky.

First starch attempt

As the starch glues showed promise due to their sticky nature, the test samples of starch glue were combined with the standardised pulp to make pulp-adhesive panels. The research into plasterboards, shown in the literature review (section 2.5.3), indicated that glues should be mixed while in the slurry/pulp stage before spreading and drying. Therefore, the starch glues were poured into the wet disintegrator, which was an excellent method for mixing the glues with pulp. The pulp used to do this was made using the standardised ratio shown in section 3.1.2 of 230 g of paper towels with 3.62 kg of water blended for 45 s in the wet disintegrator. Multiple batches of pulp were made to create a large portion of pulp. 200 g of this pulp was used with 160 g of starch glue. This ratio was followed for each of the types of starch products. While the starch glue was shredded and mixed with the pulp, as the batch was already close to room temperature, the glue was mostly set. Lumps of glue were apparent throughout the mixture rather than nicely blended, so for the next batch, the starch glue was added to the pulp while still hot and in liquid form.

Second starch attempt

The tapioca starch glue was made by cooking 100 g of starch with 800 g of water until boiling. This starch glue was then added to 1100 g of pulp and blended in the wet disintegrator immediately, so it was still hot. Blending was done until the mixture had the consistency of mashed potato (Figure 22).

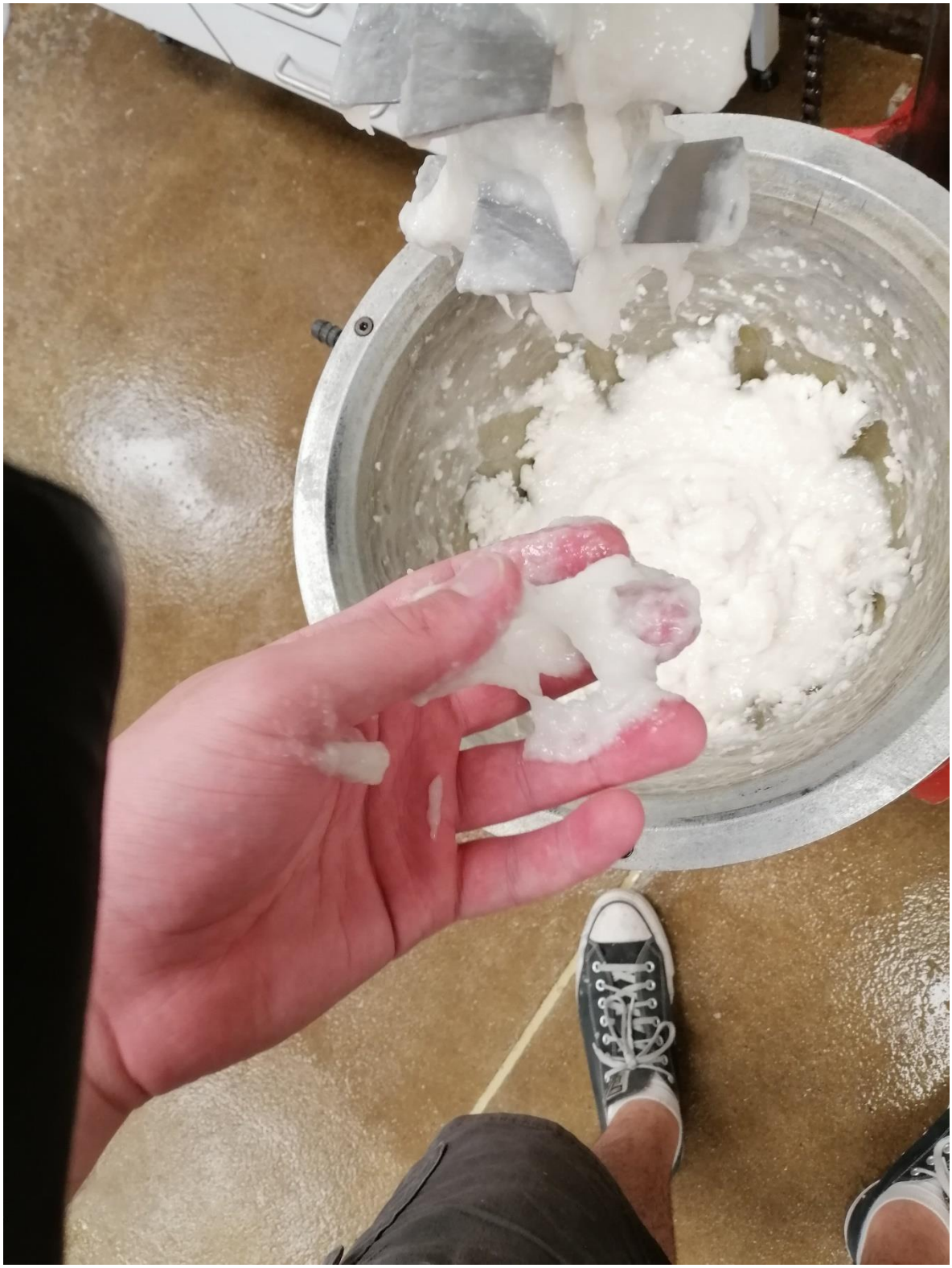

Figure 22: Tapioca starch glue mixed with pulp (mashed potato consistency).

This worked much better as there were no lumps throughout the mixture, except at the bottom of the wet disintegrator, where there was some unmixed pulp. This is likely due to the more viscous pulp-starch mixture not being well mixed or agitated under the impeller at the base of the bowl.

1500 g of this pulp and starch mixture were put in the mould and compressed. Compressing this mixture did not work as a fluid-like mixture squirted everywhere when under compression. This caused a large portion of the pulp-starch mixture to be lost, and only a small layer remained in the bottom of the mould. Also, the top mould plate adhered to the base due to its stickiness, so it had to be pried off. While this method was not ideal, the fact that the glue caused resistance between the metal plates was very promising as a potential adhesive.

Third starch panel attempt

Following this, another glue batch was tried with ratios of 100 g of tapioca starch with 600 g of water and cooked before mixing with 1000 g of pulp in the wet disintegrator. 200 g less water was used in this batch to have a more viscous mixture, which could be handled easier with less wastage. The glue in the wet disintegrator was half poured in before any pulp to try and blend with the bottom of the bucket, followed by all the pulp, and finally, the rest of the glue. After blending, the pulp/glue mix was not compressed due to the spurting issue but instead placed into a foil baking tray of dimension 200 mm x 140 mm x 27.5 mm and dried in the oven at 103°C.

Figure 23: Tapioca starch panel after removal from foil baking tray.

The dried panels came out of the oven with a more rigid outer layer than the regular panels (figure 23). The foil stuck to the panel after drying and broke apart when removed. The panel-forming process was repeated as described, but a rectangular, non-stick cake tin was used.

Optimising the mould used for the tapioca starch panel

This starch-pulp mixture formed a consistent-looking panel from the outside. A panel was cut to assess the inside structure, as shown in figure 24.

Figure 24: Cross section of tapioca starch panel.

The tapioca starch panel had a thick outer layer with an inside like the cross-section of a regular panel – dried pulp with no obvious starch mixed in. Initially, this was thought to be due to the two layers of glue poured into the wet disintegrator, though the texture after blending is the same throughout. The same result occurred when repeated by pouring all

glue in at once for another panel. The drying must, therefore, cause the shell to form and is likely caused by gelatinisation, which causes the mixture to thicken, as discussed in the literature review. As the outer layers are exposed to more heat than the inner layers in the oven, these may go through gelatinisation at 85°C to 96°C, whereas the inner layers may just dry. This is just a hypothesis; further research is needed to determine this and is outside the scope of this project. The potato and corn starch panels similarly had a thick outer layer; however, the inside had lots of air gaps, as shown in Figures 25 and 26, so the panels were not consistent throughout. Air gaps could be reduced through compression, however, losses of the mixture would occur due to the pulp mixture being forced out at the edges of mould.

Figure 25: Cross section of the potato starch panel, showing lots of air gaps in its internal structure.

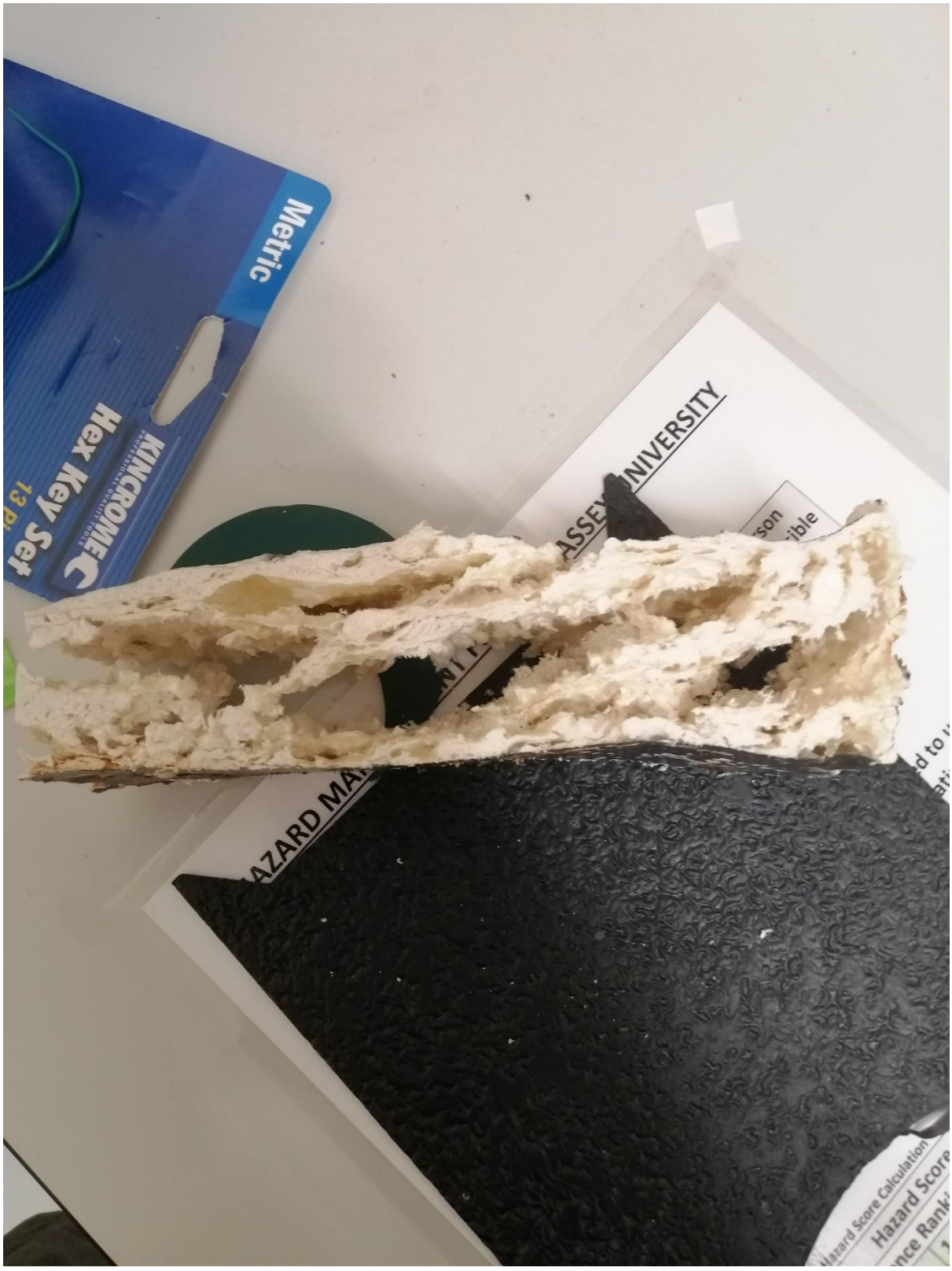

Figure 26: Lots of air gaps in corn starch panel.

As this was not ideal for its end use case, where the panels would likely have to be cut to be fitted, or for testing purposes, where test pieces would have to be cut from the panels, the potato and corn starch glues were discontinued. The tapioca adhesive panel, however, was taken forward for more testing.

As the cake tins used were rectangular with a tapered wall, this created ingot-shaped panels (Figure 27).

Figure 27: Tapioca panel made from rectangular cake tin.

A square, non-stick cake tin with releasable sides was used to be closer to what was required for a product and for creating test specimens. After drying, the panel got stuck in the bottom of the tin. Even with the removable sides, the adhesion from the glue stuck to the walls, so upon removal, portions of the panel ripped apart and had to be scraped off the tin. The glue was so strong that even some of the non-stick lining of the cake tin was removed along with the panel. To fix this problem, both silicon release spray and baking paper methods were tried separately in the tin before placing it in the glue mix. The baking paper worked well at preventing the glue from sticking to the sides of the tin once dried but caused some of the edges of some samples to not be completely flat due to lumps in the baking paper. Silicon spray did not help with the sticking issue, so it was not used following this. The baking paper method was sufficient at this project stage to create usable samples for testing, as when cutting cross sections, the undesirable parts were not used anyway.

Standardising the process to fit the square cake tins for testing purposes

The tapioca glue was scaled up to have the ratio of 320 g of starch with 1500 g of water and then mixed with 2000 g of pulp in the wet disintegrator. More water was used for this final batch to thin the tapioca glue out more, as the glue was still thicker than needed. The glue was still cooked for 15 minutes, which is the approximate time to bring it to a boil. The glue/pulp mix was run in the wet disintegrator for 30 s, as this was enough time to blend the pulp and glue together. The resulting mixture provides enough mass to cover multiple sample panels. A typical panel used around 620 g of this mixture to fill the cake tin. This was then dried in the oven at 103°C. See Appendix 8.2.2 for the final versions of starch glue quantities used.

3.2.3 Casein Adhesives

Casein glue was another trialled adhesive due to its organic and moisture-resistant nature. Initially, a quick test was performed to create casein glue from skim milk and other household ingredients. This was done loosely following the process documented by (Zinski, n.d.).

First test batch

The process was as follows:

- 300 g of skim milk was poured into a cooking pot and heated for five minutes, without reaching its boiling point.
- 46 g (about 15% of the milk mass) of vinegar was then mixed in to break down the milk into curds (milk solids) and whey (liquid portion). After completing this process, the pot was taken off the heat.
- The next stage involved taking a cheesecloth to filter the curds from the whey, as the curds would be used for the casein adhesive.
- After filtration, the curds were rinsed with a small amount of water and 15 g of baking soda to neutralise any vinegar still present.

This process made about 104 g of runny solution (figure 28).

Figure 28: Runny solution made from first attempt.

Second test batch

Other variations were tried, such as using casein powder obtained from the Massey pilot plant instead of starting from the milk phase. Only 40 g of powder was used, as no whey needed to be separated in this case. The process for this was the same, except it did not have a filtration stage as this was not needed due to already being casein. The powder was cooked for five minutes and had 50 g of vinegar added to it, followed by rinsing with water and adding 15 g of baking soda. This created 67 g of casein glue that was very sticky and hardened into solid rocks (figures 29 and 30).

Figure 29: Very sticky casein glue formed that started to harden quickly.

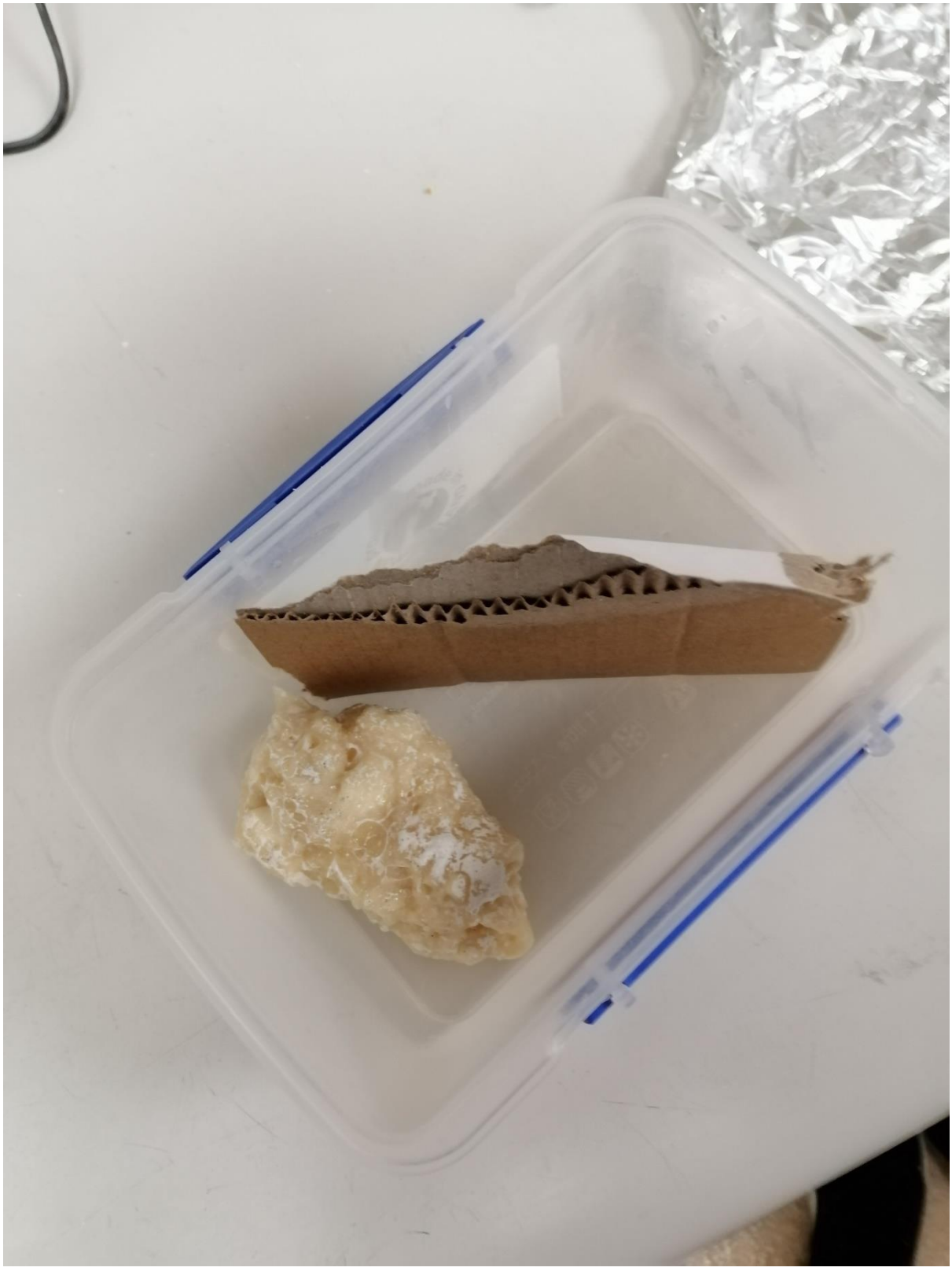

Figure 30: Hardened casein glue.

The casein powder was taken forward over the milk method due to its super strong nature and the fact that the separation of curds and whey process could be skipped as it was already in its desired form.

Third test batch

Another source provided a more in-depth method of creating casein glues and had a variety of recipes listed with different benefits (Forest Products Laboratory & U. S. Department of Agriculture, 1961).

The generic recipe for casein glue is listed as follows in parts by weight (PBW):

- 100 PBW casein powder soaked in 150 PBW water for 15 to 30 minutes
- Add 11 PBW Sodium hydroxide to a further 50 PBW water, then mix with the powdered solution and stir until lumps are removed.
- Finally, add 20 PBW Calcium hydroxide (hydrated/slaked lime) to a further 50 PBW water and then add to the rest of the mixture and stir until the glue becomes well mixed.

This recipe was replicated for testing, but made with a double quantity of the given recipe, e.g., 200 g of casein powder with 300 g of water, etc. Two times was used to create enough glue to make multiple samples. The first stage of using the casein powder and water included cooking and stirring until it was observed that the powder and water had blended together. While this was taking place, the other ingredients to be added were prepped. 22 g of sodium hydroxide pellets were dissolved in a beaker containing 100 g of water, and in a separate beaker, 40 g of calcium hydroxide dissolved in 100 g of water. After cooking at 300°C for approximately 15 minutes, the mixture became more resistant to stirring, so the sodium hydroxide solution was mixed in. As per the literature, stirring was performed until lumps were removed. Finally, the calcium hydroxide solution was poured in as well. The mixture of casein glue was taken off the heat and was later added to 1000 g of pulp in the wet disintegrator and blended for 30 s. The first batch of casein glue was made alongside the first starch glues, and the same issue of drying too quickly occurred, so hard rocks formed that did not break up well in the wet disintegrator.

Fourth test batch

The above process was repeated for a second attempt, though this time, the casein glue was poured into the wet disintegrator while it was still hot. This fixed these issues, and the glue mixed well with the pulp. As this was successful, the pulp/casein-glue mix was poured into the ingot-shaped cake tins and placed in the ovens at 103°C. After a few days, the tin was removed from the oven. The casein glue had adhered pretty strongly to the sides of the tin, so it needed to be prised out. The panel structure appeared very strong and had a distinct orange colour from the casein drying (figure 31). Cutting open the panel showed a nice cross-section with some holes scattered throughout, which was potentially promising for future insulation testing (figure 32). Pouring this into the big mould and pressing it was also attempted; however, similarly to the starch glues, the casein glue squirted everywhere and even flooded between the mould joints, so it required cleaning to not glue the mould joints together.

Figure 31: Casein panel in ingot shaped cake tins.

Figure 32: Cross section of casein panel.

Standardising the casein glue

The final test batch followed the starch glues by using the square cake tins for easier release and to make panels closer to the desired shape of uniform flat panels. The quantities used for this standardised method followed the third and fourth batches. This method was used for creating samples for testing (figure 33). See Appendix 8.2.2 for the final versions of casein glue quantities used.

Figure 33: Casein panel made from square cake tins.

It was found after developing panels that while casein powder was readily available in New Zealand, much of it was used as a protein supplement. The feedstock was supplied through Massy University as a waste feedstock from the food labs. Unfortunately, it was found through phone conversation that places such as Fonterra only sell this in large quantities as

it is a valuable resource. Buying it commercially is not viable due to the large quantity needed for making panels; however, as panels were already made with casein, these were tested and still provide a comparative example. If the price ever drops or a waste feedstock of casein powder becomes available, this may be a viable method.

4.0 Testing Methods

The testing methods include moisture content, exposure to different humidity in controlled environments, and mechanical tests such as compressive strength, bending strength, and impact resistance. The moisture content will be used to check how consistent each panel is during the manufacturing process, determining whether there is a lot of variation in specimens for other tests. Testing specimens under controlled humidity will determine how much moisture is absorbed into each panel and their mould growth in both household and more extreme humidity. Minimising moisture and mould are important, as outlined in the literature on the building code.

The insulation will be tested by measuring its thermal conductivity and using this to determine its R-value. This is then compared to industry products and checked against the minimum criteria outlined in the building code literature.

Mechanical tests such as compressive strength, bending strength, and impact resistance are important to determine the panel's durability to see if it would meet the durability requirements at the bench scale. These tests are performed on plasterboards, so it will be good to see how they compare and perform against various forces the panels may encounter in their lifetime, depending on their use case. These tests will give a good indication of the overall performance of the panels. If these perform well, P21 bracing will be performed in future work to check durability against earthquakes and wind, which is vital for certification and meeting building code durability requirements.

Table 11 outlines the sections the tests are discussed in:

Table 11: Testing Sections

Section
4.1 Moisture Content
4.2 Humidity Testing (Saturated Salt Solutions)
4.3 Thermal Conductivity
4.4 Compressive Strength
4.5 Bending Strength
4.6 Impact Resistance

4.1 Moisture Content

ISO 13061-1 (2014) discusses how to determine the moisture content of wood specimens. Moisture content is the percentage of moisture present and is calculated by oven-drying a test sample to determine the change in mass. This change in mass is the amount of water dried off, i.e., the moisture content. The test samples are weighed to give an initial mass value and then dried in the oven at 103 ± 2°C. After a minimum of 8 hours (the panels were, in reality, weighed once every 24 hours), the panels were reweighed, and their current mass was compared to their previous mass. If the change in mass is not more than 0.2%, the samples are considered constant mass and assumed to be dried of moisture. To calculate the moisture content from the initial mass and final mass, a formula is used (equation 1):

$$Moisture\ Content\ (\%) = \frac{Initial\ Mass - \ Final\ Mass}{Final\ Mass} * 100$$

Equation 1: Moisture content formula

The dry content percentage of the samples can also be calculated by working out the difference in moisture content percentage from 100%. Following this, samples were placed into the humidity room.

This process was repeated for samples in the 20°C 65% humidity environment, where samples were weighed once every 24 hours until constant mass. This was calculated the same way, except the moisture content percentage increased due to the panels reabsorbing moisture after completely drying.

4.2 Humidity Testing (Saturated Salt Solutions)

Testing how the different panel blends perform in different humidities will determine how much moisture is absorbed in different climates. Comparing the moisture content gain, appearance, and structure changes are all important for building products and customer perception. The humidity was controlled using saturated salt solutions in an enclosed container to create different relative humidities. Three different RH environments were created: $MgCl_2$ to give a relative humidity of 33% at 20°C, NaCl to give 75% at 20°C, and KNO_3 to give 95% at 20°C. Specimens conditioned at 65% were cut from multiple panels before being weighed to gain an initial mass reading. Afterwards, they were placed into the saturated salt containers and reweighed daily until the change in mass between 24-hour readings was less than 1%, following the method for standard moisture content. For some specimens, the mass kept changing for more than 1% after 24 hours due to mould growth, so to ensure the mass would not be affected by mould grown on the specimens too much, the final reading was taken 7 days after being placed into the containers. The moisture content was then calculated by using the initial and final mass.

4.3 Thermal conductivity

The thermal conductivity was measured using the needle probe transient method (Massey University, 2013). This method uses a thermocouple needle that provides a heat source into the panel. As heat dissipates throughout the material, the sensor in the probe records the temperature and corresponding time at the source. This data is used to find the thermal diffusivity and thermal conductivity (Meter Group, n.d.).

The theory for this test assumes that the probe should be infinitely long and thin and that the material it is placed into is large enough so that no temperature gradient will develop at the surface during the measurement (Massey University, 2013). The power provided to the probe should be constant, and the initial temperature difference between the probe and the panel should be negligible. The probe was left to equilibrate between tests to minimise any temperature difference between the probe and the measured specimen. All panels were measured under the same conditions at 20 ± 3°C. The sample is also assumed to be homogeneous (Wechsler, 1992). As these assumptions in the theory are unrealistic in the real-world application, there will be some variation from this.

The testing process involves inserting the needle carefully into a side of the panel to cover the needle completely. The probe is turned on, and the temperature is recorded at 1 s intervals. Once the temperature-time curve begins to flatten, the button is released to stop the heat and the test is ended. The process from heating to finish typically occurs between 1 to 2 minutes. This test was repeated on all four sides of each panel and repeated for five panels.

From the temperature time profile, the thermal conductivity is calculated in the following way. The temperature vs. ln(time) is plotted, and the slope of the linear region is determined (figure 34).

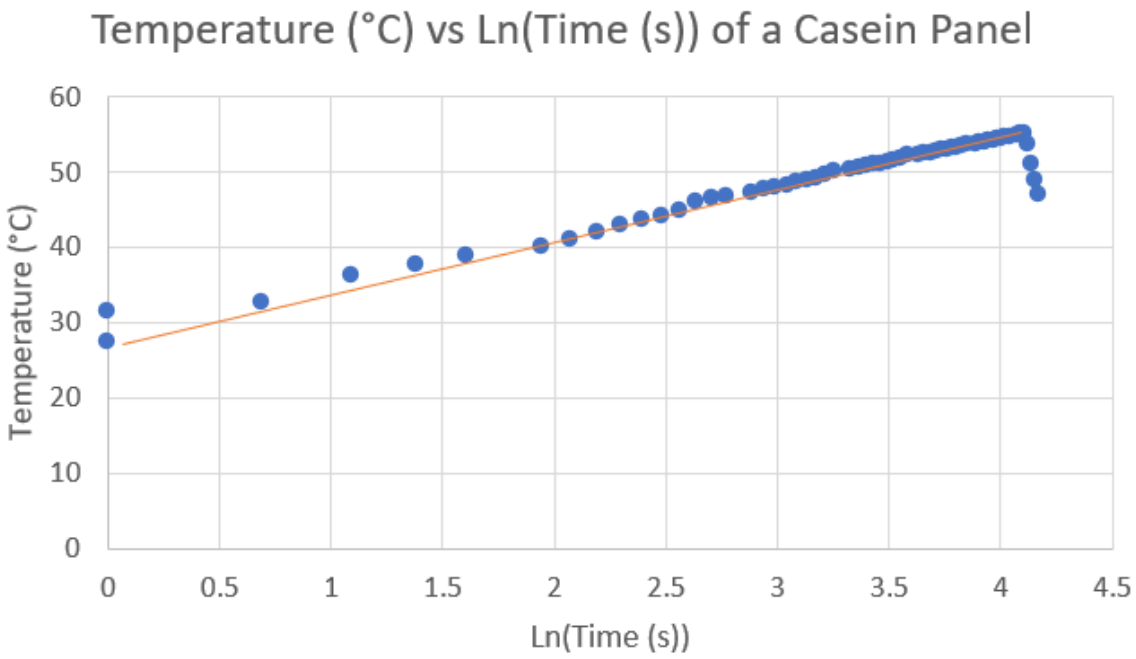

Figure 34: The slope of the linear region of a casein panel

This linear region S (slope) is represented by the following equations (equation 2) (Massey University, 2013):

$$S = \frac{Q}{4\pi\lambda} \text{ or } S = \frac{(\theta 2 - \theta 1)}{\ln\left(\frac{t2}{t1}\right)}$$

Equation 2: Slope of linear region equation

where Q is the power per unit length and is a constant 5.0 Wm^{-1},

θ1, θ2 is the corresponding probe temperature (°C) for t1, t2,

t1, t2 is the time (s) at the start and the end of the slope, respectfully after power on,

and λ is the thermal conductivity ($Wm^{-1}K^{-1}$)

The first equation was then rearranged to find λ, the thermal conductivity using the S value from the data.

To calculate the R-value of panels, which is a relevant metric for insulation in New Zealand homes, the measured thermal conductivity of the panels was used. The R-value is the thickness (m) of the material over the thermal conductivity ($Wm^{-1}K^{-1}$) (equation 3) (Knauf Insulation, 2023b):

$$R - value\ \left(\frac{m^2K}{W}\right) = \frac{Thickness\ (m)}{Thermal\ Conductivity\ (W/mK)}$$

Equation 3: R-value formula

This test was validated by using expanded polystyrene foams (EPS) samples and conducting the test before comparing results to those found in the literature. According to (Simpson, Rattigan, Kalavsky, & Parr, 2020), the thermal conductivity of EPS is in the range of 0.030 $Wm^{-1}K^{-1}$ to 0.038 $Wm^{-1}K^{-1}$. The measured values of 0.028 ± 0.003 $Wm^{-1}K^{-1}$ fall shy of the lower end of the range but not too far off to invalidate the test. The standard deviation falls within the bounds of the range. The test was shown to be repeatable with minimal variation by the low standard deviation from the EPS tests. This gives confidence that the test will provide a good indicator for the manufactured panels. The EPS density was also accurate as (Simpson et al., 2020) record theirs as 17 kg/m^3.

4.4 Compressive Strength Testing

The ISO 13061-5 standard was used to measure the compressive strength. This standard outlines the process for determining the compressive strength of wood specimens. This was used for all specimens, including non-wood samples, to enable a fair comparison across all materials. The specimen dimensions should have a height between 20 mm and 50 mm, a length 1.5 to 3 times the height, and a width greater than 0.5 times the height. The dimensions chosen for the specimens were a 40 mm height, a 60 mm length, and a 50 mm width. This falls within the bounds of the standard requirements. Specimens were conditioned at 20°C with a relative humidity of 65% to constant mass before undertaking the test. The testing machine used for this test was the Instron 5967. The testing procedure involved placing the specimen into the machine with the 60 mm x 50 mm face flat on the lower loading platen (figure 35) before applying the compressive load at a suitable rate so that the test is completed between 1 and 5 minutes. The rate chosen for the test was 5 mm/min as this rate was slow enough to take longer than 1 minute to perform the test but fast enough not to exceed the limit. The data recorded by the machine is the force applied and the displacement of the loading platen. The loading platens are 150 mm in diameter, exceeding the surface area of the testing specimens to ensure an equivalent load across. Initially, the upper loading platen is jogged down to touch the sample lightly, without applying any load, before zeroing the Instron to get accurate force and displacement measurements. The test is stopped when the displacement exceeds 5 % of the height of the test specimen. Five replicates were performed for all materials. The compressive stress is calculated by dividing the force by the area (equation 4):

$$\sigma = F/A$$

Equation 4: Stress formula

Where σ is the compressive stress (N/mm^2),

F is the force (N),

And A is the area (mm^2)

Figure 35: Loading platens used for compression test

4.5 Bending Test

AS/NZS 4266.1-2017 outlines the process for conducting a three-point bending test for reconstituted wood-based panels. The standard is used as a general guideline but not completely followed as the standard is for wood-based specimens.

The three-point bending test applies a centralised load to a test piece supported at two points. This test determines the bending strength of each test piece by measuring the maximum force upon rupture. The standard recommends six samples per panel for a batch process.

The procedure involves taking the thickness measurement of the test piece at the intersection of the diagonals of the piece and the width at its mid-length. The test pieces should have a length of 15 times the nominal thickness plus 50 mm and fall between 150-1050 mm. The width shall be 50 +/- 2 mm. The centre of the support distances should be chosen so that the distance falls within the +/- 1mm range of 15 times the nominal thickness. This centre distance between supports should be between 100 mm and 1050 mm and measured to the nearest 0.5 mm. The test piece should be flat and right-angled to the supports. The constant loading rate during the test should be 10 +/- 5mm/min. The test is performed until the test piece undergoes failure.

The dimensions of the pulp panels and the equipment available for the three-point bending test meant that some changes were made to the specimen dimensions. Based on the panel width, the dimensions should be 650 mm x 50 mm x 40 mm (largest case). However, panels made in the big mould have dimensions of 290 mm x 290 mm x 24 mm. Moreover, the maximum centre distance between supports on the Instron three-point bend test (figure 36) fixtures is 400 mm. Attempts to decrease the panel thickness by applying more force in the hydraulic press (98.1 kN or 10 ten tons of mass) caused distortion in the panel, which was not ideal for the bending test as this required a flat surface. An alternative is to cut the panel along its thickness; however, this is not representative of the panel as the structure on the outside and inside varies, and when this was tried, the panels had noticeably less structural integrity just through normal handling.

The chosen dimension for the test pieces was 200 mm x 50 mm x thickness, with the centres of the supports to be modified to be 25 mm from the length of the material on each side. With the different specimen sizes, this test will give an indication of bending strength and provide a means of comparing the different materials to determine which may perform better. However, the results will not be comparable to published data using the AS/NZS 4266.1-2017 standard. The standard's equation below (equation 5) is a function of the thickness, so the variation between thick test panels and thinner building products can still be compared. All standard requirements, such as the loading rate, will remain unchanged.

$$\sigma = (3FL)/(2wd^2)$$

Equation 5: Bending strength formula

Where σ is the bending strength,

F is the maximum force applied,

L is the length of the specimen,

w is the width of the specimen,

And d is the depth of the specimen.

Figure 36: 3-point bending test apparatus

4.6 Impact Testing

Impact resistance measures how well a material can resist deformation from impact. This is important as it will determine how easy it is to fracture the panels, such as when an object is thrown at it. Building walls may undergo damage by stones, furniture, and human body-related impacts such as punches or falls (ISO, 1988).

ASTM D256-10 (2018) is the standard for impact resistance of plastic materials via the Izod Pendulum method. As this is for plastics, the standard will be used as a general guideline to give comparative data between test specimens of various materials. This standard was used as there was no apparent wood standard for the available equipment. This test is universal for many material types and has been used to test things such as metals (Xometry, 2023), so it should be acceptable for this application. Also, (ISO, 1988) is a similar test for measuring impact on walls and uses a weighted pendulum to create impact on the samples. This shows that weighted pendulum tests are readily performed for impact resistance.

The test involves a pendulum with a hammer-like attachment that swings from a known height to break a test specimen (figure 37). The energy absorbed while breaking the specimen is read off the gauge and follows potential energy theory.

The test method followed from the standard was Test Method A. This method involves holding the specimen vertically and breaking it in a single pendulum swing. To control where the sample breaks, a tapered notch of 0.25 ± 0.12 mm radius is to be cut on the specimen 22.0 ± 0.05 mm below the striking point of the pendulum hammer. This notch is to be on the surface facing the point of impact and aligned with the vice jaw grip.

The recommended pendulum length should be between 0.33 and 0.40 m. The Zwick impact tester used in this work had a pendulum length of 0.39 m. The pendulum selected should be picked based on the estimated energy required to break the specimen. In this case, the 7.5 J pendulum was picked as it was the lowest energy pendulum available and could easily break the specimens.

The specimens should be conditioned according to the standard at 23 ± 2°C and 50 ± 10 % relative humidity. The specimens were conditioned to 20°C at 65% humidity, as this was what other wood-based products were conditioned to for the other tests, which is close to the bounds of the test. Also, as the test is for plastic materials, the conditioning requirements are more suited, while 20°C at 65% humidity is better for wood products. Five specimens were measured from different panels as the standard recommends at least this many.

Figure 37: Impact tester used with pendulum arm

To determine the testing machine's inaccuracy due to friction, test runs were performed before placing in specimens. The pointer on the gauge is set to zero before letting the pendulum free fall from its starting height and measuring the energy expended with no specimens on the gauge. There are no specimens, so the expected reading should be zero

joules, as no energy is lost to breaking. The recorded value of one reading during this pre-test is a reading of Factor A according to the standard. For Factor B, the test with no specimen is performed again, though this time without resetting the pointer to its zero position. This records the additional amount the pendulum moves. Factor B is repeated until the change in pendulum position is negligible, and the final reading is recorded. This whole process of measuring Factors A and B was performed three times and averaged to determine the machine's inaccuracy.

Following the accuracy tests, specimens were clamped in the vice, and the pointer reset to zero and allowed to fall from its starting position. This pendulum swung and broke the specimen, leaving the pointer on the amount of energy expended. The impact resistance was calculated by dividing the energy expended in breaking the specimen by the specimen width to obtain the impact resistance under the notch (J/m). The impact strength is obtained by dividing the energy expended in breaking the specimen by the cross-sectional area under the notch by (J/m^2).

5.0 Results and Discussion

The results section will discuss the data collected for each of the tests. A range of tests were conducted to quantify and characterise the fibre panels. Testing of mechanical properties includes compressive strength, bending strength, and impact resistance. Other testing performed includes moisture content, humidity testing, and insulation testing. Data is compared between pulp panels, pulp plus additive panels, and industry products. This will provide a comparison in performance between products. The complete overall data is shown in Appendix 8.2 to Appendix 8.7.

5.1 Moisture Content and Density

The moisture content of the panels is important to know for ensuring the panels have minimal variation during the manufacturing process. The differences in panel density are also covered in this section.

5.1.1 Moisture Content of Panels from Pulp to Oven Dry Data

The moisture content data of the panels from the wet pulp stage of manufacture in the mould to oven dry are shown in Appendix 8.2. The averages of each panel are shown below in Table 12.

Table 12: Moisture content, wet mass, and density of the panels after oven drying. Values are mean and standard deviation of 5+ replicates. Pulp Panel (Big) was made in the big mould, Pulp Panel (Small) was made in the small mould, and Tapioca Panels and Casein Panels were made in cake tins.

Material	Moisture Content of Wet Material in Mould (%)	Wet Mass (g)	Oven Dry Density (kgm^{-3})
Pulp Panel (Big)	84.1 ± 0.2	2000.52 ± 0.18	286.03 ± 4.19
Pulp Panel (Small)	85.9 ± 1.2	1630.44 ± 63.05	216.96 ± 17.56
Pulp Sample	82.9 ± 1.6	60.80 ± 29.03	n/a
All Pulp	84.8 ± 1.7	n/a	n/a
Tapioca (Thin Glue) Panel	86.4 ± 0.4	609.50 ± 24.49	232.61 ± 4.95
Tapioca Starch (Regular Panel)	84.4 ± 0.7	2002.32 ± 2.96	143.97 ± 6.20
Tapioca + Pulp Sample	84.0 ± 0.3	70.225 ± 54.02	n/a
All Tapioca Starch	85.0 ± 1.2	n/a	n/a
Casein Panel	78.3 ± 0.5	2001.08 ± 2.03	232.94 ± 5.29
Casein + Pulp Mix Sample	76.8 ± 0.7	105.5 ± 13.65	n/a
All Casein	77.7 ± 1.0	n/a	n/a

The volume of the samples was not recorded as they were just being used to validate the moisture content, so the density is listed as n/a.

There is a difference in the average density between the small pulp panels and the big pulp panels. This is likely due to more pulp losses in the smaller mould, as it was harder to pack the pulp into the mould plate before the compression stage. The smaller mould plate was much harder to pack in approximately 1700 g of pulp than 2000 g in the large mould, as there was more volume to spare. This issue with pulp losses can also explain the larger standard deviation of the smaller panels, making the forming process less repeatable. The dimensions of the small panel are 172 mm x 143 mm x 43 mm, with a volume of 0.00106 m^3, and the dimensions of the large panel are 292 mm x 293 mm x 13 mm, with a volume of 0.00111 m^3. While the densities are different, the average moisture content of all pulp samples is very similar, with minimal variation at 84.8 ± 1.7%

The casein panels were found to have a similar density to the pulp panels, with an average oven-dry density of 232.94 ± 5.29 kg/m^3. These were also shown to be relatively consistent as the casein panels had a small standard deviation and similar results with dried casein glue mixed with pulp samples. The casein panel's moisture content was less than that of the pulp panel, with a moisture content of 77.7 ± 1.0%.

The tapioca starch panels were much less dense than the pulp panels, with an average oven-dry density of 143.97 ± 6.20 kg/m^3. The thin glue tapioca panels resulted in a similar density

to the pulp panels. The moisture content was similar to the pulp panels at 85.0 ± 1.2% with minimal variation.

The consistent moisture contents within each material type are promising, showing that manufacturing these panels is very repeatable. Using a minimum of five replicates should be fine for future tests as it is proven that the panels are very similar in nature.

5.1.2 Moisture Content of Panels from Oven Dry to Constant Mass in Conditioning Environment

The equilibrium moisture content of the pulp and panels was determined after conditioning at 20°C at 65% relative humidity (table 13). These are the standard testing conditions used for wood-based products in most AS/NZS and ISO testing methods.

Table 13: Moisture content of panels after conditioning at 20°C 65% relative humidity following oven drying. Mean and standard deviation of 5 replicates.

Material	Density after Conditioning (kg/m^3)	Moisture Content (%)	Final Mass after Conditioning (g)
Pulp Panel (Big)	313.60 ± 5.92	9.1 ± 0.3	352.60 ± 0.14
Pulp Panel (Small)	245.74 ± 15.02	11.5 ± 6.3	259.93 ± 15.88
All Pulp	n/a	10.5 ± 4.6	n/a
Tapioca starch panels (Thin glue)	256.92 ± 5.96	10.5 ± 0.6	91.5 ± 2.07
Tapioca starch panels (Regular)	160.43 ± 7.59	10.2 ± 3.0	348.35 ± 16.48
All tapioca starch	n/a	10.4 ± 1.3	n/a
Casein panels	267.65 ± 6.53	14.9 ± 0.4	498.28 ± 12.61

As the samples were oven-dried to constant mass, it was assumed that the moisture content of the panels upon entry into the humidity room was 0%, so the average moisture content in the table refers to how much moisture content the panels regained before reaching constant mass. For pulp panels, this was found to be 10.5 ± 4.6%; for casein panels, this was found to be 14.9 ± 0.4%; and for tapioca starch panels, this was found to be 10.4 ± 1.3%. Again, the variation is low, so the panels absorbed similar amounts of water in the same conditions. This supports using fewer replicants for testing as it shows that there is still minimal variation after conditioning.

5.2 Humidity

The effects on the panels by placing in saturated salt solution containers is shown in table 14 below. Comparing the effect of different humidities on the panels will show whether they are comparable in moisture absorption and mould growth to commercially available building products such as GIB (Sheetrock and Aqualine), MDF, SaveBOARD, and plywood.

Table 14: Moisture content percentage of the pulp, panels, and comparative industry products across a range of relative humidities at 20°C.

Material	33%RH	75%RH	95%RH
Pulp panel 1	5.6%	9.9%	16.9%
Pulp panel 2	3.1%	15.8%	16.5%
Casein panel	10.8%	19.5%	40%
Tapioca starch panel	11%	11%	16.6%
Painted tapioca starch panel	6.9%	10.3%	67.6%
SaveBOARD	5%	6.9%	11.2%
MDF	2.4%	7.2%	15.2%
5ply Wood	9.6%	13.8%	46.6%
5ply Box Lid	11.6%	17.8%	35.5%
MgO	12.1%	19.3%	29.6%
Sheetrock (GIB)	21.1%	33%	39.2%
Aqualine (GIB)	19.1%	16.3%	19.2%

Table 14 shows that the pulp panels and tapioca starch panels perform similarly to industry standards such as MDF and SaveBOARD. The casein panel was within the same range as these, though it seemed to have a massive increase in moisture content of 40.0% when exposed to KNO_3's humidity. This could indicate that mould grows faster in the casein than other panel types, but more testing should be done to determine this. However, this is irrelevant as casein is being removed due to not being financially feasible. The other industry standards, such as GIB products like Sheetrock and Aqualine, had higher moisture contents than the pulp and tapioca starch ones, as did the plywood products. The painted starch panel was a quick experiment to see the effects of painting the outside of a dried pulp panel with tapioca starch glue and redrying to have a coating. This had extreme mould growth quickly on the outside of the sample when subjected to KNO_3. The average household in New Zealand has an internal humidity of 30%-65% in dry houses or 50%-75% in damp houses (Level, 2023) during the daytime. Overnight cold rooms can reach 80-90%, so the materials may be exposed to similar conditions to KNO_3 in the worst of cases, though, as is shown in the results table above, industry products like MDF or GIB (sheetrock and Aqualine) also have a severe increase in moisture content and mould growth. Figures 38-47 show the mould growth and close ups of the panels after constant exposure for a week at the low to high humidities:

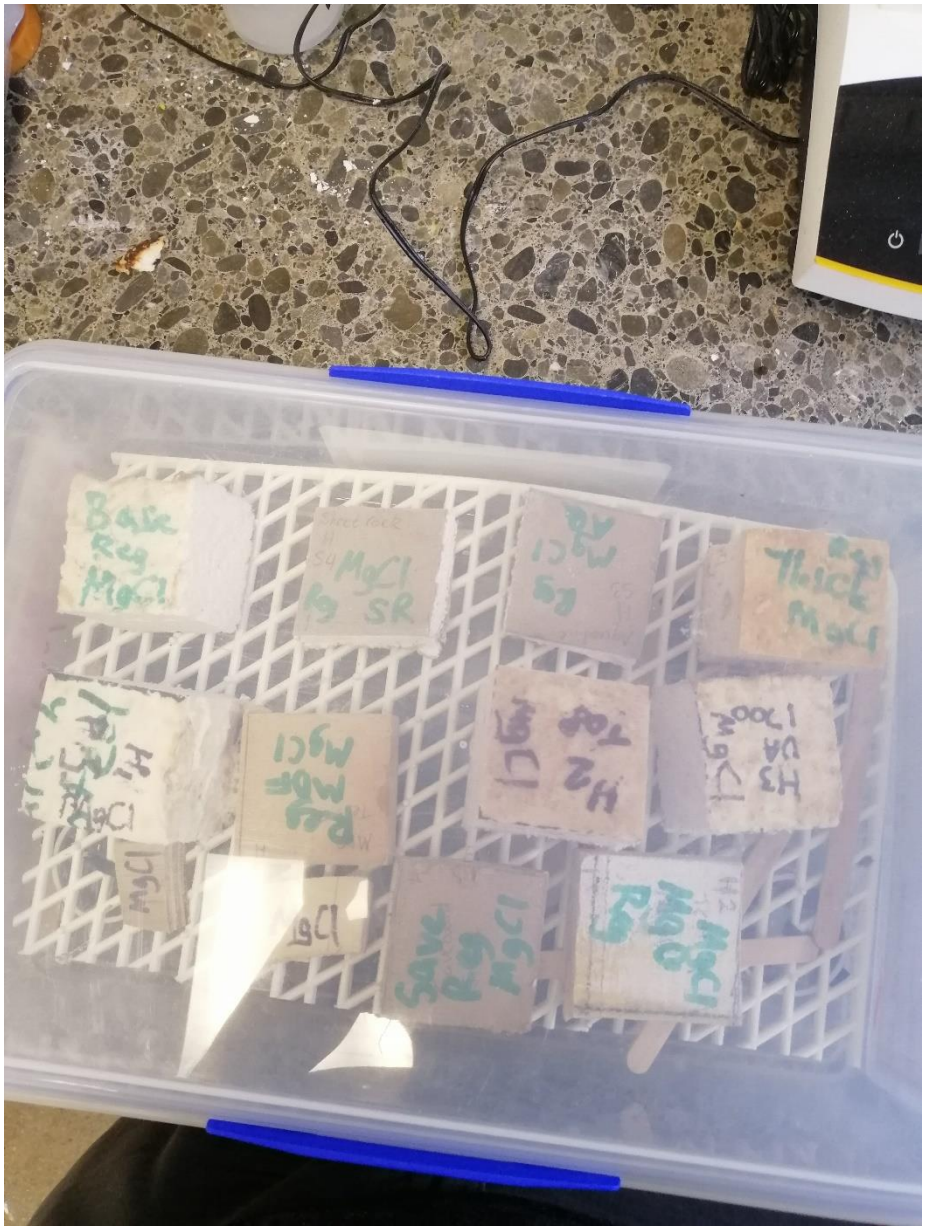

Figure 38: Specimens exposed to $MgCl_2$

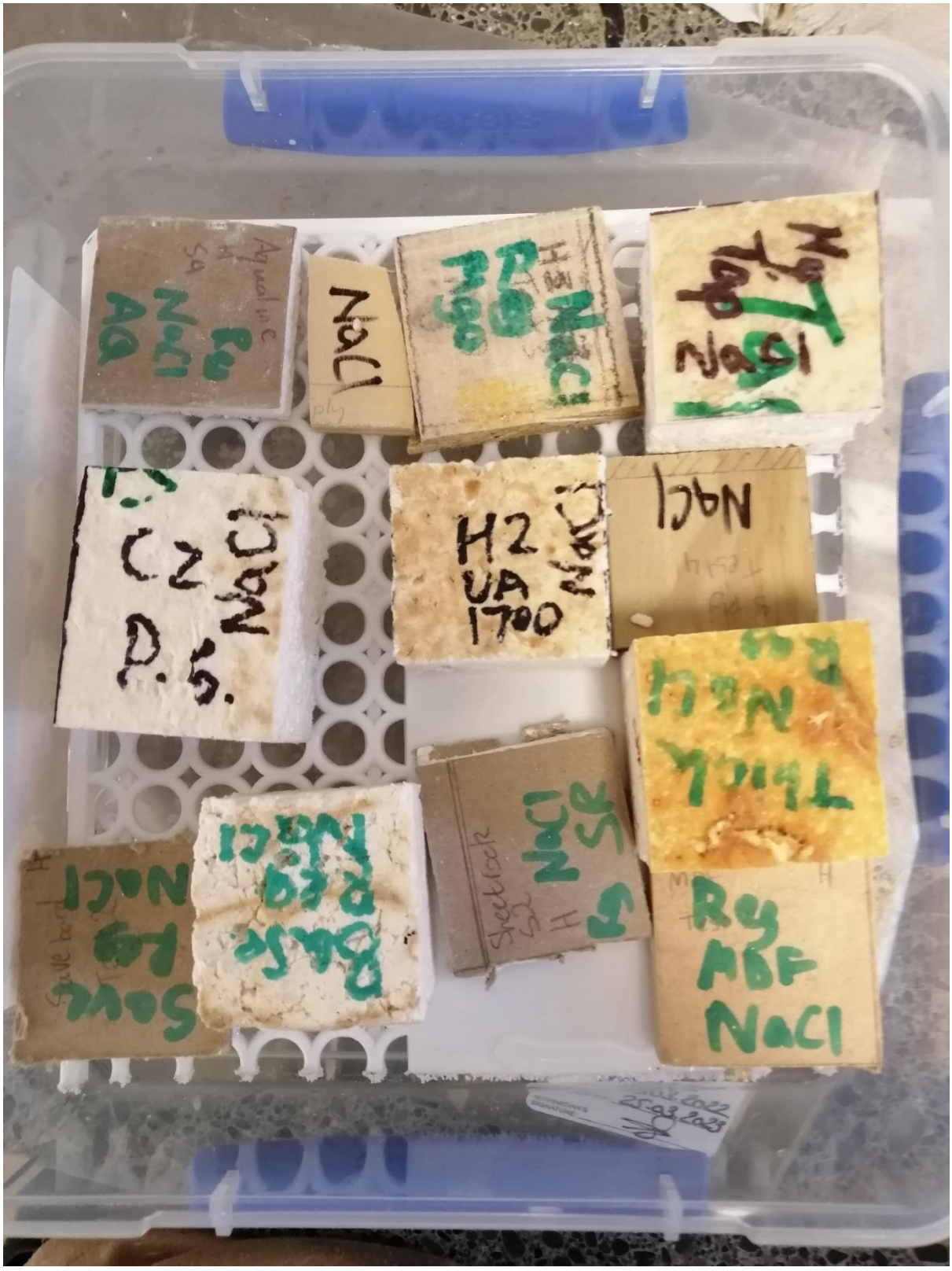

Figure 39: Specimens exposed to NaCl

Figure 40: Specimens exposed to KNO_3

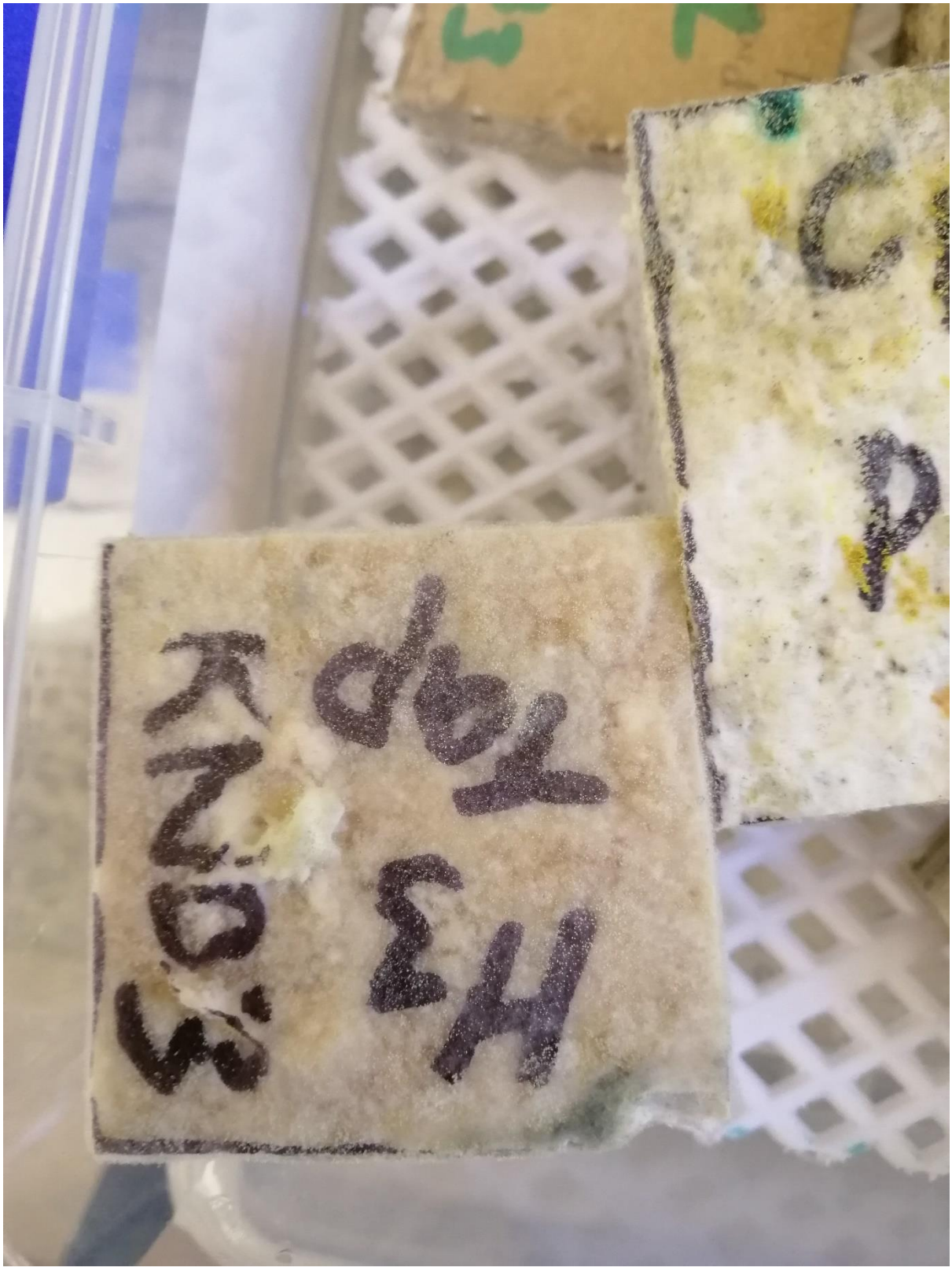

Figure 41: Close up of Tapioca Panel after exposure to KNO_3

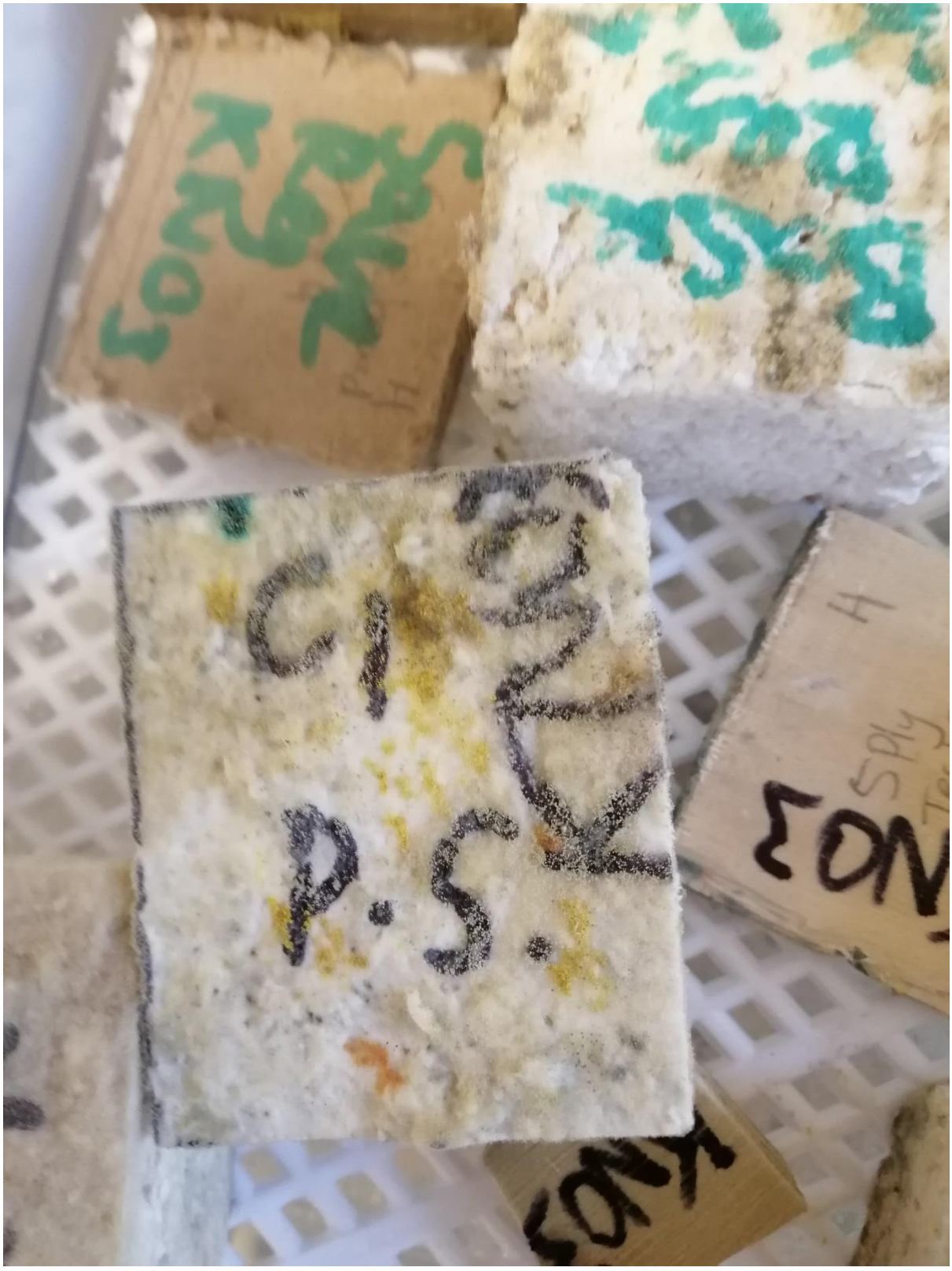

Figure 42: Close up of Painted on Tapioca Panel after exposure to KNO_3

Figure 43: Close up of regular panel (just pulp) after exposure to KNO_3

Figure 44: Close up of Sheetrock (GIB) (unreadable panel) after exposure to KNO_3

Figure 45: Close up of Casein Panel after exposure to KNO_3

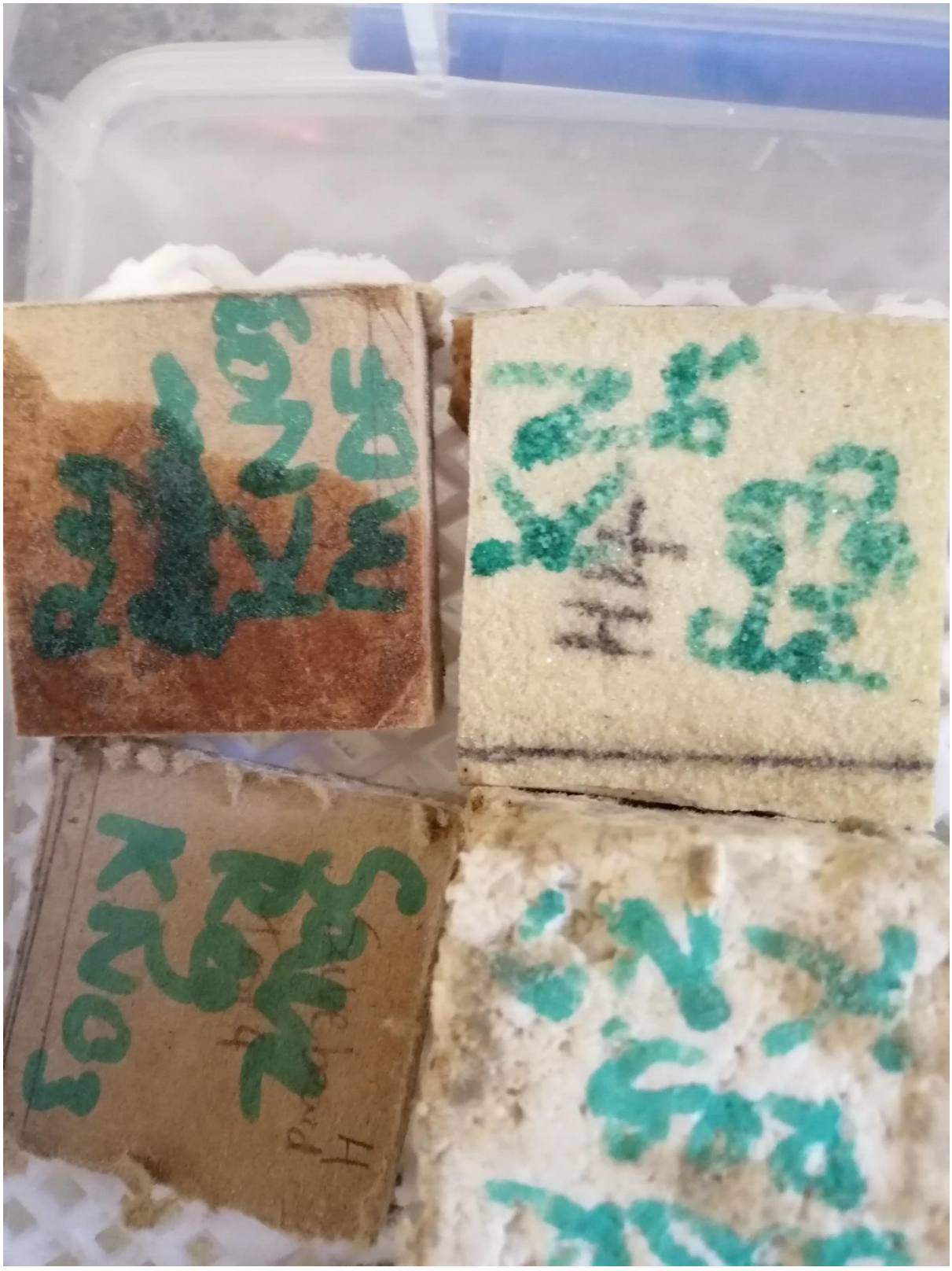

Figure 46: Close up of MDF and SaveBOARD (left) after exposure to KNO_3

Figure 47: Close up of rear of MDF after exposure to KNO_3

This shows that some industry products, such as MDF and GIB (Sheetrock), had more mould growth than the tested panels. SaveBOARD had less to no mould growth, likely due to being plastic.

5.3 Insulation (Thermal Conductivity)

5.3.1 Thermal Conductivity Data

As was discussed in the methods section, the thermal conductivities are being compared between samples, as opposed to R-values. This is because the thermal conductivities provide a better comparison while the panel thickness is still ambiguous at bench scale and not a finalised product. A better metric for insulation will be to compare this way and then compare to insulation products with specified thicknesses by applying the same thickness.

Table 15 shown below shows the average thermal conductivity of different materials.

Table 15: Average thermal conductivities of panels.

Material	Average Panel Density (kg/m^3) after humidity control	Average Thermal Conductivity (Wm^{-1}K^{-1})
Pulp panel (small)	364.4 ± 33.52	0.076 ± 0.033
Pulp panel (large)	368.1	0.064 ± 0.016
Casein	256.21 ± 32.45	0.056 ± 0.010
Tapioca Starch	155.48 ± 7.55	0.046 ± 0.005

The manufactured panels with glue additives (casein panels and tapioca starch panels) performed better than the generic pulp panels, as shown by their lower thermal conductivities. As there are differences in the manufacturing between pulp and pulp-additive panels due to no hydraulic compression for the pulp-additive, the pulp-additive panels have more air pockets through their structure, resulting in better thermal properties.

5.3.2 R-testing Analysis

The most common insulative building materials in New Zealand include EPS, glass fibre (Pink Batts), loose fill, polyester wool, and spray foam. Table 16 provides a comparison of the panels with Pink Batts. Similar glasswool products, such as earthwool and mammoth, provide similar values for the same dimensions, so Pink Batts will represent glasswool in the table. Pink Batts produce various products of varying dimensions, as outlined in (Pink Batts, 2021). It has their product range with varying lengths and widths for different applications (different densities), and their nominal thicknesses are listed alongside its R-values. For roof insulation, their thickness ranges from 50 mm at an R-value of 1.2 (R1.2) for their roof insulative blanket to 260 mm at R 7.0 for their Ultra ceiling insulation. For walls, they have 40 mm at R1.0 for their Masonry wall insulation to 140 mm at R3.2 to R4.3 for their wall range. Finally, for flooring, they have 70 mm at R 1.6 for the Snugfloor, to 150 mm for their acoustic Midfloor. Therefore, these thicknesses will be applied to the average thermal conductivities found for the pulp and pulp-additive products to determine their predicted R-values at given thicknesses. The R-value is calculated by R-value (m^{2}K/W) = Thickness (m)/Thermal Conductivity (Wm^{-1}K^{-1}).

Table 16: A comparison of thermal conductivity and R-vales of selected panels made in this work and common insulative materials used in construction. The Pink Batts thermal conductivity is calculated from the provided thicknesses and R-values.

Material	**Average Thermal Conductivity ($Wm^{-1}K^{-1}$)**	**Location**	**Thickness Range (mm)**	**R-value Range**
Pulp Panels (small and big)	0.076 for small, 0.064 for big	Flooring	70-150	R0.92-R1.97 for small R1.09-R2.34 for big
Casein Panels	0.056	Flooring	70-150	R1.26-R2.70
Tapioca Starch Panels	0.046	Flooring	70-150	R1.53-R3.27
EPS	0.028	Flooring	70-150	R2.54-R5.45
Pink Batts	0.042 – 0.067	Flooring	70-150	R1.6-R2.6
Pulp Panels (small and big)	0.076 for small, 0.064 for big	Roof	50-260	R0.66-R3.42 for small R0.78-R4.06 for big
Casein Panels	0.056	Roof	50-260	R0.90-R4.67
Tapioca Starch Panels	0.046	Roof	50-260	R1.09-R5.68
EPS	0.028	Roof	50-260	R1.82-R9.45
Pink Batts	0.037 – 0.042	Roof	50-260	R1.2-R7.0

Material	Average Thermal Conductivity ($Wm^{-1}K^{-1}$)	Location	Thickness Range (mm)	R-value Range
Pulp Panels (small and big)	0.076 for small, 0.064 for big	Walls	40-140	R0.53-R1.84 for small R0.63 - R2.19 for big
Casein Panels	0.056	Walls	40-140	R0.72-R2.52
Tapioca Starch Panels	0.046	Walls	40-140	R0.87-R3.06
EPS	0.028	Walls	40-140	R1.45-R5.09
Pink Batts	0.033 – 0.040	Walls	40-140	R1-R4.3

As for what this means regarding meeting building code regulations, the theoretical panel R-values should be compared to the R-value requirements for New Zealand, as discussed in section 2.4.1 of this thesis. The climate zones for New Zealand are also shown there and outlined in table 17.

Table 17: R-value requirements for building elements in New Zealand climate zones (South Peak Homes, 2022).

Building element	Climate Zone 1	Climate Zone 2	Climate Zone 3	Climate Zone 4	Climate Zone 5	Climate Zone 6
Roof	R6.6	R6.6	R6.6	R6.6	R6.6	R6.6
Wall	R2.0	R2.0	R2.0	R2.0	R2.0	R2.0
Floor (Slab-on ground flooring)	R1.5	R1.5	R1.5	R1.5	R1.6	R1.7
All other Flooring	R2.5	R2.5	R2.5	R2.8	R3.0	R3.0
Windows and Doors	R0.46	R0.46	R0.46	R0.46	R0.50	R0.50
Skylights	R0.46	R0.46	R0.54	R0.54	R0.62	R0.62

Comparing testing results to requirements, the pulp and pulp-additive panels are all within the requirements for walls and flooring at thicknesses similar to the ones used by industry products. This shows promise in using this as a flooring or wall product with insulative properties.

Glasswool products have a thermal conductivity of around 0.033 $Wm^{-1}K^{-1}$ - 0.067 $Wm^{-1}K^{-1}$ (different densities). It can achieve and exceed the minimum R values required at practical thicknesses. The average thermal conductivity of the pulp panels is 0.064 $Wm^{-1}K^{-1}$ for the small and 0.076 $Wm^{-1}K^{-1}$ for the big. Tapioca starch panel is 0.046 $Wm^{-1}K^{-1}$ and Casein panel is 0.056 $Wm^{-1}K^{-1}$. At practical flooring and wall insulation thicknesses, R-values that meet the building requirements could be achieved by manufactured panels, though they fall short of the industry product performance. Tapioca starch panel is the most promising as it has a thermal conductivity closer to glass wool insulation due to the lower density of these panels.

Only the Glasswool and EPS achieve the necessary requirement for roofing at their similar thicknesses, so the panels would not be suitable for roof insulation with their current properties.

5.4 Compressive Strength

The compressive strength is calculated from the recorded force and sample area data and tabulated in Appendix 8.5. The average compressive strength is shown in Table 18 below.

Table 18: Compressive strength of panels compared to common industry construction materials.

Material	Average Density (kg/m^3) after conditioning	Compressive Strength at 5% specimen height displacement (N/mm^2)
5-plywood Lid	549.88 ± 21.77	0.030 ± 0.056
5-plywood	533.57 ± 12.22	0.021 ± 0.010
Aqualine	667.33 ± 45.77	0.006 ± 0.005
Sheetrock	575.15 ± 45.21	0.007 ± 0.004
Thin Casein	259.17 ± 5.59	0.028 ± 0.009
Thick Casein	260.83 ± 18.46	0.020 ± 0.012
MDF	626.79 ± 8.89	0.020 ± 0.018
SaveBOARD	774.29 ± 24.51	0.0031 ± 0.0030
Tapioca	179.31 ± 18.41	0.015 ± 0.005
Pulp panel 2000 g	372.78 ± 73.97	0.0080 ± 0.0030
Pulp Panel 1700 g	338.34 ± 45.70	0.056 ± 0.023

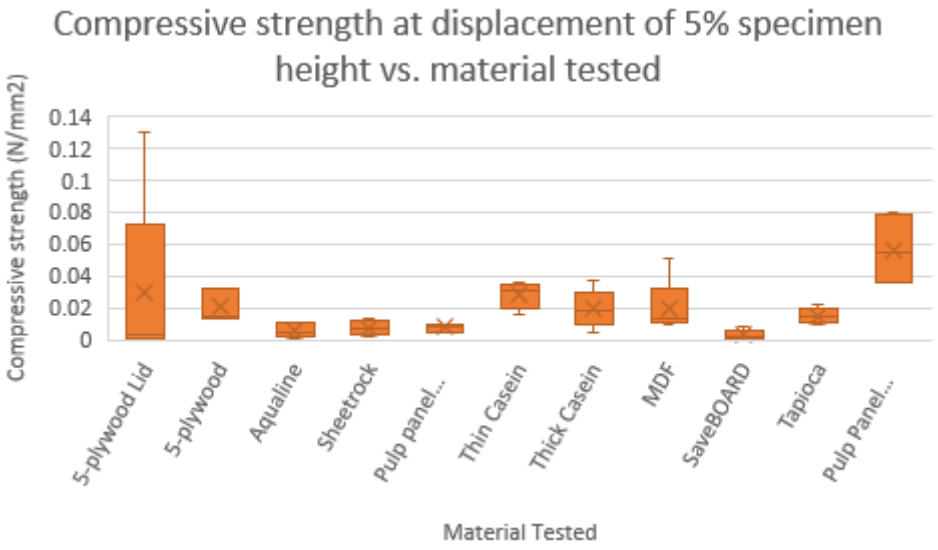

Figure 48: Compressive strength at displacement of 5% specimen height vs. material tested

Figure 48 shows the comparative data between the samples at 5% displacement. When tested on its 50 mm x 60 mm face under compressive load at 5% displacement, the lowest performing material was SaveBOARD, with an average compressive strength of 0.0031 ± 0.0030 N/mm^2. During the test, it was observed that the plastic in the material was displaced rapidly in the initial phases of the test, causing a lower compressive strength. This was followed by the GIB plasterboards, such as Sheetrock and Aqualine, which crumbled under the downward force, resulting in lower compressive strengths. The denser pulp panels (2000 g pulp in at the start of the process) were marginally better than Sheetrock, so they performed similarly to plasterboard. The other less dense pulp panels (1700 g) performed extremely well with a compressive strength of 0.056 ± 0.023 N/mm^2. Tapioca starch glue panels and thick casein panels were the following performers at roughly double and more than double the compressive strength of the dense pulp panels. Thin casein panels performed better than thick ones as the structure had fewer air pockets. Due to their more rigid structure than other tested materials, plywood and MDF performed better than most of the additive panels, with the exception of the thin casein and 1700 g pulp panels. The other plywood material from the box lid performed better than the thin casein, though it had higher variation than its store-bought plywood counterpart.

The high variation in the density values is likely due to measuring the specimens after they were cut, as opposed to measuring them in store-bought sheet form with greater precision. In hindsight, this should have been done on the full-scale product before cutting into specimens.

The regular panels were the best performers for compressive strength at 5% displacement. Figures 49-55 show the performance up to 5% displacement in graph form. From looking at the graphs, the force in all the samples seemed to increase at a constant rate except the plywood sample who's force rapidly increased with minimal displacement before eventually displacing. This indicates that wood samples are more resistant to displacement than the panel samples as the force required to do so was much higher.

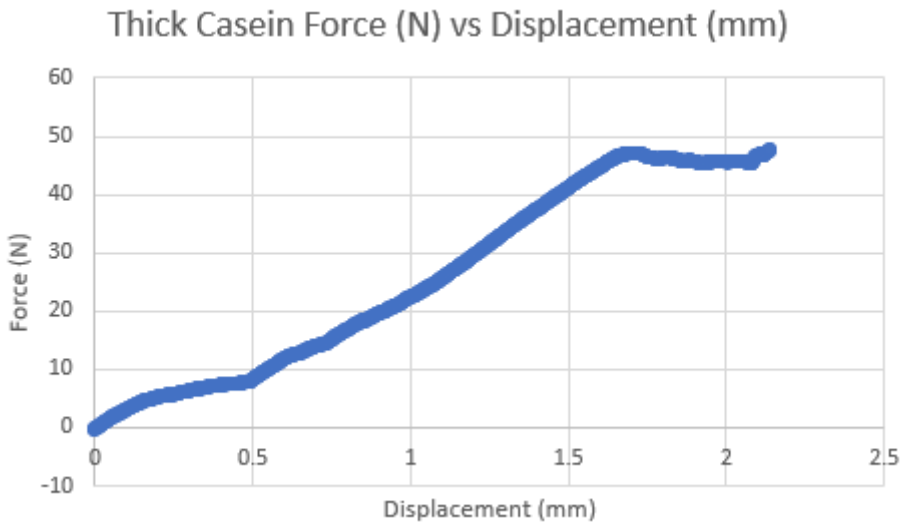

Figure 49: One specimen test of a thick casein panel sample.

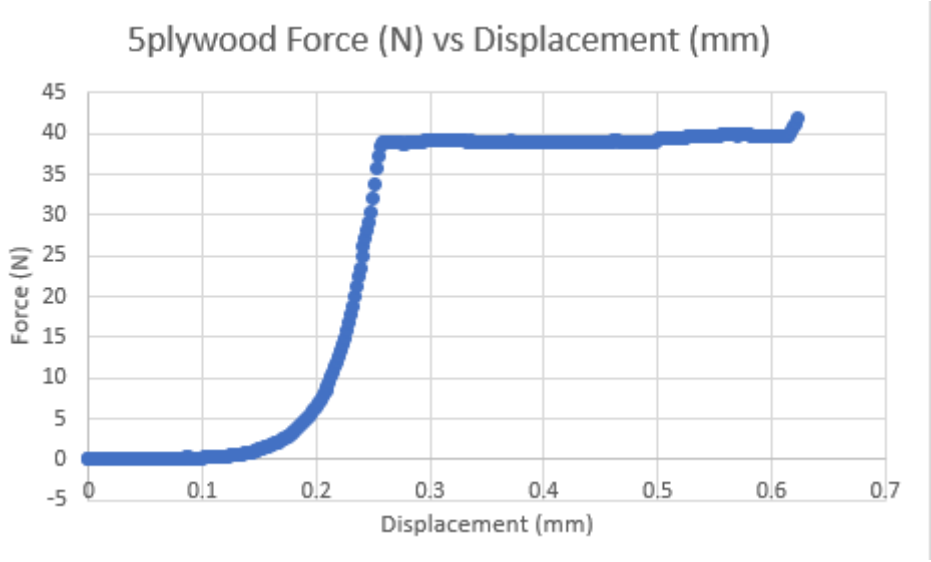

Figure 50: One specimen test of a 5-plywood sample.

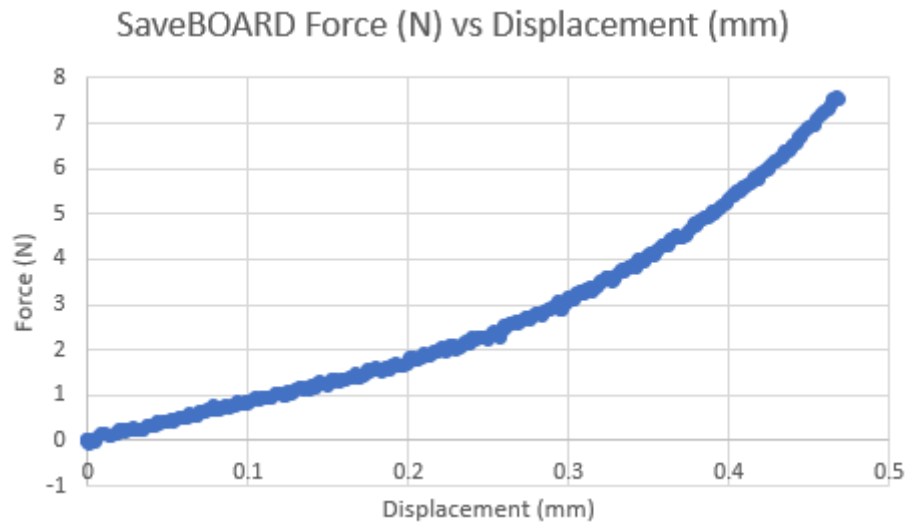

Figure 51: One specimen test of a SaveBOARD sample.

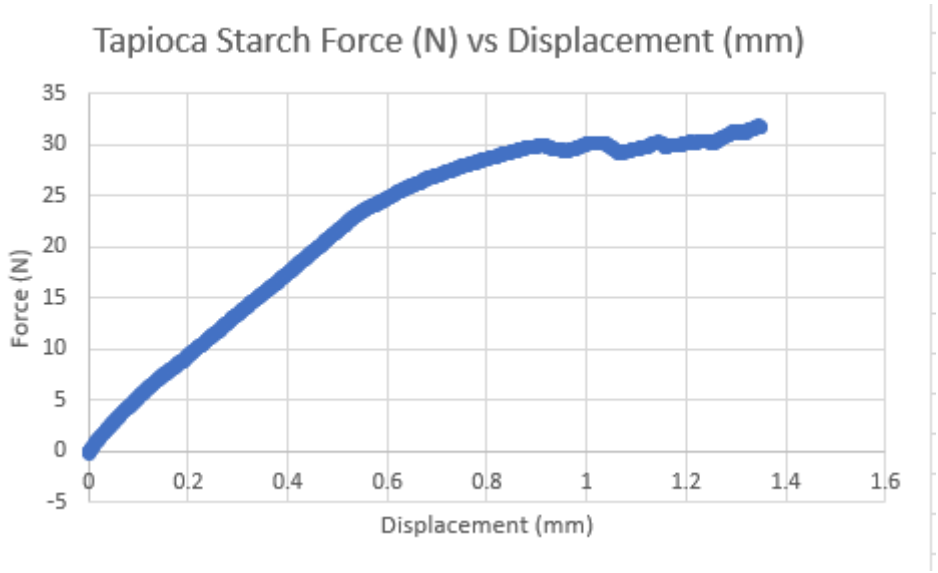

Figure 52: One specimen test of a tapioca starch panel sample.

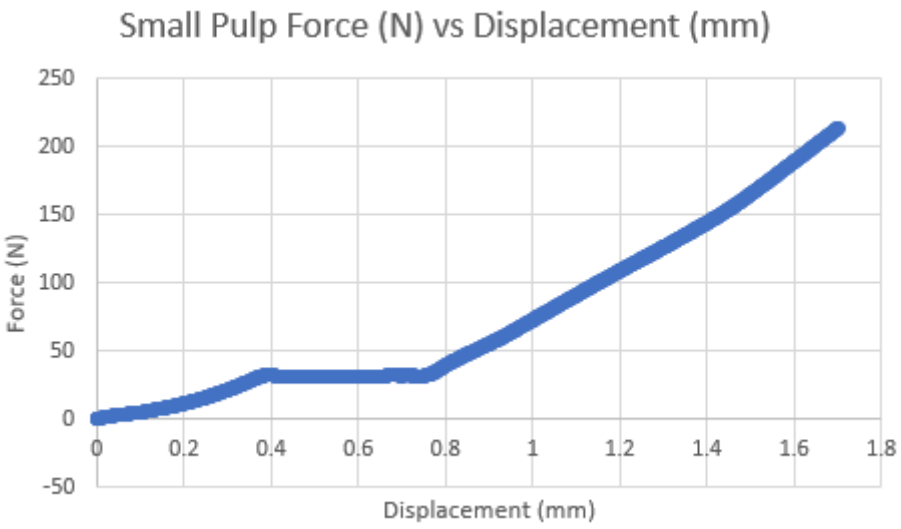

Figure 53: One specimen test of a small pulp panel sample.

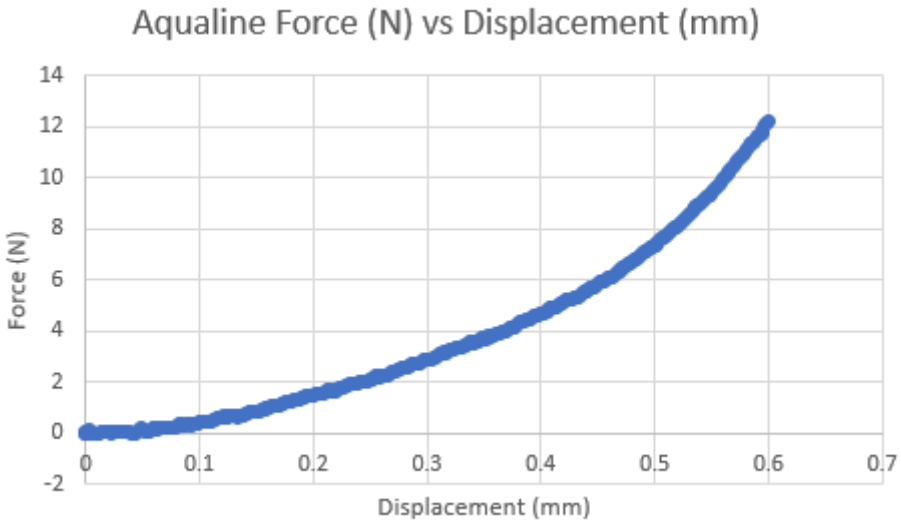

Figure 54: One specimen test of an aqualine sample.

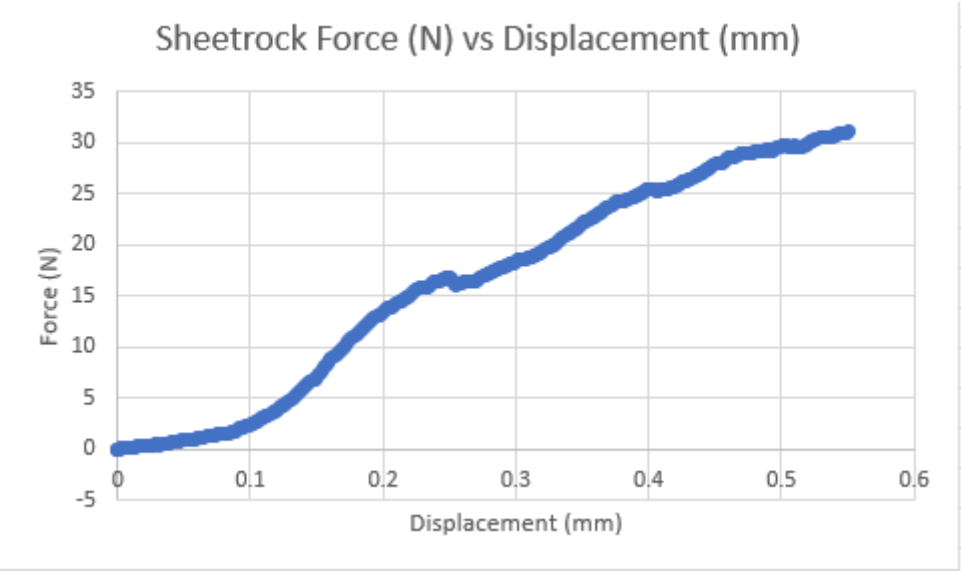

Figure 55: One specimen test of a sheetrock sample.

These graphs showed the panel samples were comparable at 5% displacement to GIB products and each other but not the plywood samples. At low forces these panels could be used as they hold up alongside GIB but for structural support with larger forces, stronger industry products may be better suited. An analysis of the mechanical strength will be in section 6.1 which will also factor in bending strength and impact resistance results.

5.5 Bending Strength

The average bending strength of manufactured panels, additive panels and comparison products are listed in table 19 below and Appendix 8.6.

Table 19: Average bending strength of panels and industry standards.

Material	Average Density after conditioning (kg/m^3)	Bending Strength (MPa)
5-plywood	537.39 ± 23.06	46.87 ± 8.55
5-plywood Lid	609.55 ± 32.93	53.85 ± 12.73
2000 g 10T Pulp	394.42 ± 27.61	0.29 ± 0.07

Material	Average Density after conditioning (kg/m^3)	Bending Strength (MPa)
1700 g 2T Pulp	367.87 ± 18.22	0.52 ± 0.13
Casein	271.28 ± 24.71	0.48 ± 0.13
MDF	632.40 ± 5.70	37.60 ± 0.73
SaveBOARD	795.81 ± 13.67	5.96 ± 1.81
Sheetrock	607.58 ± 4.62	2.84 ± 0.11
Aqualine	735.65 ± 13.29	7.27 ± 2.30
Tapioca	205.00 ± 31.94	0.92 ± 0.49

The values of plywood were used to check the accuracy of this test. The modulus of rupture (maximum bending stress before failure) of plywood is between 38.3 MPa and 68.9 MPa (Civil Jungle, n.d.), which the 5-plywood and 5-plywood lid samples, on average, fall under.

The data shows that all of the manufactured pulp and pulp-additive panels had lower bending strength than GIB and SaveBOARD products and significantly lower than all tested wood products. This indicates that the pulp-based materials should not be used as load bearing but could still be used in conjunction with another load-bearing material. Of the manufactured materials, tapioca performed better than casein or pulp, which indicates this structure is marginally better. Figures 56 and 57 show some of the materials after failure has occurred from bending.

Figure 56: Bending test on plywood sample

Figure 57: Bending test on casein panel sample

5.6 Impact Resistance

The average impact resistance of the manufactured panels, additive panels, and comparison products are shown in Table 20 below and Appendix 8.7.2. The accuracy of the testing machine was checked before the test and is shown in Appendix 8.7.1.

Table 20: Average impact resistance of panels and industry comparisons.

Material	Average Specimen Density (kg/m^3) after humidity control	Average Impact Resistance under notch (J/m)
2000 g in at start 10T Base (Just Pulp)	308.50 ± 26.76	0.0099 ± 0.018
4000 g in at start 5T Base (Just Pulp)	315.69 ± 16.68	0.062 ± 0.027
Sheetrock (GIB)	549.51 ± 41.33	0.0051 ± 0.0031
Aqualine (GIB)	670.21 ± 35.58	0.0081 ± 0.0030
5-plywood Lid – random plywood on hand from box lid	563.08 ± 32.82	0.096 ± 0.053
SaveBOARD	750.88 ± 55.11	0.10 ± 0.075
Tapioca	195.94 ± 11.85	0.070 ± 0.043
Casein	244.77 ± 16.74	0.036 ± 0.024
MDF	554.30 ± 21.45	0.13 ± 0.0085
5-plywood – thicker store bought plywood	504.20 ± 22.79	0.18 ± 0.056

The lowest performers in terms of impact resistance were the GIB products at 0.00501 ± 0.0031 J/m for Sheetrock and 0.0081 ± 0.0030 J/m for Aqualine, as the plasterboard nature caused the specimens to break easily upon impact. The casein panels at 0.036 ± 0.024 J/m were better performers than the plasterboards, though they were outperformed by the slightly denser pulp panel (4000 g at 5T) and tapioca panel. As the 4000 g panel underwent

49 kN (5 tons of mass) of compression during manufacturing compared to the 19.6 kN (2 tons of mass), fewer air pockets will be present in the structure, and the material will be slightly stronger. Surprisingly, the tapioca starch glue panel performed almost twice as well as the casein glue. All of these are, however, slightly outperformed by the plywood lid, MDF, and SaveBOARD and massively outperformed by the store-bought plywood, which came in at a value of 0.18 ± 0.056 J/m. From these results, it can be determined that the panels are average at impact resistance as they have comparable results. However, they offer no benefits over existing products, which suggests this should not be a selling point of the panels. Impact resistance is helpful to know if the panels were ever used as a cladding-type product on the exterior layer of the walls, which suffer external damage from things such as stones (ISO, 1988). Figures 58-60 show how some samples failed under impact.

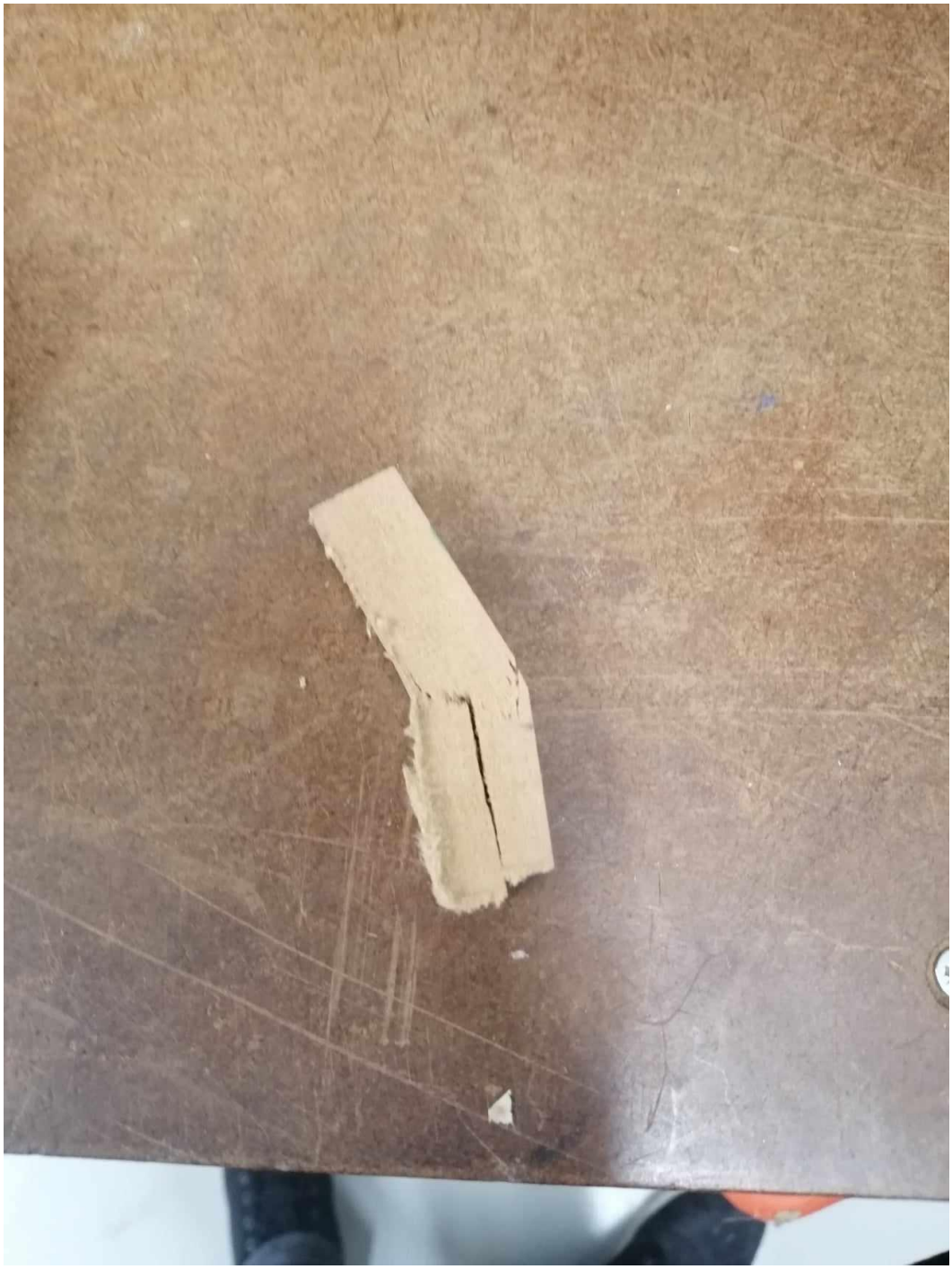

Figure 58: MDF sample failure after impact

Figure 59: Pulp sample loaded in testing rig before impact

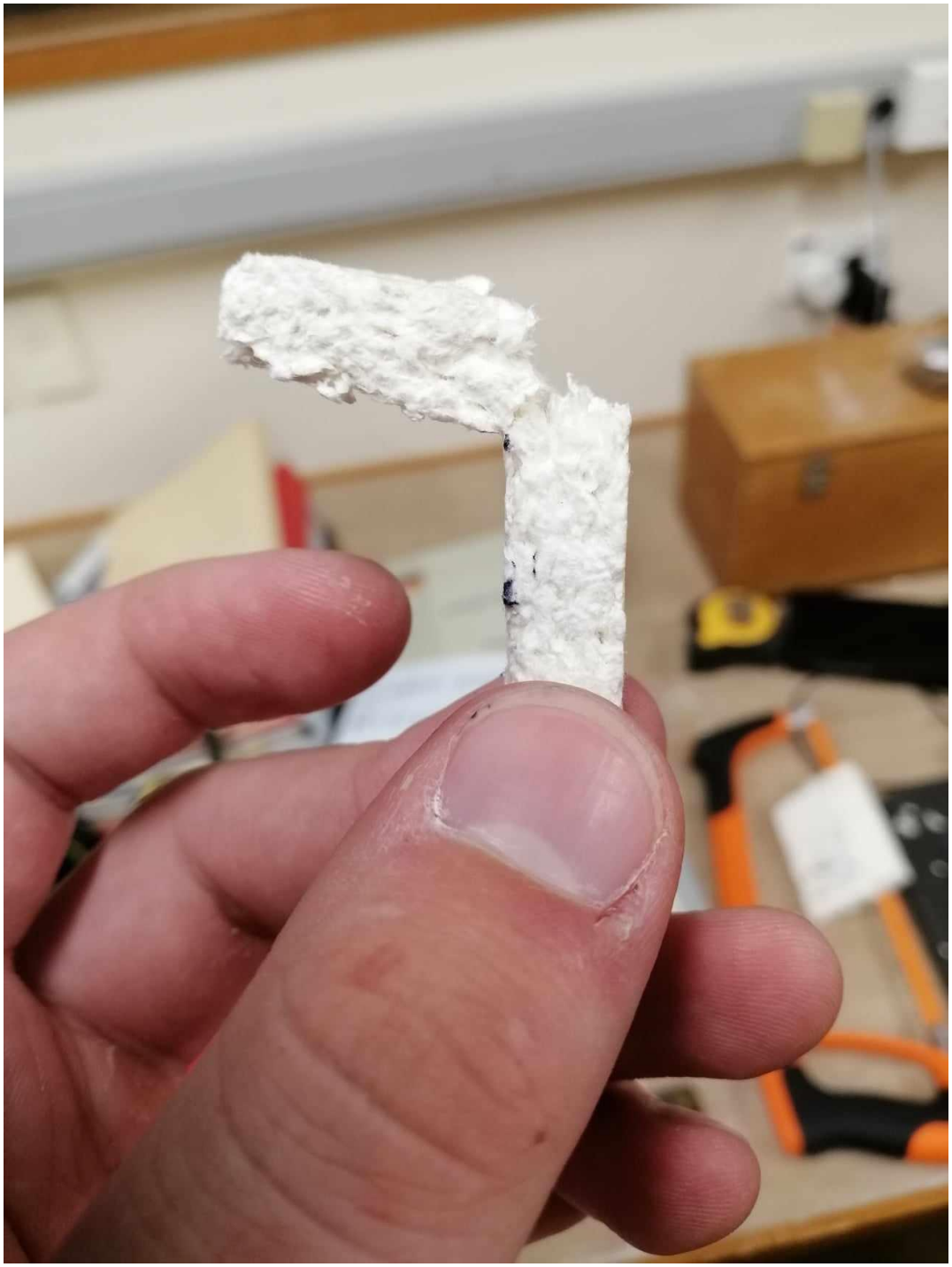

Figure 60: Pulp sample failure after impact

6.0 Conclusions and future development

This thesis covered the research, development, and testing of fibre insulation panels and showed the progression from a benchtop concept to a viable panel with specifications comparable to existing products. Tests followed those done on similar products such as wood products, plasterboards, and relevant sections in the building code.

The research questions, as outlined in the introduction, were met.

- What manufacturing methods and binders are used for similar products in the industry that can be incorporated into the panel-making process? – Research and development of binders was undertaken. Different binders and adhesives were incorporated into the panels, with the tapioca starch being found to be the most promising. The manufacturing processes followed were similar to the methods used to produce MDF and plasterboard.
- What certifications and standards need to be met to be viable for New Zealand homes? – Certifications and standards were outlined by research into the Building Code and by looking into similar products, including wood products and plasterboards, to determine what was required.
- What tests must be done to meet these certifications and standards, and how will they be performed? – Following the research into certifications, standards, and similar products, testing was devised using the test method and are outlined in the methods section (section 4.0).
- What can be done to improve these panels further after the scope of this research is finished? – This was outlined based on what testing is still required to convert the panels into a commercially viable product and is discussed in 6.3.

The rest of this section will cover how the panels performed overall, what the best performer was, and how it compares to industry products and the building code. A discussion will be made of potential applications for this panel, including alternative use cases. Future development will outline the following steps to scale up the product: future tests, new manufacturing techniques, certification, and more stakeholder interaction (builders and building companies).

6.1 Overall Performance of Panels Against Building Code and Similar Products

Density, Moisture and Mould Growth

As is shown in section 5.1, the tapioca starch panel (regular) had the lowest density of the tested panels at 143.97 ± 6.20 kg m-3. This is ideal as a lighter panel will be easier to handle and install for builders. At general room conditions where panels were conditioned to 20°C at 65% relative humidity, the pulp and tapioca panels only absorbed about 10% humidity, while the casein panel absorbed about 15%. In the humidity tests (section 5.2), again, casein absorbed more moisture than pulp and tapioca starch panels. Water absorption was a desirable trait in similar properties, as outlined in the literature review on similar products, as it allowed for condensation to be removed from the household. In this regard, the casein panel is marginally better due to a higher moisture content than other panels across the

different humidity. However, further testing on how increased moisture content affects its performance to structural tests should be done before determining this. However, as the panels are not used for structural purposes, this is irrelevant (see mechanical performance below).

The pulp panels and tapioca starch panels all compared well in different humidity against industry products like MDF and SaveBOARD and had better mould resistance than GIB Sheetrock and were comparable to MDF (see table in section 5.2). Casein had a lot of mould growth at high humidity, indicating the panel may not be desirable. So, in the moisture and mould growth regard, the panels are similar in performance to industry products, which means it should be fine for the building code internal moisture.

Insulation Performance

The tapioca starch panel was the best insulator of the manufactured panels as it had the lowest thermal conductivity compared to the casein panels and pulp panels.

The thermal conductivity of the pulp and pulp-additive panels ranges from 0.046 ± 0.005 to 0.076 ± 0.033 $Wm^{-1}K^{-1}$. In comparison, common insulation materials (pink Batts, earth wool, EPS, and mammoth) have reported thermal conductivity values of 0.033 $Wm^{-1}K^{-1}$ to 0.067 $Wm^{-1}K^{-1}$, so they outperform the manufactured panels in the best case. In order to meet their top insulation R-value of R7.0, the best-performing panel in this work (tapioca starch), would need to be 19.3% thicker than the other insulation. This was chosen over the roof requirements of R6.6 to better compare to what competitor products can achieve. In most construction, the wall thickness is constrained, and the pulp panels would not be suitable. Underfloor and ceilings may be an option for increased thicknesses as from the literature; it was only found that there is a minimum thickness. The panels did have good insulative properties, so they can be used in conjunction with another material to help a home meet the minimal insulation requirements set out in the building code or potentially used in ceilings or under flooring depending on the insulation market saturation (outside the scope of this Master's).

Mechanical Performance

At the standard 5% height displacement for compressive displacement, the panels were comparable to MDF and plywood and outperformed GIB products.

In the three-point bending, the panels did not come close to being comparable to wood, as they differed by approximately two orders of magnitude. For example, a pulp panel had a bending strength of 0.52 ± 0.13 MPa, compared to 5-plywood, having a bending strength of 46.87 ± 8.55 MPa. They were somewhat comparable to SaveBOARD and GIB (5.96 ± 1.81 for SaveBOARD, 2.84 ± 0.11 for Sheetrock, and 7.27 ± 2.30 for Aqualine), though it was still outperformed by these by an order of magnitude. Tapioca starch was the best out of the pulp or pulp-additive panels. Scaling up the panel may cause structural integrity issues where it may fail under its weight, though this will have to be tested. Fixing the panel to other objects will mitigate this issue (see sections 6.2 and 6.3).

The tapioca starch panel had the highest impact resistance of the panels developed in this work (0.070 ± 0.043 J/m), followed by the casein (0.036 ± 0.024 J/m) and the regular pulp panel (0.0099 ± 0.018 J/m for the 2000 g 10 T panel, and 0.062 ± 0.027 J/m for the 4000 g 5T panel). The impact resistance of these panels compared favourably to some standard industry boards, including GIB (0.0051 ± 0.0031 J/m for Sheetrock and 0.0081 ± 0.0030 J/m for Aqualine), and was higher than SaveBOARD (0.10 ± 0.075 J/m). As expected, the impact resistance of MDF and plywood were significantly higher at 0.13 ± 0.0085 J/m (MDF), 0.18 ± 0.056 J/m (5-plywood store-bought), and 0.096 ± 0.053 J/m (5-plywood lid).

Overall, the results from the mechanical performance tests indicate that panels made in this work would not be suitable for bracing or structural support as the relevant properties are inferior to the existing alternatives, namely market leaders GIB, MDF, plywood, and more. Even alternative products like SaveBOARD outperformed the panels overall. It is recommended that the P21 bracing test will not be necessary for future testing. These tests have demonstrated that the pulp panels would perform poorly against this standard and are unlikely to meet structural Building Code requirements.

The best-performing panel of the manufactured ones was tapioca starch, as it was the least dense, best in insulation, and marginally better than the other pulp panels at bending strength and impact resistance. This method will be taken forward for further development.

6.2 Potential Use Cases

Conversations with building stakeholders

Through conversations with the Natural Building workshop, they have identified some areas in which the panels may be used. As a non-load bearing internal wall, the panel would not need bracing and maybe not fireproofing – though this should be followed up on with BRANZ (Natural Building Workshop, 2023).

They suggested the panel could be used for internal insulation attached to GIB or other wall materials to provide non-thermal bridging. Non-thermal bridging refers to heat flow between conductive materials (Progressive Foam, 2023). This source also outlines that 25% of the materials in a household wall (overseas) are made of wood studs that create cold spots with no insulation. Insulation is used to cover the studs, so this could be a potential place the panels could be used by looking into how and where studs are installed and seeing if there is a way to cover these with the panels.

A different conversation with another company (X-Frame, 2023), provided some ideas for use cases, such as looking into the panel's acoustic properties and using it as a PET acoustic replacement panel. They said replacing PET is ideal because it is made of plastic. Replacing it would need a stable thickness with minimal variation, consistent colouration, a nice finish, and uniform panels that are 12 mm thick for households. As the current acoustic properties of the tapioca panel are unknown, this should be tested before going down this avenue. The stable thickness and uniform panels are hard to achieve at bench scale, so it would require significant development to achieve this in a pilot plant. Another suggestion was softboards, which are used at schools and are relatively low-cost boards.

ITI Timspec discussed a few uses for this panel (ITI Timspec, 2023). Placing between frames in a building where EPS foam is, was a potential use case, though it would need to be 90 mm thick. Replacing it would require the same or better insulative properties, and through testing, this has been determined not to be the case, so this should not be the use case. They suggested another placement for the material as an air-tight seal for the nogging space of a house, which is a part of the house's framing. In future development, this will be looked into as a potential area to place the panels.

Other conversations with Massey staff in Wellington have suggested looking into furniture potential use cases and seeing if the material can be extruded into different forms rather than made into a panel (Massey University Wellington Staff, 2023).

Conversations with an architect also discussed looking into prefabricated walls that can be made to a set size and placed up quickly, like in example builds (Sutherland, 2023).

6.3 Future Development

Conversations with building stakeholders

The Natural Building workshop also said some areas to develop further in the future. Looking into breathability/vapour transmission between materials is an important factor that improves homes' air quality. Further research and testing will determine how the tapioca starch panel performs compared to industry products and against standards (Natural Building Workshop, 2023).

Other areas of consideration include how fixings are performed between the panel and whatever it is attached to. They said methods of attachment without glues are more desirable as the product can be broken down at its end of life without any unsustainable product attached to it (Natural Building Workshop, 2023).

ITI Timspec suggested looking into a multi-layer dense board with a denser part on the exterior side and a less dense one on the internal side. Something similar can likely be tried at a bench scale and tested, so this will be done. Another suggestion was to consider how the product would be used, such as how to trim or run wiring, fit the toilet system, what hand tools can be used to cut this material, etc. (ITI Timspec, 2023).

Other future development

To scale up the product, more discussions, and potential partnerships with BRANZ and building industry people will help get the panel to market. Scaling up will be done in two stages. The first will involve moving to larger batch processes. The second involves scaling up to a pilot plant. Scaling up will include manufacturing a bigger mould to create larger panels. A shredder or wet disintegrator will still be used for churning the paper towels into pulp.

Similarly, a larger press, such as a roll press system, will be needed to flatten the pulp and additive into a large panel. These processes could be combined into a hot roller press system. Pressing the panels less so there are more air gaps and a thicker panel will be

desirable for higher insulation. Doing so will result in more water that needs to be dried out of the panel. A more efficient method should be investigated including leaving the pulp to drain naturally through a mesh before the pressing stage or putting less water into the wet disintegrator.

A different drying method may need to be done, as larger panels may not fit in an oven unless smaller panels are made with a joining method that attaches multiple panels together. Looking into waste heat could be an option as well. The waste heat from industrial processes could dry the panels, as 60°C works well for drying. Other testing that should be done is acoustic testing to determine the properties and see if going that pathway is viable. Finances are another area that needs further development. Operating Expenditures (OpEx) and Capital Expenditures (CapEx) should be looked into to optimise the financial aspects of this product and determine its viability.

Optimising the formula and manufacturing methods of the panels still needs to be done to find the best-performing combination of ingredient quantity, processing time (wet disintegrator, oven dry, etc.) and desired panel by the building industry. Many of these will be determined at the pilot plant scale.

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8.0 Appendix

This Appendix includes raw data for all tests. Average tables are included in the results section 5.0 under their relevant sections. The panel numbers are used to show that data came from different panels. If data comes from the same panel it is labelled “sample number.specimen number” to show where the specimens came from.

8.1 Pulping Water Losses and Moisture Content

Table 21: Measuring water lost through cheese cloth process

	Paper Towels in Wet Disintegrator (g)	Water in Wet Disintegrator (g)	Water drained out of cheese cloth (g)	Water remaining in pulp after draining (g)	Mass of pulp after draining (g)	Moisture content after cheese cloth draining (%)	Solid content after draining (%)
	232.1	3725	2430	1295	1527.1	84.8	15.2
	231.8	3710	2645	1065	1296.8	82.1	17.9
	232.8	3685	2715	970	1202.8	80.6	19.4
	231.5	3595	2715	880	1111.5	79.2	20.8
	230.2	3680	2710	970	1200.2	80.8	19.2
	230.8	3510	2640	870	1100.8	79	21
	229.9	3515	2730	785	1014.9	77.4	22.6
	230.0	3455	2710	745	975.0	76.4	23.6
	230.4	3640	2890	750	980.4	76.5	23.5
	230.7	3745	3040	705	935.7	75.3	24.7
Average (g)	231.0	3626	2723	904	1134.5	79.2	20.8
Std Deviation	1.0	102	159	180	180.8	2.9	2.9

8.2 Moisture Content

This contains the raw data of the moisture content of paper towels, the raw data from the pulp stage to oven dry, and the raw data from oven dry to constant mass at relative humidity.

8.2.1 Moisture Content of Paper towels

Table 22: Paper towels moisture content

Material	Initial Mass (g)	Final Mass (kg)	Moisture Content (%)	Water Content (g)
Used paper towels slightly damp from sitting in storage room a while	28.3	21.4	24.38163	6.9
Fresh paper towels from same storage room	11.3	10.4	7.964602	0.9

8.2.2 Moisture Content Start to Oven Dry Raw Data

Pulp Panels

Table 23: Moisture content raw data for small pulp panels (SP), big pulp panels (BP) and pulp samples (PS).

Material	Panel Number	Mass of pulp in (g)	Oven Temperature (°C)	Force Applied (kN) – if any	Final mass (g) – Constant mass after 24 hr weighing	% Moisture Content of panel after hydraulic press	Water Content (g)	Dry Content (g)
SP	1	1600.7	60	19.6	227.9	85.8	1372.8	227.9
SP	2	1650.6	60	19.6	233.4	85.9	1417.2	233.4
SP	3	1701.0	60	19.6	233.6	86.3	1467.4	233.6
SP	4	1501.2	103	19.6	237.4	84.2	1263.8	237.4
SP	5	1600.1	103	19.6	211.2	86.8	1388.9	211.2
SP	6	1600.4	103	19.6	216.5	86.5	1383.9	216.5
SP	7	1650.2	103	19.6	218.7	86.7	1431.5	218.7
SP	8	1700.0	103	19.6	212.2	87.5	1487.9	212.2
SP	9	1600.2	60	19.6	228.7	85.7	1371.5	228.7
SP	10	1700.0	60	19.6	275.1	83.8	1424.9	275.1
BP	1	2000.5	103	98.1	323.4	83.8	1677.0	323.4
BP	2	2000.7	103	98.1	313.6	84.3	1687.1	313.6
BP	3	2000.7	103	98.1	313.5	84.3	1687.3	313.5
BP	4	2000.4	103	98.1	322.1	83.9	1678.3	322.1
BP	5	2000.3	103	98.1	318.2	84.1	1682.1	318.2
PS	1	67.2	103	n/a	13.1	80.6	54.1	13.1
PS	2	98.5	103	n/a	15.9	83.9	82.6	15.9

Material	Panel Number	Mass of pulp in (g)	Oven Temperature (°C)	Force Applied (kN) – if any	Final mass (g) – Constant mass after 24 hr weighing	% Moisture Content of panel after hydraulic press	Water Content (g)	Dry Content (g)
PS	3	45.6	103	n/a	7.4	83.9	38.2	7.4
PS	4	31.9	103	n/a	5.4	83.2	26.6	5.4

Casein Panels

Table 24: Casein Panel Ingredients.

The additives were made in batches and used for multiple panels. The panels it was used for are listed in the table.

Casein Glue Mix Number	Used for panels	Casein Powder (g)	Water with casein powder (g)	Sodium Hydroxide (g)	Water with Sodium Hydroxide (g)	Calcium Hydroxide (g)	Water with Calcium Hydroxide (g)	Pulp used with casein glue mix (g)	Total Mass of Mix (g)
1	1, 2 & sample 1	502.9	750.1	55	250.1	100.0	251.3	2501.7	4411.1
2	3, 4 & sample 2	503.1	751.2	55	250.9	100.0	249.5	2500.1	4409.8
3	5 & sample 3	500.6	751	55	250.6	102.6	253.5	2501.6	4414.9

Table 25: Moisture content raw data for casein panels (CP), and casein and pulp samples (CPS)

Material	Panel Number	Mass of mixture in (g)	Oven Temperature (°C)	Final mass (g) – Constant mass after 24 hr weighing	% Moisture Content of panel after Wet Disintegrator blending	Water Content (g)	Dry Content (g)
CP	1	2000.2	103	418.7	79.1	1581.5	418.7
CP	2	2000.0	103	439.5	78.0	1560.5	439.5
CP	3	2000.4	103	434.5	78.3	1565.9	434.5
CP	4	2000.1	103	430.9	78.5	1569.2	430.9
CP	5	2004.7	103	444.7	77.8	1560.0	444.7
CPS	1	90.1	103	21.1	76.5	69.0	21.1
CPS	2	116.1	103	26.1	77.5	90.0	26.1
CPS	3	110.3	103	26.2	76.2	84.1	26.2

Tapioca Starch Panels

Note: Panel 4 was made with combination of mixtures. This will still be used for moisture content calculations of the panel as the amount of mass to create the panel is known but don't know exact ingredient mass, though all are very similar. There are plenty of samples to prove accuracy anyway.

The thin glue panels were experimental by being made with more water. The first mix of thin glue was made with all water directly into the pot, though it took longer to cook with all the extra water as a heat sink that had to be boiled off, leaving a very similar end result as regular method. The second batch of thin glue had the standard amount of water put in with the tapioca starch (1500 g), and once it was all cooked, an additional 1000 g was added to water down the mixture.

Table 26: Tapioca Starch Panel Ingredients

Tapioca Starch Glue Mix Number	**Used for panels**	**Tapioca Starch (g)**	**Water with tapioca starch (g)**	**Pulp used with tapioca (g)**	**Total Mass of Mix (g)**
Regular 2	1 & sample 2	320.0	1500.3	2000.5	3820.8
Regular 3	2 & sample 3	320.4	1531.0	2000.9	3852.3
Regular 4	3 & sample 4	320.1	1526.2	2000.1	3846.4
Regular 5	5 & sample 5	323.9	1527.2	2000.0	3851.1
Regular 4	3, 4 & 5 leftovers	n/a	n/a	n/a	n/a
Thin Glue (extra water) 1	Thin panels 1, 2 & 3	300.0	2518.0	2001.3	4819.3
Thin Glue (extra water) 2	Thin panels 4 & 5	300.0	2500.0	2000.0	4800.0

Table 27: Moisture content raw data for tapioca panels (TP), and thin tapioca panels (TTP) and tapioca and pulp samples (TPS)

Material	Panel Number	Mass of mixture in (g)	Oven Temperature (°C)	Final mass (g) – Constant mass after 24 hr weighing	% Moisture Content of panel after Wet Disintegrator blending	Water Content (g)	Dry Content (g)
TP	1	1998.8	103	318.2	84.1	1680.6	318.2
TP	2	2002.5	103	309.0	84.6	1693.5	309.0
TP	3	2002.4	103	333.2	83.4	1669.3	333.2
TP	4	2001.0	103	299.8	85.0	1701.2	299.8
TP	5	2006.9	103	302.8	84.9	1704.1	302.8
TTP	1	623.4	103	85.1	86.3	538.3	85.1
TTP	2	641.2	103	84.4	86.8	556.8	84.4
TTP	3	612.6	103	81.4	86.7	531.2	81.4
TTP	4	583.5	103	81.7	86.0	501.8	81.7
TTP	5	586.8	103	81.6	86.1	505.2	81.6
TPS	2	42.2	103	6.7	84.2	35.5	6.7
TPS	3	145.0	103	23.1	84.1	122.0	23.1
TPS	4	72.2	103	11.5	84.1	60.7	11.5
TPS	5	21.5	103	3.5	83.6	18.0	3.5

8.2.3 Moisture Content Oven Dry to Constant Mass in Controlled Humidity (20°C 65% Humidity)

Note: It is assumed that the moisture content of the panels after completely drying in the oven is 0%

Pulp Panels

Table 28: Moisture content data of small pulp panels (SP) and big pulp panels (BP) from oven dry to constant mass in controlled humidity (20°C 65% Humidity)

Material	Panel Number	Mass entering humidity room (g) – Mass after completely drying in oven	Final Mass (g)	Change in moisture content after conditioning in humidity room (%)	Water Content (g) - Assuming 0 g after oven, just change in mass is water absorbed	Dry Content (g) – Should just be mass after drying in oven
SP	1	227.9	246.2	8.0	18.3	227.9
SP	2	233.4	252.4	8.2	19.1	233.4
SP	3	233.6	282.5	20.9	48.9	233.6
SP	4	237.4	258.6	8.9	21.1	237.4
BP	1	323.4	352.7	9.0	29.3	323.4
BP	2	313.6	Contaminated sample (fell in salt bath)	n/a	n/a	313.6
BP	4	322.1	352.5	9.4	30.4	322.1

Casein Panels

Table 29: Moisture content data of casein panels (CP) from oven dry to constant mass in controlled humidity (20°C 65% Humidity)

Material	Panel Number	Mass entering humidity room (g) – Mass after completely drying in oven	Final Mass (g)	Change in moisture content after conditioning in humidity room (%)	Water Content (g) - Assuming 0 g after oven, just change in mass is water absorbed	Dry Content (g) – Should just be mass after drying in oven
CP	1	418.7	478.8	14.4	60.1	418.7
CP	2	439.5	507.5	15.5	68.0	439.5
CP	3	434.5	499.9	15.1	65.4	434.5
CP	4	430.9	494.5	14.8	63.6	430.9
CP	5	444.7	510.7	14.8	66.0	444.7

Tapioca Panels

Table 30: Moisture content data of tapioca panels (TP) and thin tapioca panels (TTP) from oven dry to constant mass in controlled humidity (20°C 65% Humidity)

Material	Panel Number	Mass entering humidity room (g) – Mass after completely drying in oven	Final Mass (g)	Change in moisture content after conditioning in humidity room (%)	Water Content (g) - Assuming 0 g after oven, just change in mass is water absorbed	Dry Content (g) – Should just be mass after drying in oven
TP	1	318.2	Broken sample	n/a	n/a	n/a
TP	3	333.2	360.0	8.1	26.9	333.2
TP	4	299.8	336.7	12.3	36.9	299.8
TTP	1	85.1	93.7	10.1	8.6	85.1
TTP	2	84.4	93.8	11.1	9.4	84.4
TTP	3	81.4	90.4	11.1	9.0	81.4
TTP	4	81.7	89.8	9.9	8.1	81.7
TTP	5	81.6	89.8	10.0	8.2	81.6

8.3 Humidity Testing (Saturated Salt Solutions)

Relative humidity levels at 20°C obtained from (The Engineering Toolbox, n.d.)

Table 31: Relative humidity table with moisture content increase.

Material	Salt	Relative Humidity at 20°C (%)	Initial Mass reading in Humidity container (g)	Final Mass reading in Humidity container (g) – 1 week	Moisture Content (%) increase - assuming initial moisture content was 0 g	Water Content (g)	Dry Content (g)
Sheet Rock	KNO_3	95	12.7	17.7	39.2	5.0	12.7
Sheet Rock	NaCl	75	12.5	16.6	33.0	4.1	12.5
Sheet Rock	$MgCl_2$	33	12.8	15.5	21.1	2.7	12.8
Aqualine	$MgCl_2$	33	15.7	18.7	19.1	3.0	15.7
Aqualine	KNO_3	95	16.0	19.1	19.2	3.1	16.0
Aqualine	NaCl	75	16.6	19.3	16.3	2.7	16.6
MgO	KNO_3	95	36.0	46.6	29.6	10.7	36.0
MgO	$MgCl_2$	33	36.1	40.5	12.1	4.4	36.1
MgO	NaCl	75	34.8	41.5	19.3	6.7	34.8
MDF	KNO_3	95	18.7	21.5	15.2	2.8	18.7
MDF	$MgCl_2$	33	19.8	20.3	2.4	0.5	19.8
MDF	NaCl	75	18.1	19.4	7.2	1.3	18.1
SaveBOARD	$MgCl_2$	33	20.4	21.4	5.0	1.0	20.4

Material	Salt	Relative Humidity at 20°C (%)	Initial Mass reading in Humidity container (g)	Final Mass reading in Humidity container (g) – 1 week	Moisture Content (%) increase - assuming initial moisture content was 0 g	Water Content (g)	Dry Content (g)
SaveBOARD	KNO_3	95	18.6	20.7	11.2	2.1	18.6
SaveBOARD	NaCl	75	18.9	20.2	6.9	1.3	18.9
Pulp Panel 1	KNO_3	95	20.5	23.9	16.9	3.5	20.5
Pulp Panel 1	$MgCl_2$	33	20.9	22.1	5.6	1.2	20.9
Pulp Panel 1	NaCl	75	21.2	23.3	9.9	2.1	21.2
Thick Casein	$MgCl_2$	33	19.9	22.0	10.8	2.2	19.9
Thick Casein	NaCl	75	22.6	27.0	19.5	4.4	22.6
Thick Casein	KNO_3	95	20.7	28.9	40.0	8.3	20.7
Tapioca	KNO_3	95	16.1	18.8	16.6	2.7	16.1
Tapioca	$MgCl_2$	33	16.6	18.4	11.0	1.8	16.6
Tapioca	NaCl	75	16.3	18.1	11.0	1.8	16.3
Painted Starch	KNO_3	95	27.9	46.8	67.6	18.9	27.9
Painted Starch	$MgCl_2$	33	26.0	27.8	6.9	1.8	26.0
Painted Starch	NaCl	75	27.1	29.9	10.3	2.8	27.1
5ply Wood	KNO_3	95	4.2	6.1	46.6	1.9	4.2
5ply Wood	$MgCl_2$	33	2.9	3.2	9.6	0.3	2.9
5ply Wood	NaCl	75	14.5	16.5	13.8	2.0	14.5
5ply Box Lid	KNO_3	95	9.1	12.3	35.5	3.2	9.1
5ply Box Lid	$MgCl_2$	33	4.3	4.8	11.6	0.5	4.3

Material	Salt	Relative Humidity at 20°C (%)	Initial Mass reading in Humidity container (g)	Final Mass reading in Humidity container (g) – 1 week	Moisture Content (%) increase - assuming initial moisture content was 0 g	Water Content (g)	Dry Content (g)
5ply Box Lid	NaCl	75	3.8	4.5	17.8	0.7	3.8
Pulp Panel 2	NaCl	75	20.3	23.5	15.8	3.2	20.3
Pulp Panel 2	KNO_3	95	18.2	21.2	16.5	3.0	18.2
Pulp Panel 2	$MgCl_2$	33	22.6	23.3	3.1	0.7	22.6

8.4 Thermal Conductivity Data

Pulp Panels

Table 32: R-Test raw data for large pulp panel (LP) and small pulp panel (SP)

Material	Density (kg/m^3) of Panel after humidity control	Thermal Conductivity (Wm^{-1}K^{-1})	Sample Number	Average of Individual Sample Panel (Wm^{-1}K^{-1})
LP	368.1	0.0549	1	0.0637
LP		0.0849	1	
LP		0.0660	1	
LP		0.0488	1	
SP	384.9	0.0573	2	0.0611
SP		0.0570	2	
SP		0.0638	2	
SP		0.0662	2	
SP	389.5	0.0593	3	0.0674
SP		0.0717	3	
SP		0.0711	3	
SP		0.0675	3	
SP	366.9	0.0812	4	0.1041
SP		0.0686	4	
SP		0.1986	4	
SP		0.0681	4	
SP	316.3	0.0649	5	0.0713
SP		0.0698	5	
SP		0.0716	5	
SP		0.0788	5	

Casein Panels

Table 33: Casein Panel R-Test Raw Data

Material	Density (kg/m^3) of Panel after humidity control	Thermal Conductivity (Wm^{-1}K^{-1})	Sample Number	Average of Individual Sample Panel (Wm^{-1}K^{-1})
Casein	257.2	0.0547	1	0.0595
Casein		0.0711	1	
Casein		0.0564	1	
Casein		0.0556	1	
Casein	311.6	0.0746	2	0.0675
Casein		0.0595	2	
Casein		0.0755	2	
Casein		0.0604	2	
Casein	230.2	0.0431	3	0.0464
Casein		0.0500	3	
Casein		0.0469	3	
Casein		0.0456	3	
Casein	239.7	0.0643	4	0.0566
Casein		0.0589	4	
Casein		0.0529	4	
Casein		0.0504	4	
Casein	242.3	0.0480	5	0.0482
Casein		0.0486	5	
Casein		0.0469	5	
Casein		0.0492	5	

Tapioca Panels

Table 34: Tapioca Starch R-Test Raw Data

Material	Density (kg/m^3) of Panel after humidity control	Thermal Conductivity (Wm^{-1}K^{-1})	Sample Number	Average of Individual Sample Panel (Wm^{-1}K^{-1})
Tapioca Starch	152.4	0.0536	1	0.0509
Tapioca Starch		0.0554	1	
Tapioca Starch		0.0457	1	
Tapioca Starch		0.0490	1	
Tapioca Starch	n/a	0.0421	2	0.0421
Tapioca Starch	149.9	0.0405	3	0.0432
Tapioca Starch		0.0461	3	
Tapioca Starch		0.0403	3	
Tapioca Starch		0.0461	3	
Tapioca Starch	164.1	0.0426	4	0.0431
Tapioca Starch		0.0402	4	
Tapioca Starch		0.0373	4	
Tapioca Starch		0.0521	4	
Tapioca Starch	n/a	0.0475	5	0.0481
Tapioca Starch		0.0486	5	

Note: Panels 2 and 5 partially broke in the mould so an accurate density measurement could not be taken. Also, only a few readings were done on the intact sides of these panels rather than one on each side.

Comparison Sample

Table 35: Comparison R-test Table

Material	Density (kg/m^3)	Thermal Conductivity (Wm^{-1}K^{-1})	Sample Number	Average of Individual Sample Panel (Wm^{-1}K^{-1})
EPS	22.8	0.0254	1	0.0253
EPS	22.8	0.0258	1	
EPS	22.8	0.0249	1	
EPS	22.8	0.0250	1	
EPS	12.4	0.0302	2	0.0298
EPS	12.4	0.0299	2	
EPS	12.4	0.0312	2	
EPS	12.4	0.0279	2	

8.5 Compressive Strength Test Data

Table 36: Compressive Strength Raw Data

Material	Specimen Number	Density (kg/m3)	Displacement (mm) at 5% of initial height	Compressive Strength at 5% specimen height displacement (N/mm^2)
5-plywood Lid	1	544.9	0.409	0.01376
5-plywood Lid	2	555.5	0.399	0.00313
5-plywood Lid	3	562.9	0.397	0.00048
5-plywood Lid	4	571.1	0.403	0.00073
5-plywood Lid	5	515.0	0.451	0.12993
5-plywood	1	550.6	0.615	0.03040
5-plywood	2	519.3	0.615	0.01342
5-plywood	3	529.0	0.625	0.01325
5-plywood	4	540.8	0.623	0.01396
5-plywood	5	528.1	0.602	0.03246
Aqualine	1	743.9	0.500	0.01123
Aqualine	2	620.9	0.601	0.00400
Aqualine	3	653.0	0.551	0.00065
Aqualine	4	655.5	0.550	0.00206
Aqualine	5	663.4	0.550	0.01125
Sheetrock	1	555.9	0.550	0.00475
Sheetrock	3	499.2	0.550	0.00913
Sheetrock	2	564.5	0.550	0.01129
Sheetrock	4	599.3	0.500	0.00208
Sheetrock	5	611.4	0.501	0.00312
Sheetrock	6	620.6	0.500	0.01262
Pulp panel 2000 g pulp in	4	302.6	0.651	0.00988
Pulp panel 2000 g pulp in	4	456.1	0.301	0.00776
Pulp panel 2000 g pulp in	2	318.9	0.651	0.00945
Pulp panel 2000 g pulp in	3	413.4	0.450	0.00405
Thin Casein	1	258.7	1.214	0.03589
Thin Casein	4	253.0	1.247	0.01568
Thin Casein	2	258.4	1.304	0.03036
Thin Casein	3	266.6	1.232	0.03012
Thick Casein	1	272.7	2.137	0.01565
Thick Casein	2	270.5	2.184	0.00436
Thick Casein	3	269.4	2.192	0.01878
Thick Casein	4	263.1	2.264	0.02194
Thick Casein	5	228.4	2.000	0.03735

Material	Specimen Number	Density (kg/m3)	Displacement (mm) at 5% of initial height	Compressive Strength at 5% specimen height displacement (N/mm^2)
MDF	1	628.0	0.612	0.01291
MDF	2	621.3	0.612	0.05145
MDF	3	620.1	0.613	0.01274
MDF	4	622.8	0.613	0.01240
MDF	5	641.8	0.600	0.00976
SaveBOARD	1	734.5	0.465	0.00773
SaveBOARD	2	789.6	0.475	0.00036
SaveBOARD	3	797.5	0.468	0.00238
SaveBOARD	4	779.8	0.468	0.00188
SaveBOARD	5	770.0	0.500	0.00294
Tapioca	4	153.1	2.250	0.02213
Tapioca	1	197.0	1.500	0.01646
Tapioca	5	195.4	1.350	0.01123
Tapioca	2	160.8	2.200	0.01809
Tapioca	6	180.5	2.100	0.01256
Tapioca	3	189.0	2.002	0.00931
Pulp Panel 1700 g pulp in	3	270.7	1.702	0.07369
Pulp Panel 1700 g pulp in	1	361.7	1.702	0.07919
Pulp Panel 1700 g pulp in	4	369.7	1.501	0.03550
Pulp Panel 1700 g pulp in	2	351.2	1.600	0.03676

8.6 Bending Test Data

Orientation of top and bottom shows which face they were tested on. This was done to create more variation in case there were differences in strength.

Table 37: Bending Test Raw Data

Material	Specimen Number	Orientation	Specimen Dimensions (mm)	Dimension (mm)	Dimension (mm)	Mass (g)	Density (kg/m^3)	Bending Strength (MPa)
5-plywood	5	Top	200	49	12	60.4	513.6	51.915
5-plywood	3	Bottom	200	48	12	62.0	537.9	32.149
5-plywood	1	Top	201	49	12	63.1	533.8	53.418
5-plywood	4	Bottom	200	46	12	63.5	575.2	49.523
5-plywood	2	Top	200	47	12	59.4	526.4	47.322
5-plywood Lid	3	Bottom	199	48	8	50.2	656.5	74.637
5-plywood Lid	4	Top	199	47	8	43.0	574.5	49.298
5-plywood Lid	2	Bottom	200	50	8	46.6	582.4	50.232
5-plywood Lid	1	Top	199	46	8	44.8	612.2	40.360
5-plywood Lid	5	Bottom	199	47	8	46.6	622.1	54.712
2000 g in 10T Pulp Panel	1	Top	198	49	9	34.0	389.7	0.304
2000 10T Base	4	Bottom	199	49	10	43.2	443.0	0.210

Material	Specimen Number	Orientation	Specimen Dimensions (mm)	Dimension (mm)	Dimension (mm)	Mass (g)	Density (kg/m^3)	Bending Strength (MPa)
2000 g in 10T Pulp Panel	1	Bottom	197	50	8	29.9	379.1	0.235
2000 g in 10T Pulp Panel	2	Top	199	50	10	37.5	377.0	0.351
2000 g in 10T Pulp Panel	2	Bottom	199	47	8	28.7	383.3	0.368
1700 g in 2T Pulp Panel	3	Bottom	178	45	27	85.7	396.4	0.549
1700 g in 2T Pulp Panel	3	Top	179	48	32	98.4	357.7	0.661
1700 g in 2T Pulp Panel	1	Bottom	178	48	31	100.4	379.1	0.349
1700 g in 2T Pulp Panel	1	Top	179	49	33	107.7	372.1	0.460
1700 g in 2T Pulp Panel	2	Bottom	178	47	33	96.0	347.7	0.439
1700 2T Base	2	Top	180	48	33	101.0	354.2	0.673
Casein	1	Top	197	49	27	81.3	312.0	0.494
Casein	4	Top	197	47	33	79.7	260.8	0.459
Casein	5	Top	198	46	35	84.1	263.7	0.299

Material	Specimen Number	Orientation	Specimen Dimensions (mm)	Dimension (mm)	Dimension (mm)	Mass (g)	Density (kg/m^3)	Bending Strength (MPa)
Casein	2	Top	198	47	31	81.5	282.5	0.336
Casein	4	Bottom	199	49	32	81.8	262.1	0.631
Casein	3	Bottom	197	47	34	80.1	254.4	0.630
Casein	2	Bottom	201	47	33	81.9	262.7	0.451
Casein	3	Bottom	196	50	35	82.8	241.3	0.671
Casein	1	Bottom	197	47	26	76.1	316.0	0.393
Casein	5	Bottom	200	47	33	79.7	257.1	0.398
MDF	4	Top	201	49	12	74.1	626.7	37.928
MDF	5	Bottom	198	47	12	70.6	632.3	37.863
MDF	2	Top	200	47	12	70.7	627.1	36.927
MDF	3	Bottom	200	47	12	72.2	640.0	38.516
MDF	1	Top	200	49	12	74.8	635.9	36.770
SaveBOARD	2	Top	198	48	10	76.1	800.3	5.235
SaveBOARD	1	Bottom	197	48	10	74.8	791.1	5.576
SaveBOARD	4	Top	198	50	10	76.7	774.2	4.555
SaveBOARD	3	Bottom	197	48	10	76.4	808.1	9.123
SaveBOARD	5	Top	200	49	10	78.9	805.3	5.302
Sheetrock	1	Top	202	50	10	61.2	605.4	2.994
Sheetrock	2	Bottom	203	50	10	61.5	606.3	2.715
Sheetrock	5	Top	199	51	10	62.5	615.4	2.884
Sheetrock	4	Bottom	200	50	10	60.7	607.3	2.861
Sheetrock	3	Top	200	50	10	60.3	603.4	2.757
Aqualine	3	Bottom	202	50	10	75.6	748.8	8.685
Aqualine	4	Top	201	55	10	80.3	726.5	7.597
Aqualine	5	Bottom	206	52	10	77.1	719.5	3.224
Aqualine	1	Top	202	51	10	77.2	749.3	8.246

Material	Specimen Number	Orientation	Specimen Dimensions (mm)	Dimension (mm)	Dimension (mm)	Mass (g)	Density (kg/m^3)	Bending Strength (MPa)
Aqualine	2	Bottom	202	51	10	75.6	734.2	8.611
Tapioca	3	Top	201	47	32	64.2	212.4	1.369
Tapioca	1	Top	203	49	30	59.5	199.5	0.417
Tapioca	2	Top	201	48	33	43.9	137.9	0.194
Tapioca	3.2	Bottom	203	47	30	64.7	225.9	0.960
Tapioca	4.2	Bottom	202	48	28	63.2	232.9	1.581
Tapioca	5.1	Top	202	50	27	60.8	222.8	0.912
Tapioca	4.1	Bottom	202	49	30	60.5	203.6	1.021

8.7 Impact Testing Data

8.7.1 Checking accuracy of Impact Tester

Table 38: Checking Accuracy of Impact Tester

Factor A Readings (J)	Average Factor A (J)	Factor B Readings (J)	Average Factor B (J)	Energy lost to friction and inertia (J) (Average Factor A – Average Factor B)
0.005	-0.00278	-0.005	-0.005	0.002
-0.005		-0.005		
-0.005		-0.005		
0				
-0.005				
-0.005				
0				
-0.005				
-0.005				

The energy lost is negligible, so the impact tester is accurate.

8.7.2 Impact Testing Data

Table 39: Impact Testing Raw Data

Material	Specimen number	Specimen Dimensions (mm)	Specimen Dimensions (mm)	Specimen Dimensions (mm)	Mass (g)	Density (kg/m^3) of specimen (humidity controlled)	Energy expended to break specimen (J)	Impact Resistance under notch (J/m)
2000 g in 10T Pulp Panel	3.4	55	9	12	2.0	307.5	0.0250	0.00265
2000 g in 10T Pulp Panel	1.1	55	9	10	1.6	302.7	0.0150	0.00160
2000 g in 10T Pulp Panel	4.1	50	9	16	2.8	370.8	0.5750	0.06117
2000 g in 10T Pulp Panel	2.1	53	9	9	1.3	284.9	0.0350	0.00384
2000 g in 10T Pulp Panel	1.3	53	7	11	1.1	275.9	0.0200	0.00283
2000 g in 10T Pulp Panel	4.2	51	10	12	1.9	330.6	0.0750	0.00788
2000 g in 10T Pulp Panel	2.2	53	7	12	1.4	315.0	0.0350	0.00500
2000 g in 10T Pulp Panel	3.1	55	7	12	1.4	302.9	0.0400	0.00575
2000 g in 10T Pulp Panel	2.5	54	7	12	1.4	303.9	0.0450	0.00636
2000 g in 10T Pulp Panel	3.2	53	9	9	1.3	290.7	0.0200	0.00226
4000 g in 5T Pulp Panel	1.2	53	9	19	3.0	324.1	0.6400	0.06816
4000 g in 5T Pulp Panel	1.4	52	7	19	2.0	296.5	0.5700	0.08546
4000 g in 5T Pulp Panel	1.3	54	9	20	3.1	326.5	0.2900	0.03255
Sheetrock	1.1	56	11	10	3.4	541.4	0.0250	0.00226
Sheetrock	1.2	56	12	10	3.5	524.9	0.0500	0.00415
Sheetrock	1.3	57	10	10	3.3	554.9	0.1000	0.00963

Material	Specimen number	Specimen Dimensions (mm)	Specimen Dimensions (mm)	Specimen Dimensions (mm)	Mass (g)	Density (kg/m^3) of specimen (humidity controlled)	Energy expended to break specimen (J)	Impact Resistance under notch (J/m)
Sheetrock	1.4	56	10	10	3.3	616.8	0.0250	0.00259
Sheetrock	1.5	57	11	10	3.1	509.6	0.0700	0.00662
Aqualine	1.1	55	12	9	4.2	670.1	0.0350	0.00289
Aqualine	1.2	55	10	10	3.5	623.6	0.1050	0.01035
Aqualine	1.3	55	10	10	3.8	685.2	0.1000	0.00985
Aqualine	1.4	56	12	10	4.2	653.2	0.0950	0.00825
Aqualine	1.5	55	11	10	4.4	718.9	0.1050	0.00936
5-plywood Lid	1.1	56	8	8	2.0	549.4	0.4950	0.06298
5-plywood Lid	1.3	56	7	8	1.9	596.3	1.1500	0.16987
5-plywood Lid	1.4	56	9	8	2.0	514.8	0.4500	0.05214
5-plywood Lid	1.5	56	8	8	2.2	589.1	0.8100	0.10075
SaveBOARD	1.1	56	7	9	2.6	699.9	0.3000	0.04274
SaveBOARD	1.2	57	10	10	4.7	842.8	2.3500	0.23130
SaveBOARD	1.3	55	9	10	3.6	755.5	0.8900	0.09900
SaveBOARD	1.4	55	7	10	2.7	724.4	0.4550	0.06436
SaveBOARD	1.5	55	7	10	2.7	731.8	0.4850	0.06989
Tapioca	1	51	8	37	2.8	200.4	1.0000	0.13141
Tapioca	2	53	8	39	3.0	188.3	0.2500	0.03213
Tapioca	3	49	10	38	3.3	180.3	0.3750	0.03811
Tapioca	4	49	10	42	4.0	199.8	0.5050	0.05255
Tapioca	5	50	10	38	3.9	210.9	0.9300	0.09759
Casein	1	50	9	42	4.5	242.4	0.2000	0.02265
Casein	2	52	7	41	4.0	255.5	0.2750	0.03825
Casein	3	50	8	42	4.3	260.4	0.1550	0.01987
Casein	4	51	13	39	6.4	248.1	1.0100	0.07710
Casein	5	52	10	41	4.5	217.5	0.2200	0.02273
MDF	1	53	9	14	3.5	530.8	1.1200	0.12785
MDF	2	53	9	14	3.6	541.4	1.2000	0.13274
MDF	3	55	9	13	3.4	545.9	1.1150	0.12935
MDF	4	52	9	14	3.8	571.7	1.0600	0.11277
MDF	5	52	9	13	3.7	581.7	1.2000	0.13378
5-plywood	1	50	7	13	2.3	489.2	1.7600	0.25036
5-plywood	2	50	11	12	3.4	500.7	1.8000	0.16364
5-plywood	3	51	10	13	3.0	476.6	1.5100	0.15795
5-plywood	4	51	9	13	3.0	530.0	0.9050	0.10238
5-plywood	5	50	9	13	3.0	524.5	1.8500	0.21216