Weaving Māori Culture into Natural Fibre Reinforced Composites

A thesis submitted in fulfilment of the requirements for the Degree of Master of Product Design at the University of Canterbury by Caleb Philps, School of Product Design, University of Canterbury, Christchurch, New Zealand 16/09/2022

Hutia te Rito

Hutia te rito

Hutia te rito o te harakeke

Kei hea te kōmako e kō?

Kī mai ki ahau

He aha te mea nui?

He at ate mea nui o te ao?

Māku e kī atu

He tangata! He tangata! He tangata, hī!

English Translation:

Pull out the shoot,

Pull out the shoot of the harakeke bush

Where will the bellbird sing?

Say to me

What is the greatest thing?

What is the greatest thing in this world?

I will say

The people! The people! The people

Abstract

Harakeke has been an important plant in Māori culture for its use in weaving and as concerns for the environment increase, sustainable materials must be created. Natural fibre composites are a promising application for plant fibres such as harakeke and All Cellulose Composites (ACCs) have seen research as a sustainable matrix material for natural fibre composites. This project set out to create composites using harakeke woven with Māori weaving patterns. Computational modelling of a Māori woven composite was trialled to compare calculated values with tested tensile strength data and methods for describing Māori weaving patterns using mathematics were investigated. An online survey was conducted to find how valuable Māori woven composites were perceived to be.

Traditional Māori methods and Tikanga for gathering harakeke were used and Māori weaving patterns were made. These weaves were used to create textile samples and composites using cellulose and epoxy matrices with samples woven by an experienced weaver being compared to those made by a novice weaver. The bonding between harakeke and matrix phase was investigated using SEM. Griswold's method for describing weaving patterns was applied to Māori weaves and TexComp was used to model a harakeke composite. A short online survey was made to gauge participants perception of Māori woven composites.

Despite trialling different treatment processes on the harakeke such as boiling and NaOH/Urea treatment, neither cellulose nor epoxy bonded well with the harakeke leaf which was seen through SEM and caused low tensile strength in the composites. Tensile strength values of between 0.5–1 MPa were achieved by the harakeke-ACC composites and 13.2–17.7 MPa for the harakeke-epoxy composites. The skill level of a weaver was not found to affect the strength of a woven textile but rather the consistency in values, with a novice weaver having standard deviation of 1.12 MPa in their weaves and an experienced weaver having 0.26 MPa. Māori weaving patterns in upright orientations were able to be described using Griswold's method based on drawdown diagrams of the weaves. People showed clear preference towards the harakeke-epoxy composite compared to the harakeke-ACC. This was due to the visibility of the Māori woven harakeke inside the epoxy.

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Glossary of Terms

ACC – All Cellulose Composite

Aho – Weft fibres

Awhi Rito – The harakeke leaves located either side of the rito

FE – Finite Element

FEA – Finite Element Analysis

Hae hae – A tool for splitting harakeke rau into strips for weaving

Hāpine – The process of softening and removing moisture from harakeke rau for weaving.

Harakeke – New Zealand flax (*Phormium tenax*)

Hāro – To scrape, the process of removing para from harakeke to get muka

Kairaranga – Weaver

Kākahu – Clothing

Karakia – An invocation/ incantation

Kūtai – Mussel shell

Matrix – Material that coats the fibres in a composite

Muka – Fibre from harakeke

NaOH – Sodium Hydroxide

NFC – Natural Fibre Composite

Para – Epidermis

Pāraerae – Footwear

PDW – Plain Diagonal Weave/Takitahi Pāraerae

PLA - Polylactic Acid

PW – Plain Weave/Takitahi

Rāpaki – A location in Banks Peninsula, New Zealand

Raranga – Weaving

Rau – Leaf

Rau Mātua – The harakeke leaves located either side of the rito, often referred to as simply "Mātua"

Rau Kaumātua – The older leaves of the harakeke fan after the Rau Matua, often referred to as simply "Kaumātua"

Rito – The middle leaf in the harakeke fan

SEM – Scanning Electron Microscope

Takirua – Diagonal 2x2 twill

Takitahi – Plain weave

Takitahi Pāraerae – Plain diagonal weave

Tikanga – Customs and traditional values and practice.

TW – Twill Weave/Whakatutu

Whakatutu – 2x2 twill weave

Whāriki – Floormat

Whenu – Warp fibres

1. Introduction

Harakeke (*New Zealand flax*) has been a key plant in Māori society and culture for its use in weaving (*raranga*), where both the leaves (*rau*) and extracted fibre (*muka*) have been used to create items such as baskets, nets, ropes and clothing. When Europeans (*Pākehā)* arrived in New Zealand, they also sought out harakeke *muka* as a local source of fibre to use in place of European flax [1].

As more Europeans settled in New Zealand, demand for harakeke *muka* increased and eventually extraction was mechanised [2]. Harakeke mills were set up across the country and some 4000 workers were employed in the New Zealand flax industry at the turn of the century [3]. However, as synthetic fibres became stronger and cheaper, demand for harakeke *muka* declined and the industry had all but died by the mid-1900s, with only one mill continuing to produce harakeke *muka* until 1985 when it was destroyed in a fire [4].

With the death of the industry, harakeke faded from Pākehā interest. However, Māori weavers continued to use both the *muka* and the *rau* for the same *raranga* they always had done. Māori weavers have kept their same method of extraction, *hāro*, which despite being far slower than the mechanised version, produces a higher quality *muka*. This makes a smoother and shinier fibre which is better suited for use in clothing (*kākahu*). The mechanised fibre often has deposits of epidermis (*para*) still stuck to it which makes it coarse and rough.

Māori weavers were consulted with and included in this research project. Most directly involved was Kerepeti Paraone, a weaver residing in Christchurch, New Zealand. He has practiced weaving since he was in his youth and has even used weaving in the form of product design, creating cuff links and ties using weaves made of harakeke. He learned the art of weaving from his grandmother Reihana Parata. Reihana Parata resides at the Rāpaki, In Te Pātaka o Rākaihautū/ Banks Peninsula and is a highly respected *Kairaranga*/weaver. Morehu Flutey-Henare is a good friend of Reihana Parata's and the two have worked together on many projects, one notable project being the paved patterns that run through the Christchurch city centre which they based upon weaving patterns derived from nature. Reihana Parata, Morehu Flutey-Henare and Kerepeti Paraone all had input into this project and it could not have happened without their knowledge and cooperation.

As climate change and other environmental issues gain more attention and concern, industries must look to try and be more sustainable. One of the major polluters is petroleum-based polymers, which includes synthetic fibres. One class of material that predominantly uses both synthetic fibres and polymers is composites. As a result, research has been led into green composites that use natural fibres and bioplastics that cause less harm to the environment. As harakeke *muka* is a natural fibre, it has seen some research as a reinforcement in composites [5-7] due to its strength and availability in New Zealand. However, research in this area has looked only into the physical and mechanical properties of the plant's fibre [8, 9]. These aspects are of course very important for composite materials, but there is room for research into using the cultural heritage of harakeke and *raranga*, too. Māori weavers developed, designed, and favoured weaving patterns that are strong and durable, as well as aesthetically pleasing, which could prove useful in composites. Māori weavers uphold *tikanga*, or rules and ways of doing things, to process harakeke. Māori knowledge and *tikanga* focusses on sustainable methods of harvesting to keep the harakeke plant healthy and has rules around handling the plant for the safety of the weaver. Such rules include never harvesting in the rain due to the higher chance of slipping in wet conditions, which can be dangerous when holding a sharp knife to cut the plant. Māori weavers developed methods of preparing harakeke with a practical focus on producing harakeke *rau* and *muka* suitable for weaving. When selecting products, consumers may be interested in the combination of sustainability and cultural heritage found in harakeke-based materials.

The aim of this research project was centred around creating sustainable composite materials made with harakeke and traditional Māori weaving patterns and to identify the value perception of these materials. In addition to making these materials, the project aimed to model and predict their behaviour and to find a way of mathematically describing the Māori weaving patterns.

2. Literature Review

2.1. Composites & Bio-composites

In the engineering world, composite materials are a favoured choice for their mechanical properties such as strength and light weight. As the name suggests, a composite material is made up of multiple parts; most often a reinforcement fibre bound by a matrix material that holds the fibres in place. Reinforcement fibres used are short fibres and long fibres, with short fibres being used in a random orientation or as a matted material for isotropic properties, and long fibres being used as textiles or as unidirectional support. The cross section of a plain-woven fibre-reinforced matrix is shown below Figure 1. The matrix transfers load to the fibres since the strength of the material comes from them and their orientation [10].

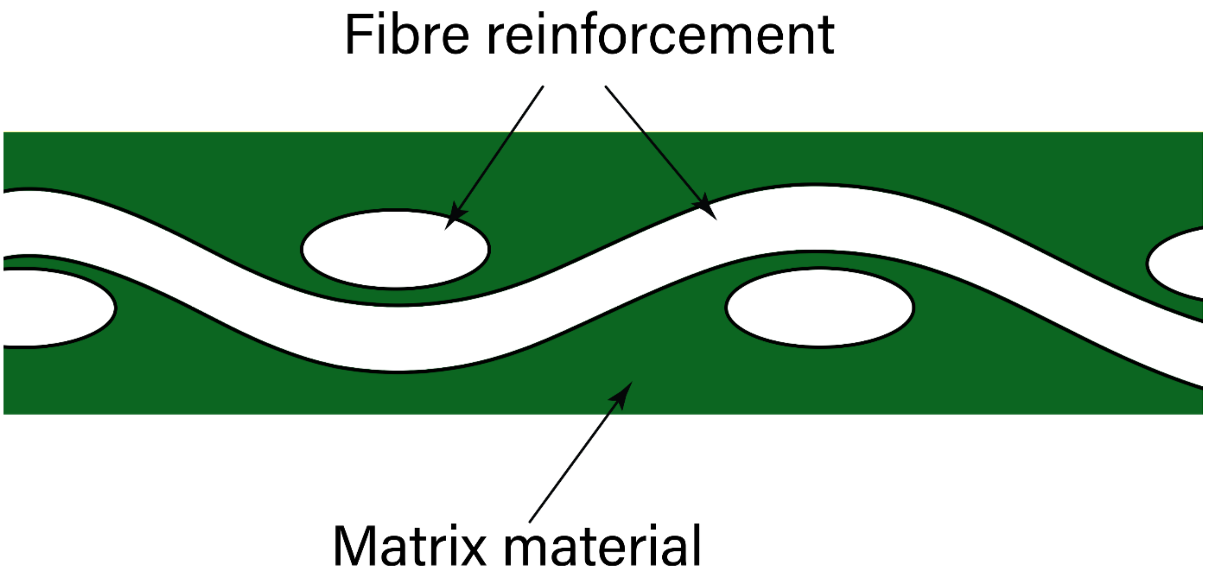

Figure 1. Cross section of a composite showing the matrix and reinforcement fibres.

Composites often use a thermoset or thermoplastic material for the matrix with thermoset matrices being stronger due to their 3-dimensional bonding [11], compared to the amorphous structures of thermoplastics [12]. Common thermoset polymers employed are polyesters, vinyl esters, and epoxies [13], with the latter being used most often [14, 15] due to its higher strength [16]. The most common fibres used are synthetic ones such as glass fibre [17], with a 7 billion dollar global market share, and carbon fibre with over a 4 billion dollar market share [18-20]. These synthetic fibres have good mechanical properties but are not recyclable [21]. As concerns for the environment have grown, efforts have been made to create renewable composites using natural fibres, biopolymers and bioplastics for both matrix and fibre reinforcement [22-24]. While thermosets see use as a matrix phase in bio-composites, thermoplastics are favoured [13], especially polylactic acid (PLA) as it is one of the most common bio-polymers [25-27] and can bio-degrade under specific conditions [17, 28-30]. Thermoplastic polymers are easily moulded and their composites tend to be reinforced with short fibres [31-33] as it is convenient to mix these fibres into the thermoplastic material when it is being injection moulded [34]. However, natural fibres do not bond well with thermoset and thermoplastic polymers which can mean that composites using these matrices do not perform optimally [35].

2.2. Natural fibres

Natural fibres are an attractive choice for reinforcement fibre since they are already grown for textiles and due to their lower density their specific strength can be similar, and in some cases superior, to the specific strength of the more dense glass fibres which are more commonly used in composites [36]. Specific strength is a material's strength per unit density, which can be important in applications where weight saving is intended for a given strength. However, fibres like aramids or carbon are much stronger, so natural fibres cannot be used as a direct substitute where low mass and high strength are required [37].

Hemp, flax, coir, kenaf, abaca, bamboo, sisal, cotton, jute and ramie are some of the most commonly used reinforcement plant fibres [35, 37]. The mechanical properties of these fibres are compared with glass fibre in Table 1 using data from [38] and [39]. Natural fibre composites (NFCs) have a market share of over USD 4.5 billion [40] with a forecast compound annual growth rate of 9% [41] compared to the forecast 6.6% growth rate of synthetic composites [42]. NFCs see use in construction and building, sports and aerospace [43], but their most common use is in automotive applications [28, 44, 45].

Plant fibres are composed of cellulose, hemicellulose, lignin, pectin and waxes as well as water. Of these chemicals, cellulose is the main component in the structure of plant fibres with some fibres such as flax, cotton and hemp containing upwards of 70 percent by weight

(70 wt. %) cellulose. Some commonly used natural fibres and their chemical compositions are shown in Table 2 using data presented in [38] and [46].

Table 1. Mechanical properties of some natural fibres.

Fibre	**Density (g/cm^3)**	**Failure strain (%)**	**Tensile strength (MPa)**	**Stiffness/Young's modulus (GPa)**	**Specific tensile strength ($MPa/g\ cm^{-3}$)**	**Specific Young's modulus ($GPa/g\ cm^{-3}$)**	**Reference**
Flax	1.5	1.2-3.2	345-1830	27-80	230-1220	18-53	[39]
Jute	1.3-1.5	1.5-1.8	393-800	10-55	300-610	7.1-39	[39]
Abaca	1.5	10-12	980	72	-	48	[38]
Sisal	1.3-1.5	2.0-2.5	507-855	9.4-28	362-610	6.7-20	[39]
Kenaf	1.22-1.40	3.7-6.9	295-930	22-53	-	18-38	[38]
Ramie	1.5	2.0-3.8	400-938	44-128	270–620	29-85	[39]
Hemp	1.5	1.6	550-1110	58-70	370–740	39-47	[39]
Cotton	1.5-1.6	3.0-10	287-800	5.5-13	190–530	3.7-8.4	[39]
Coir	1.2	15-30	131-220	4-6	110–180	3.3-5	[39]
Harakeke	1.3	4.2-5.8	440-990	14-33	338–761	11-25	[39]
Glass Fibre	2.5	2.5	2000-3000	70	800–1400	29	[39]

Table 2. Chemical compositions of some natural fibres.

Fibre	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)	Pectin (wt.%)	Reference
Flax	65–85	14-18.6	2-3	1.8-2.3	[38]
Jute	51-72	12-20.4	5-13	0.2	[38]
Abaca	60.8-64	21	12	0.8	[38]
Sisal	43-88	10-13	4-12	0.8-2	[38]
Kenaf	36	21	18	2	[38]
Ramie	68.6-76	13.1-15.0	0.6-1	1.9-2	[38]
Hemp	70-78	17.9-22	3.7-5	0.9	[38]
Cotton	82.7-92	2-5.7	0.5-1	5.7	[38]
Coir	43	0.3	45	4	[38]
Harakeke	60.9	27	7.8	-	[46]

Cellulose typically comes in semicrystalline form with both crystalline regions and amorphous regions along the same fibre [21, 47]. Cellulose has 4 main allomorphs which have slight variations in their molecular structure [48], these being cellulose I, II, III, and IV [48]. Cellulose I, or native cellulose, is the most common while the other three allomorphs are scarcely found in nature [49]. Native cellulose is the strongest allomorph with a theoretical ultimate tensile strength of 13-17 GPa [50]. This theoretical value is never seen in practice due to the semicrystalline nature of plant fibres that have areas of amorphous cellulose which are weaker than crystalline forms. These properties and variations in cellulose are of interest when considering the use of cellulose in the manufacture of ACCs.

2.3. All Cellulose Composites (ACCs)

Cellulose has been investigated as a matrix phase for use with natural fibre reinforcement. The All-Cellulose Composite (ACC) consists of a cellulose matrix, and a cellulosic/natural fibre to reinforce it [15, 51]. ACCs have not been used commercially but cellulose is seeing research for use as a matrix material due to it solving one of the main drawbacks of using natural fibres – their poor adhesion to thermoset and thermoplastic polymers [35]. Natural fibres are hydrophilic while thermoplastic polymers are usually hydrophobic, and this results in poor bonding [52, 53]. Since the natural fibres are made of cellulose, using a matrix made of the same material results in better interfacial bonding and load transfer in the composite [51].

While natural fibres can bond well with a cellulose matrix, the usual preparation of the fibres is necessary to achieve good adhesion. One such pre-treatment that can be applied is mercerisation which involves soaking fibres in a weak sodium hydroxide (NaOH) solution to remove impurities (such as lignin and hemicellulose) from their surface [40, 54, 55]. In addition to removing impurities, mercerisation also rearranges the crystalline structure of cellulose I into cellulose II [56] and helps to break up fibre bundles into smaller fibres which promotes better adhesion due to larger surface area [35]. Mercerisation can employ NaOH concentrations of between 1-40% depending on the fibre, temperature of the process [57, 58] and the desired change in cellulose crystallinity [45].

Manufacture of ACCs can be done via two methods as described by Huber et al [51]: the "2-step method" and "1-step method". The 2-step method, first published by Nishino et al [59], requires a cellulosic material to be completely dissolved in a solvent and then introduce undissolved cellulose to regenerate the dissolved cellulose around the undissolved cellulose.

The 1-step method sees the surface of the cellulosic reinforcement partially dissolved and then regenerated back around the undissolved portion, creating a matrix. This method was discovered by Gindl et al [60] and has also been referred to as the partial dissolution method [61]. The 1-step/partial dissolution method is considered more realistic for industrial upscaling [27].

Various solvents have been used for cellulose dissolution with ionic liquids, such as sodium hydroxide (NaOH) aqueous solution, being favoured for their efficiency [62] and for being "green solvents" with potential to be upscaled with little harm to the environment [63]. In the case of sodium hydroxide, urea can be added at a ratio of 7 wt.% NaOH/12 wt.% urea/81 wt.% water [64] which enhances dissolution when at sub-zero temperatures [51]. Additional cellulose in powdered form can also be mixed in with the 7 wt.% NaOH/12 wt.% urea solvent. It is possible to make up to a 6 wt.% solution [65] and the additional cellulose will bind to the fibres creating a larger matrix.

After dissolution of the cellulose, regeneration is required to build the matrix around the undissolved cellulose. Water, ethanol and methanol are some of the mediums used to regenerate cellulose via coagulation [27] as they remove the solvent from the cellulose, reestablishing hydrogen bonds between the dissipated cellulose [66]. In doing so the dissolved cellulose is precipitated in place around the undissolved cellulose. When using the 7 wt.% NaOH/12 wt.% urea/cellulose solution, before introducing water to the system it can be heated which will cause irreversible gelling to occur [65]. After the solution has gelled, it can be washed in water or another medium to remove solvent. When thoroughly washed, the gel must be dried. This can for example be achieved through heating, paper towel absorption or vacuum, or a combination of all three [67].

Many natural fibres have been investigated for use in ACCs, and while harakeke has seen applications in general bio-composites [7-9, 68] no published work has focussed on using it in ACCs. Furthermore, different types of fibre layup and laminae have been looked at for reinforcement in ACCs [69, 70] but little has been looked at comparing characteristics of weave pattern behaviour in ACCs.

2.4. Perception of Composites

The appearance and aesthetics of a product play a large role in consumer decision making [71-73] and it was found that 47% of consumers care about sustainability when purchasing [74], with over half stating that they would be willing to pay more for sustainable goods [75]. Unfortunately, consumers cannot distinguish bio-composites from synthetic composites due to the similar appearance of fibres and the matrices used in both [76]. This means that while consumers may desire to purchase more sustainable goods, they are unable to identify the sustainable option in bio-composites.

2.5. Weave Behaviour

The main weaves used in composite reinforcement are plain weave, twill weave and satin weave [77]. Plain weave is the simplest and most common weave, where the warp yarn crosses over one weft yarn before going underneath another, and repeating in a 1x1 fashion. Twill weave is similar although it can come in varying patterns. Common twill patterns include 1x2, where one yarn threads through two perpendicular yarns to then tuck under the next two and repeat the pattern, and 2x2 where two yarns staggered by one perpendicular yarn travel over two yarns and then under two for the repeating pattern. Satin weaves have one yarn travel over a set harness count, after which it goes under one more yarn and then back up to repeat the pattern [20]. These weaves are shown below in Figure 2.

The shape of the yarns traveling over each other is called crimp. Plain weave has the most crimp due to its 1x1 structure giving it the highest interlacement. Twill weaves have less interlacement than plain weaves and this causes less crimp with larger floats, the section of straight yarn travelling over the perpendicular yarns. Plain and twill float and crimp are compared in Figure 3. Satin has the lowest crimp and highest float in its structure due to its harness count, which is often higher than that of twill. High interlacement causes high crimp, but it reduces drapability which is the flexibility of the weave structure. Drapability is important in composite manufacture as high drape weaves will fit into moulds more easily than low drape fabrics which will often wrinkle. High interlacement also impacts the stability of a weave as yarns with higher interlacement will not fall out of the weave or lose their shape as easily [78].

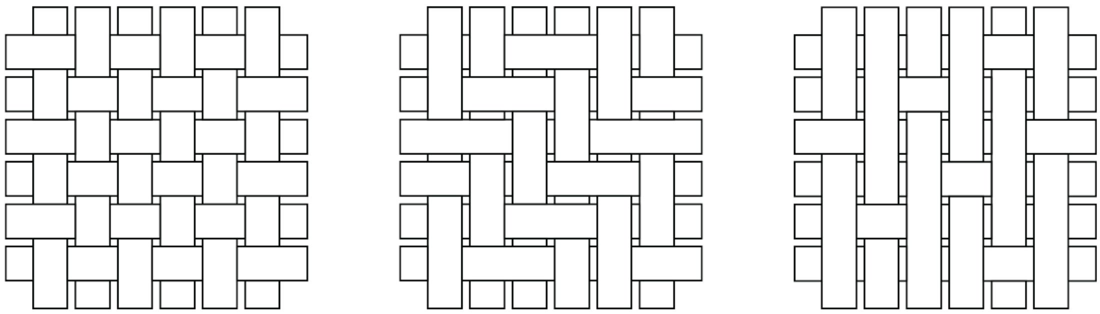

Figure 2. Three common weaves. From left to right: plain, 2x2 twill and 5 harness satin.

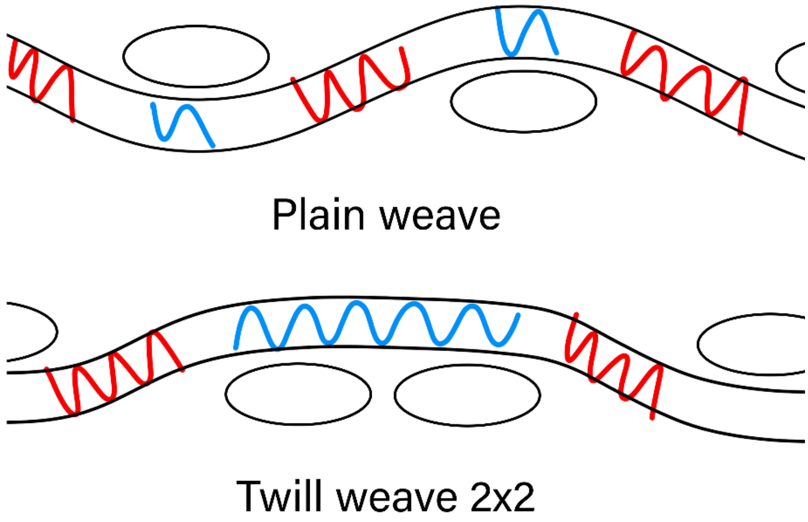

Figure 3. Twill 2x2 and plain weave compared. Crimp regions shown in red and float regions in blue.

The mechanical properties of weaving patterns are difficult to predict as they are influenced by the structure of the weave and shape and size of the yarns [79, 80]. This explains why there is apparent disagreement between published findings in the literature. There are claims that weaves with larger floats such as twill and satin have higher tensile strengths due to their lower crimp ratios which means there is more fibre strengthening the direction of loading [81]. In other works, however, it has been observed that plain weaves are the strongest textile due to higher interlacement of the yarns which increases friction, resisting breakage [82, 83]. In the literature of woven composites, the same disagreement persists, where twill and satin are claimed to create stronger reinforced composites in some works [84-86], but plain is found to be stronger by others [87, 88].

Māori weavers have used many different types of patterns to create the things needed in their craft such as clothes, traps and nets and baskets or storage devices. Some of the weaves they have used include the weaves used in industrial textile and composite manufacture, but they have Te Reo names and all Māori weaves are made by hand. *Whakatutu* means "to be upright" and is identical to a 2x2 twill weave. *Takirua* means "over and under sets of two", and as the name suggests it is also a 2x2 twill weave. The difference in these weaves is that *takirua* has the pattern oriented diagonally with the yarns ± 45° and *whakatutu* is upright [89]. *Takitahi* is the plain weave and means "check pattern" describing its appearance [90, 91].

These weaves can be made using *muka*, but most often are made with *rau* for kete or floor mats (*whāriki*). A diagonal variation on the *takitahi* weave was used for footwear (*Pāraerae*) where the weave is made with a ± 45° bias and in a fashion similar to a braid, the edges are locked in by crossing the *rau* over and bringing it back into the weave. This locking in of the weave means that the *whenu* and *aho* (warp and weft) are the same yarns, alternating between either option every time they lock in the weave.

2.6. Weaving Mathematics and Griswold's Method

Weaving patterns can be described using "Drawdown Diagrams" which illustrate their structure using coloured squares. These are useful for displaying biaxial weaves on paper and can be used to design patterns before creating them. Shown in Figure 5 is a 10x10 drawdown diagram depicting a *takitahi* weave. The different coloured squares represent the *whenu* and *aho* of the weave. As the diagram uses two colours, they can be described using a binary array of 1s and 0s to describe the *aho* and *whenu* of the pattern. Shown below in Figure 4 is the binary array translated from the 10x10 *takitahi* drawdown diagram:

```
1010101010
0101010101
1010101010
0101010101
1010101010
0101010101
1010101010
0101010101
1010101010
0101010101
```

Figure 4. 10x10 takitahi binary array.

Griswold's work looked at describing weaving patterns in this way which then allowed for use of Boolean arrays to find logical consistencies or patterns within them [92, 93]. By using Boolean operators, the structures and rules found in weaves can be understood mathematically, and new patterns can be created by combining rules and patterns [94].

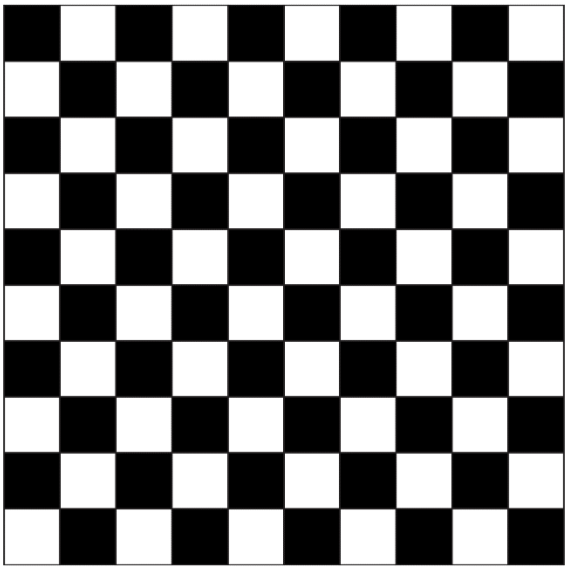

Figure 5. Drawdown diagram of Takitahi weave consisting of 10 aho and 10 whenu.

2.7. Modelling of Weaving Patterns

Finite Element Analysis (FEA) is a useful tool in engineering which can be used to predict complex stress equations in modelled geometry. It is not without disadvantages as variability in material properties and user error can produce inaccurate results [95]. It is nevertheless a tool that can be used for preliminary testing of structures at low cost, since no physical product is required to analyse.

Given that composite materials are geometrically complex due to their components; fibre and matrix, specialised software has been made to model to produce their geometries. One such program is WiseTex which produces Finite Element (FE) models of composites and a variety of different weaves, including novel and 3-dimensional weaves [96]. The reinforcement fibre and matrix material's mechanical values are input and then the pattern is described as a unit cell. The produced FE models can then be exported to FEA packages, such as Ansys or Abaqus, where analysis can be conducted on the behaviour under stress. FE models can also be exported to other programs such as TexComp which can perform other calculations using the modelled geometry. TexComp is a software designed to calculate the stiffness of a composite using the mechanical values of fibre and epoxy [97]. Like FEA, TexComp calculations can be inaccurate due to user input errors and assumptions made in the software. This must be considered when analysing calculated values and it is wise to compare them with physically tested samples.

2.8. Objectives

The current literature has seen harakeke *muka*/fibre used in bio-composites using various matrix materials, and ACCs show promise for their sustainability as well as their bonding capabilities with natural fibres in composites. However, ACCs have not been manufactured using harakeke weaves. Mathematical methods of describing weaving patterns have been found to be effective using binary arrays to represent interlacement, but no Māori weaving patterns have been systemically described using binary arrays. While modelling of woven composites has proven a good way of preliminary testing of the properties of composite materials, Māori woven composites have not been modelled. Consumers show interest in sustainable materials but perceived value in Māori woven composites has not been investigated.

Given these gaps in the literature, this project set out to create ACCs using harakeke woven into Māori patterns and investigate the nature of bonding between matrix and harakeke. Describing the Māori weaves using mathematics and modelling Māori woven composites to predict their mechanical properties were also goals of the project. Given that sustainability concerns seem to be on the rise amongst consumers, a goal of the project was to find out how consumers perceive Māori woven harakeke composites and how financially valuable they believe them to be.

3. Methods & Materials

3.1. Materials

Harakeke *rau* is the primary material used for fibre reinforcement, although harakeke *muka* was investigated for short fibre composites. All harakeke used in composite manufacture was sourced from the same plant of an unknown cultivar, which was identified to most likely be a hybrid of harakeke cultivars.

Some basic weaves commonly used in Māori *Raranga* were chosen by Kerepeti Paraone for use in this project. These weaves were *Whakatutu* (twill 2x2), *takitahi* (plain), and *takitahi pāraerae* (diagonal plain) shown below in Figure 6, and Figure 7 shows the activity of weaving. Compared with more complex patterns, these were easier to manufacture by a novice weaver while still representing a selection of appropriate weaves that see use in *raranga*. The same patterns were used for the fibre glass samples except for the diagonal plain weave, where a normal plain weave section was simply cut to shape at a 45° bias.

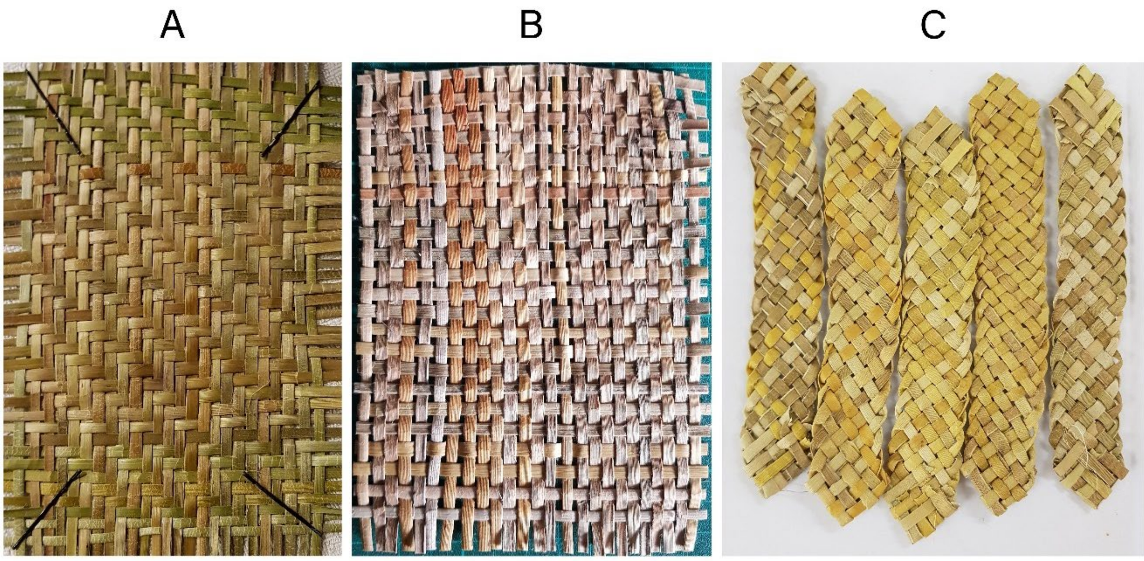

Figure 6. The three weaves used in this project. A: Whakatutu, B: Takitahi and C: Takitahi Pāraerae. The Whakatutu weave shows how bobby pins can be used to hold it together when weaving.

Figure 7. Kerepeti Paraone and the author weave samples together.

Sigmacell cellulose powder, Type 20 (average particle diameter 20 µm), and urea (ACS grade) from Sigma-Aldrich (St. Louis, MO, USA) were used as received. Sodium hydroxide (purity 97%) in pellet form from Thermo Fisher Scientific (Waltham, MA, USA) was used as received.

A two-part epoxy and hardener Epoxy Marine Laminating System from New Zealand Composites was purchased from New Zealand Fibreglass Ltd (Auckland, New Zealand) and used as received.

3.2. Tikanga of working with Harakeke

Māori weavers operate by following *tikanga*, which can be described as "the correct way of doing things". *Tikanga* outlines the best ways to harvest from the harakeke plant while keeping it healthy. The harakeke plant grows in a fan shape, with multiple fans growing close together shown in Figure 8. The *rau* grow outwards from the middle of the fan, with older leaves at the edges and the young *rau* at the centre. The central *rau* is the youngest and is called the *rito*. Either side of it are the *mātua*, otherwise known as the *awhi rito.* The *mātua* is next youngest *rau*. None of these leaves should ever be harvested, for the sake of keeping the plant healthy. The outermost leaves are the *kaumātua* and these are the *rau* that can be cut for *raranga* or *muka* extraction. The fan represents a family, with the *rito* and *mātua* being the child and parents, it is the vitality of the plant. The *kaumātua* are considered the grandparents in the fan, so these leaves can be removed.

Figure 8. The leaves in the harakeke fan: red is the Rito, blue the Mātua, and yellow the Kaumātua.

When cutting the harakeke, the incision should be made as low on the plant as possible. The angle should be rather steep, which will naturally be encouraged by the shape of the fan. This is so that water will run down the flanks of the cut leaves rather than pooling in the base of the fan which could rot the plant. See Figure 9 for the steps in harvesting harakeke.

Figure 9: A, B, C. The Process of Harvesting the kaumatua of the harakeke fan. A: The kaumatua are identified. B: The cut is made C: How the fan should be left, with a low cut angled downward, away from the centre of the fan.

Harvesting should never happen in the rain. During an interview conducted on Oct. 14, 2021 at *Rāpaki*, Paraone and Parata shared that they suspect this *tikanga* is largely a form of health and safety, as rain may cause the ground or plant to be slippery. This could be dangerous when harvesting using a sharp blade.

A *karakia*, which is similar to an incantation, is usually offered before harvesting. This is done to respect and acknowledge the resource that one is gaining from the harakeke plant and from nature. Once the *rau* have been harvested from the plant, they can be processed. Different methods of processing are used for extracting *muka* and processing the *rau* for weaving.

To make the *rau* best suited to weaving, a process called *hāpine* is followed which softens and removes moisture from the leaf [98]. First, the butt of the *rau* should be cut away as it is denser and stiffer than the rest of the *rau* and is more difficult to work with. How far up the butt that is cut is subject to the preference of the weaver and the nature of the cultivar being used. Then the spine and edges of the rau are removed. This can be done with a knife or bare fingernails and the *rau* is folded in half then cuts made from one side through both halves of the folded leaf. One cut will be in from the edge of the *rau*, and one from the spine. By threading a finger through both cuts and then running it up the length of the *rau*, these sections are removed, shown in Figure 10: A and B.

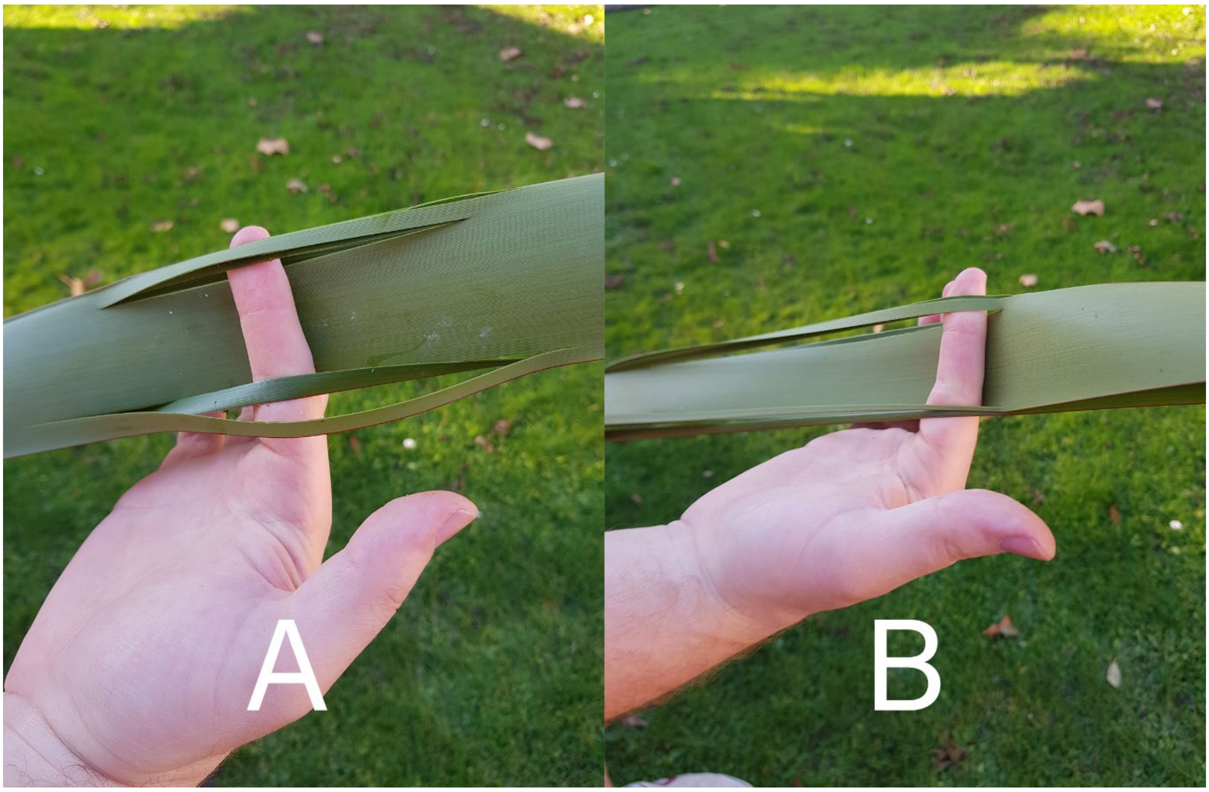

Figure 10: A and B, Removing the edges and spine of the rau for weaving. A: Fingers being inserted through the cuts made in the rau. B: The cuts are extended by running the finger up the length of the rau to remove the edges.

Now two halves of the *rau* are left and these can be cut into thin strips so that they are easier to work with. Shearers combs are an ideal tool for this as they have a uniform distance between teeth and can be inserted and run up the length of the *rau*. Other similar tools can be used to pierce the leaf and split it into uniform strips. These tools are referred to as a *hae hae*, shown in Figure 11.

Figure 11. A custom hae hae tool made for this research project based on a shearing comb hae hae used by Kerepeti Paraone (left) and Reihana Parata's hae hae (right).

The strips of *rau* will be rather stiff at this point, and if left to dry will curl up lengthways, which will make them hard to weave with. To prevent this, the blunt side of a butter knife of a mussel shell (*kūtai*) can be used to apply pressure the length of the *rau,* shown in Figure 12. Performing this will remove moisture from the strip and will make it more ductile or ribbon-like. Finally, the strips can be boiled to remove surface waxes. Boiling time may change depending on the cultivar used but is usually around 10-15 minutes. The strips can now be used to weave and will keep for a long time. If left to dry, they can be soaked in water for a few minutes to rehydrate and will be suitable for weaving again.

Figure 12. A kūtai is used to soften the rau by running the rau across its top. Note the green para collecting on the shell – this will also deposit on the weavers' hands and must be washed off before handling food.

To get *muka* from the *rau*, the same first step mentioned above is taken to remove the butt, sides, and spine. If the cultivar being used is known to have poor *muka*, the leaves should be soaked in water beforehand for a day which will soften them and make extraction easier.

Then the remaining *rau* is sized up into workable widths. This is up to personal preference but is usually between 10 and 30 mm wide. Next, the shiny and dull sides of the *rau* must be identified. The shiny side is smooth, and this is the side opposite to the spine when growing. The dull side must be cut perpendicular to the length of the plant. The depth of this cut should not be too deep, otherwise the fibres will be cut in the leaf. The cut needs to be deep enough to be close to the fibres, which will help removing the epidermis, or *para* later.

Then the *rau* is flipped with shiny side upward, and gripped above the incision, away from the user. A mussel shell, *kūtai,* is then gripped with the other hand with the straight side contacting the *rau* and the curved edge facing away from the user. With the *kūtai* hand, the index finger holds the *rau* in place as it is pulled back towards the user with the other hand, scraping away the *para*. Figure 13 shows some exposed *muka* after the *para* has been scraped from the shiny side using a *kūtai*. Depending on the cultivar, this may need to be repeated a few times however good *muka* cultivars favoured by experienced weavers will have the *para* removed easily.

Figure 13. Muka visible in a strip of rau after scraping away para with a kūtai.

With the *rau* held in the same orientation, the grip on it is now brought back to behind the incision made on the dull side, which is still facing down. The same motion with the *kūtai* is applied, only now it begins above the incision, which will release the *para* underneath from the *muka* as pressure runs its length. This may need to be repeated if the cultivar is not good for *muka*.

The *rau*, now with half its length stripped of the *para*, is reoriented to repeat the same process. The extraction of the *muka* by scraping away the *para* is called *hāro* [99]. The *muka* can now be stored for use. Some weavers will soak the *muka* in water and soap, which will further soften and whiten the fibres.

Tikanga states that neither of these processes should take place in a location where food is prepared or consumed. This is because harakeke has laxative properties and both processes will release moisture and *para* from the *rau* which could contaminate food.

Harakeke fibre from the Templeton Flax Museum was processed using the industrial methods utilised in the Pākehā New Zealand flax industry. This fibre is coarser than hand-stripped *muka* due to not all the *para* being removed since the machinery used is not as precise as the hand-held *kūtai*.

3.3. Composite Manufacture

3.3.1. ACCs

A commonly used solvent from the literature was used, of 7 wt % NaOH/12 wt % urea/81 wt % water [64]. This solvent was used to dissolve the outer layer of the harakeke *rau* to improve bonding [7] and was also the base for creating the cellulose solution used as the matrix of the composite.

To make the solvent, 12 wt % urea was weighed in powdered form and then 7 wt % of NaOH in pellet form was weighed using A&D FZ-500i scales supplied by Scalelogic Limited (Wanganui, New Zealand). The NaOH was added to the 81 wt % water in a large glass bottle and mixed on a Heidolph Hei-Connect magnetic stirrer supplied by Sigma-Aldrich New Zealand Co (Auckland, New Zealand). The NaOH was added in small amounts so as not to heat up the water via exothermic reaction. Then the urea was added and the solvent stored in an Acqua GY-NE325RFW refrigerator supplied by Jalmac Sales & Marketing Ltd (Rolleston, New Zealand) set to 5 degrees Celsius.

To then create the solution, 5 wt % cellulose was added to the solvent and was mixed using a Silverson L5M-A Laboratory Mixer made by Silverson Machines, Inc. (East Longmeadow, MA, USA) until the cellulose was dissolved. This usually took under 5 minutes of stirring after all cellulose had been added.

The mixture was then put in a Rollex Medical Freezer (Auckland, New Zealand) set to -11 degrees C for 2 hours, long enough for dissolution to occur without the solution freezing as detailed in the literature [65]. The solution was checked every half hour to make sure freezing was not occurring. This was done in small batches of around 300 ml which would be used within 7-14 days to stop aging of the solution, which could reduce its quality [100].

More cellulose would later be added to the 5% solution to reach desired levels for forming a matrix. The cellulose added to the 5 wt % solution was mixed in by hand until paste-like and then added to the harakeke leaf weave. Total cellulose percentages between 15 wt % and 35 wt % were made, increasing by 5% as concentrations were trialled. 25 wt % was the concentration used for manufacturing the ACCs used in testing due to it being the easiest to work with and suffering less cracking than lower concentration mixtures.

The weave coated in the paste was then put in the -11 degrees C freezer for another 2 hours to further dissolve outer layers of cellulose in the leaf. After the 2 hours in the freezer, the paste was placed in a Contherm designer 8100 oven supplied by Contherm Scientific LTD, (Lower Hutt, New Zealand) set to 60 degrees C for another 2 hours to gel.

After the 2 hours of gelling in the oven, the sample was then washed in water overnight. The sample was placed in a container of water to draw out the NaOH and Urea. The water was replaced every two hours until the water was no longer of an alkaline pH, around 7.5. Another method used for rinsing the samples was to leave them overnight under a tap pouring steadily so that the water was moving and replaced over time. No difference between the two methods was noticed.

After rinsing the pH of the water bath was between 7.5 and 8.5, which was indicative that the NaOH had been rinsed from the cellulose gel. The next step was to wash the sample in a >70% solution of ethanol for 24 hours which would further remove NaOH and urea from the gel while also dehydrating the sample. Finally, the sample could be dried to remove water and ethanol content and leave the cellulose matrix surrounding the leaf structure. Drying was initially done in an oven set to 60 degrees C for half an hour but this proved to be too fast a process and caused cracking of the samples. Leaving them between paper towels and a small weight to dry at room temperature took longer (24-48 hours) but caused less cracking of the cellulose matrix.

3.3.2. Epoxy Composites

The 7 wt % NaOH/12 wt % urea/81 wt % water [64] solvent was used to soak the *rau* for 2 hours at minus 11 degrees C to remove outer layers of leaf material and encourage bonding to the epoxy. After this, *rau* samples were dried in an oven at 60 degrees C for 24 hours to dehydrate them and improve epoxy bonding.

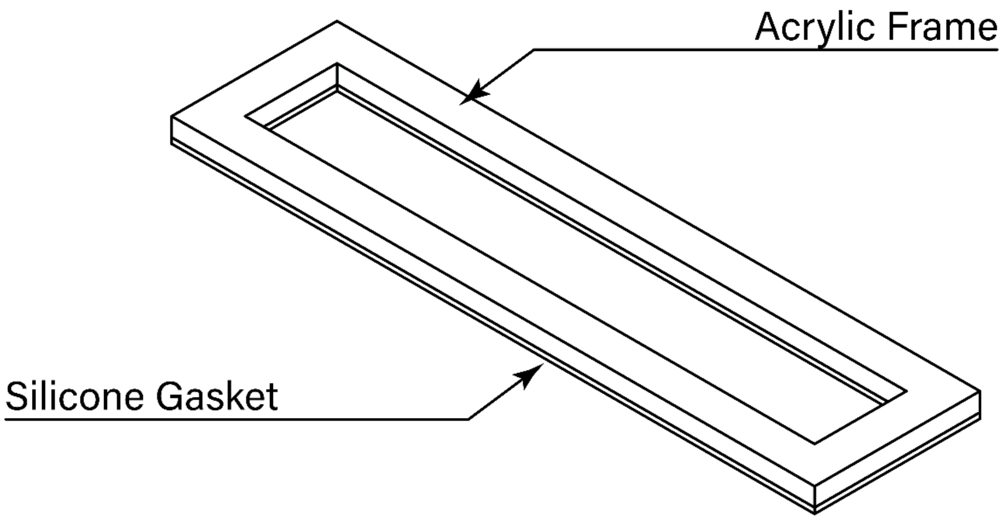

Figure 14. Acrylic frame with silicon gasket glued to its base.

Frames of acrylic were made using silicone gaskets to open cast the *rau* in epoxy. The gaskets were glued to the base of the acrylic frame shown in Figure 14, and these frames sat atop an acrylic baseplate shown in Figure 15. The silicone gasket prevented epoxy from leaking out.

The *rau* samples were weighed and then sat in the frames. Epoxy was mixed and degassed in an EC20 Industrial Vacuum Pump made supplied by Vacuum Pumps NZ Ltd (Auckland, New Zealand) before being poured into the frame around the *rau*. The framed samples were then put in an oven at 60 degrees C for a few hours to speed up curing of the epoxy.

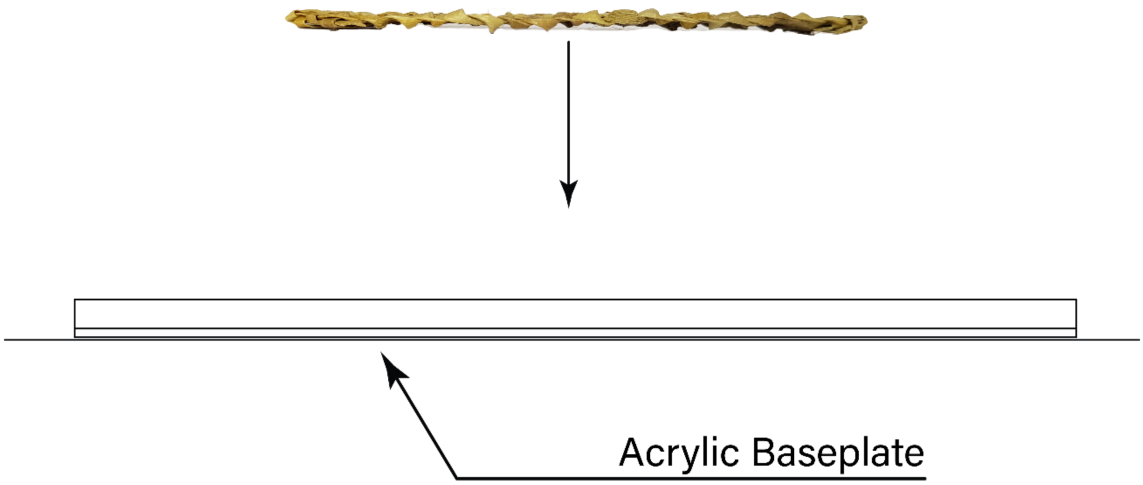

Figure 15. Side view of the frame and gasket sitting atop the acrylic baseplate. The harakeke weave is inserted from the top into the frame and then is epoxy poured in.

3.3.3. Glass fibre epoxy composites

Glass fibre bonds well with epoxy so a more common method of compositing these samples was used. The glass fibre was cut to size and laminated in 2 layers each. The samples were then laid on a plate and covered with a sheet of plastic stuck down with vacuum sealant tape. The system was completely closed and a pipe inserted which was connected to the vacuum pump to vacuum bag the glass fibre. Excess epoxy was removed via the vacuum after 30 minutes and the glass fibre was set aside with the coating of epoxy to cure.

3.4. SEM

For an effective insight into the bonding between *rau* and matrix, a fracture surface was required, rather than a shear surface. ACC Samples were immersed in liquid nitrogen for around 10 seconds at a time, when bubbling stopped, then cut with a scalpel following the method used by Karadagli, et al. [101]. When not frozen, ACC samples tended to crumble rather than fracture.

The epoxy samples were stronger than the ACC and could not be fractured with a scalpel. Instead, after being submerged in the liquid nitrogen, pliers were used to split them apart.

They were then made smaller by belt sanding a non-fracture surface which also provided a more stable base for mounting in the carbon tape.

A JSM-IT300 Scanning Electron Microscope with a LaB6 electron source was used to view the samples and to take photos. A 50mm holding plate was used to hold the samples and carbon tape was used to hold them in place. Cellulose samples were coated in palladium using a Q150T Plus Turbomolecular pumped coater supplied by Quorum (East Sussex, UK) before viewing but the epoxy samples were not coated and instead were viewed using low vacuum.

3.4.1. Sample Catalogue

Samples were named using the following procedure. The type of weave was the first part of the name followed by a dash and the matrix material then another dash and a number between 1-5 since 5 samples in each series were made. For example, the first twill harakeke sample with a cellulose matrix would be named "TW-C-1". In the case of the glass fibre samples, "GF" is put in place of the matrix material since all glass fibre composites were made with epoxy. The *rau* weaves that were tested as textiles and not as composites have no matrix code since they did not have one.

The plain diagonal *rau* weaves have an extra letter following the "PD" code to identify who wove the sample. "PDC" samples were woven by the author who is a novice weaver and "PDK" samples were woven by Kerepeti Paraone, a skilled weaver. Having different skilled weavers manufacture this set of weaves was done to see if skill level impacted their behaviour at all. The code conventions are shown below in Table 3 and Table 4.

Table 3. Weave codes.

Code	**Weave**
PDK	*Takitahi Pāraerae*/Plain diagonal, Kerepeti
PDC	*Takitahi Pāraerae*/Plain diagonal, Novice
PW	*Takitahi*/Plain
TW	*Whakatutu*/Twill

Table 4. Matrix suffix codes.

-C	Cellulose, ACC
-E	Epoxy
-GF	Glass fibre, Epoxy

ACC SEM samples included a range of different cellulose concentrations used in the matrix to see how this affected bonding. Both short cut *rau* in random orientation and woven *rau* were used. Short cut *rau* were used in the pretesting of making ACCs as it was quicker to use random orientated *rau* than to weave all the samples. The form of *rau* was not anticipated to affect bonding at all. All samples were pre-treated in the 7 wt. % NaOH/12 wt. % Urea/water solvent prior to being composited, except for one sample which was left untreated to compare under the SEM. The last variable was the method used to impregnate the *rau* with the cellulose paste being either vacuum bag forming or pressing. The samples and their variations are described in Table 5.

Table 5. ACC SEM Sample IDs

Sample ID	**Description of ACC sample**
ACC-1	30 wt. % cellulose, short *rau*, pre-treated, pressed.
ACC-2	35 wt. % cellulose, woven *rau*, pre-treated, vacuum bag.
ACC-3	20 wt. % cellulose, short *rau*, not pre-treated, pressed.
ACC-4	20 wt. % short *rau*, pre-treated, pressed.
ACC-5	30 wt. % woven *rau*, pre-treated, vacuum bag.
ACC-6	20 wt. % woven *rau*, pre-treated, vacuum bag.

Three epoxy samples were prepared for the SEM; two *rau* samples and one *muka* sample. These samples are described in Table 6.

Table 6. Epoxy SEM sample IDs

Sample ID	**Description of epoxy sample**
E-1	*Muka*, pre-treated, open cast mould.
E-2	Woven *rau*, pre-treated open cast mould.
E-3	Woven *rau*, untreated, vacuum bag formed.

3.5. Tensile Testing

Preparation of samples for tensile testing differed between samples. The non-composite woven *rau* textiles had wooden clamps cut and glued to their ends to protect them from damage in the machine. They were then stored in a controlled environment with humidity and temperature set to 20 degrees C and 50% humidity for 4 days before testing.

The cellulose samples also had protective wood clamps made and glued to them and were stored in zip lock bags as soon as they were removed from the freeze drier to protect them from moisture.

The epoxy samples required some machining to remove excess material resultant of the open casting method. After this, they were stored in zip lock bags until testing.

The tests were carried out using an MTS Criterion Model C43 supplied by Australian Calibration Services (Collingwood VIC, Australia) with data acquisition set to 10 points per second and test speed to 2 mm per second. For the textile and ACC samples, a 2.5 kN load cell was used while the epoxy and glass fibre samples required a 10 kN load cell. The MTS Criterion Model C43 is accurate to 1% of the load cell force which is why the 2.5 kN load cell was used for the weak textile and ACC samples.

3.6. Ethnomathematics and Griswold's Method

Drawdown diagrams of the weaves can be made to illustrate their structure. The drawdown diagrams work well to illustrate Griswold's binary method since the diagrams are coloured black and white which become 1's and 0's in the code. In Table 7, plain and twill designs are described in a binary array with the corresponding drawdown diagrams shown in Figure 16. In the "General" row of the table, ellipsis is used to indicate that the pattern of 1's and 0's can continue indefinitely in the horizontal direction, and the word "repeat" to indicate that the set of rows above it can be repeated as a block indefinitely in the vertical direction.

Table 7. Griswold's Boolean method of describing weave patterns based off drawdown diagrams.

Plain	Twill 2x2
General: 1 0 1 0 1 0 … 0 1 0 1 0 1 … repeat	General: 1 0 0 1 1 0 0 1 … 0 0 1 1 0 0 1 1 … 0 1 1 0 0 1 1 0 1 1 0 0 1 1 0 0 … repeat

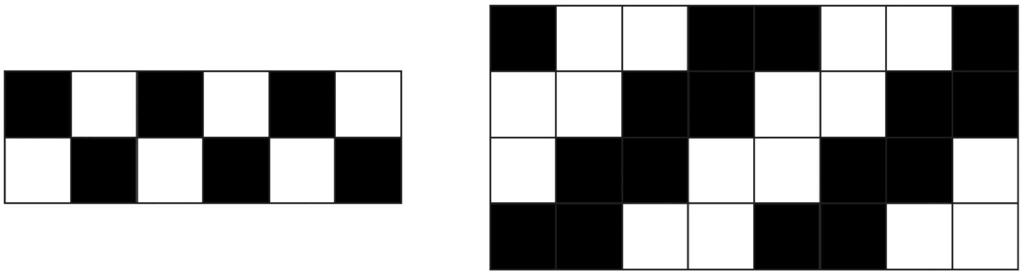

Figure 16. Drawdown diagrams of plain (left) and twill 2x2 (right) weaves.

This work is based on Griswold's mathematical study of Western weaving [92, 93]. The first step in Griswold's method is to find what is called the unit motif. This is the smallest section of the binary array that can be made where the weave pattern is able to be repeated infinitely simply by repeating this section. For the plain weave, the unit motif is:

1 0
0 1

Repeating this block of four binary numbers in the horizontal and vertical directions will generate a plain weave of any size. For the twill weave, the unit motif is:

1 0 0 1
0 0 1 1
0 1 1 0
1 1 0 0

Unit motifs can often be found by looking closely at the pattern when the structure is simple as with plain and twill weaves. However, in a more complex design, care is needed when determining the motif. The process consists of an initially row-based comparison between the weave pattern and a test pattern made by repeating the first number of the binary array over and over, then the first two numbers, and so on, until the test and the pattern match. This process is repeated for columns using the unit motif of the first row, then the first two rows, and so on.

3.7. Weave modelling and Finite Element Analysis

To model the harakeke weaves, the program WiseTex was used. To start, the known mechanical values of harakeke fibre were inserted into the programme. These values were density, Tex and fibre diameter which are needed for WiseTex to perform calculations on how a fibre will behave. Then the “tow” of the *rau* was replicated by counting the average fibres in a strip used for weaving. These values were then applied to a twill weave in the programme and exported to Ansys to be modelled. See Appendix 1.

Modelling proved very difficult due to the nature of the geometry of the weaves having many boundary conditions including the interaction between faces of the *rau* as they passed over one another. In a Zoom interview (Dr S. Lomov, private communication, Sept. 27, 2021) it was decided that FEA using WiseTex models would be too difficult for the project. Transferred FE models from WiseTex can face issues in FEA packages due to interpenetration of yarn geometry and matrix phase [102]. Instead, Dr S. Lomov provided expertise in the software TexComp to calculate theoretical values of the samples elastic modulus which could be compared to the tested physical versions.

The values used were quite arbitrary and many assumptions had to be made when inputting values to WiseTex and TexComp. This is because information in the literature was focussed on the properties of the *muka* of the harakeke with almost no focus on the *para* and composition of the *rau*. The value of Tex, which is linear density (g/m), for harakeke *muka* was used from Lowe et al [98]. This value of 17 Tex meant that the volume fraction of *muka* within the *rau* is 0.123. Images of cross sectional area of harakeke *rau* show that fibre concentration is low in the *rau*, so *muka* making up only 12.3% of the mass is possible [6]. The value for density of harakeke used was 1.27 g/cm^3 [9] but this value was calculated for *muka*, not the *rau*. Since no values were found in the literature for the density of the *rau*, this was used instead.

3.8. Perception Study

To gauge the value perception of the harakeke composites, a study was conducted via online survey made using Qualtrics. The survey was anonymous but did ask for age and gender. It consisted of three questions relating to composites and had 56 participants who were recruited via a social media post to Instagram.

The first question asked participants to rank the importance of four factors in composite materials: Aesthetics, Cultural Significance, Sustainability and Strength. This was to understand what consumers may be looking for when purchasing composites.

The second question was in three parts, asking participants to use a Likert scale to rate 3 composites based on an image of each: a harakeke ACC, an Epoxy-harakeke composite and a glass fibre composite. The Likert scale had five levels: Strongly Disagree, Disagree, Neutral, Agree and Strongly Agree. These statements were chosen against three factors of the composite: Aesthetic Pleasantness, Cultural Significance and Sustainability. Participants stated their level of agreement with each factor against the three composites.

The final question asked if participants would be willing to spend more money in purchasing products made from materials with historic and cultural significance, such as composites made with Māori weaving patterns and harakeke. These questions are shown in Appendix 2.

4. Discussion & Results

4.1.1. Process of Manufacturing Composite Samples

Natural fibre composites are almost always reinforced with the fibres from a plant. However, for this project where the weave patterns were of interest, harakeke *muka* could not be used as it is more difficult to weave with. The types of weaves this study employed would usually be made with the *rau* since they are common weaves for making *kete*, *whāriki* and *Pāraerae*.

Using the *rau* as composite reinforcement presented issues of bonding between the *rau* and both the epoxy and cellulose matrices. This issue of bonding complicated the process of creating composites and attempts were made to overcome the poor adhesion between matrix and *rau*.

The main reason for the poor adhesion of the *para* can be found in its chemical composition. The *para* of the harakeke plant is coated in waxes [103] just like many other plant leaves. Suberin and cutin are waxes often found in the epidermis of leaves and act as a protective barrier for the plant [104]. The epidermis, suberin and cutin are all hydrophobic compounds [105] since the epidermis protects against a range of potential contaminants, with water being one [106]. This is likely a cause for the nature of the *rau para* and its poor bonding capabilities with the cellulose matrix phase, as cellulose bonds via hydrogen bonding and therefore doesn't bond well with hydrophobic chemicals. Epoxies are generally hydrophilic too, so the presence of the waxes in the *para* can be identified as the reason that the *rau* did not bond well with the epoxy matrix [107].

To remedy this and improve bonding, the 7 wt % NaOH/12 wt % urea/81 wt % water solvent was used in an attempt to remove the waxes on the *para*. To test if there was a noticeable difference in bonding, epoxy was poured over pre-treated *rau*. Figure 17 shows that there was some epoxy sticking to the *rau*, which was an improvement over the untreated *rau* where the epoxy would run off the surface and leave only small deposits. Even with some visible improvement, the overall bonding was still not strong enough to form composites in a conventional manner using vacuum bag forming and the epoxy would form inconsistent deposits on the *rau*. Instead, open cast moulding was used to fully encase the *rau* in epoxy to provide a matrix around it. In addition to pre-treatment of the *rau* weaves, they were dried in an oven for 24 hours at 60 degrees C to remove moisture in an attempt to achieve better bonding to the epoxy. If moisture is present on the *rau* it can disrupt bonding due to the fact that epoxy will bond with the water rather than the *rau*, as it is hydrophilic [107, 108].

Figure 17. Experimenting with the bonding between pre-treated rau and epoxy.

Cellulose samples were pre-treated from the start of testing since previous works have discussed the need to mercerise harakeke *muka* before compositing. One sample was made with untreated *rau* to investigate its bonding under SEM microscope. Figure 18 shows a sample that was made to test the bonding and process of making ACCs with *rau*.

Figure 18. 20% short rau pressed ACC sample made early in the project to investigate bonding.

The cellulose composites suffered from cracking in the matrix when drying and gelling. No pattern was determined in where the cracks would occur, but they were likely exaggerated by the shrinking of the *rau* as it dried. This shrinkage was most severe during the gelling phase of the process since the cellulose matrix was not being dehydrated, it was being gelled, but the harakeke *rau* was dehydrating under the conditions, shrinking more quickly than the gel. This is shown in Figure 19.

Figure 19. A 25 wt.% ACC sample which has cracked during the gelling phase. The harakeke rau can be seen to have already dried out despite the gel being moist. The brown colour in the cellulose matrix is due to it not having been washed yet, which happens after gelling.

Cracks were deep and opened up the matrix so that the *rau* was visible behind the cellulose matrix. Different ratios of cellulose were tested in the paste, with higher amounts of cellulose reducing shrinkage and cracking. However, at 30 wt.% cellulose, the paste became difficult to mix and apply to the samples. Different drying methods were also employed with the first being oven drying. The oven was set to 60 degrees C and samples were dried for half an hour at this temperature but this proved to be too rapid and caused significant cracking. Drying between paper towels at room temperature for 48 hours was the next method tried, and less cracking was found to occur. Despite this, there was still cracking and so a freeze-drying method was used. This produced a foam like matrix phase with less cracking than paper towel drying at room temperature so this was the method used in the final batch. A comparison of drying methods and matrix wt.% of cellulose are shown in Figure 20.

Figure 20. Comparison between 20 wt.% cellulose matrix cracks after drying via oven (top) and 25 wt.% matrix cracks after freeze drying (bottom).

The *rau* samples could have been pre-dried before being turned into ACCs but it is possible that in the washing stage the *rau* would simply rehydrate and swell, which would stress the matrix and likely cause cracks.

4.2. Tensile Testing

The first tests were conducted using *rau* woven samples in a textile form. This is how they would usually be used by Māori weavers when made into things such as kete. This would provide insight into how the weaves behave when in textile form. The next samples were the harakeke composites, using epoxy and cellulose as their respective matrix materials. Finally, glass fibre samples were made using the same epoxy matrix used for harakeke, with weaves mimicking the woven *rau*. Industrially woven plain and twill 2x2 glass fibre textiles were used for this. To mimic the harakeke diagonal weaves, the glass fibre plain weave was cut at a 45° angled bias.

4.2.1. Woven Textile Samples

The *rau* weaves did show differing behaviour to one another which can be seen in both the shape of the graphs and the table describing their properties. Below in Figure 21 representative samples of twill, plain weave and plain diagonal weaves are shown alongside each other. For full data sets see the Appendix.

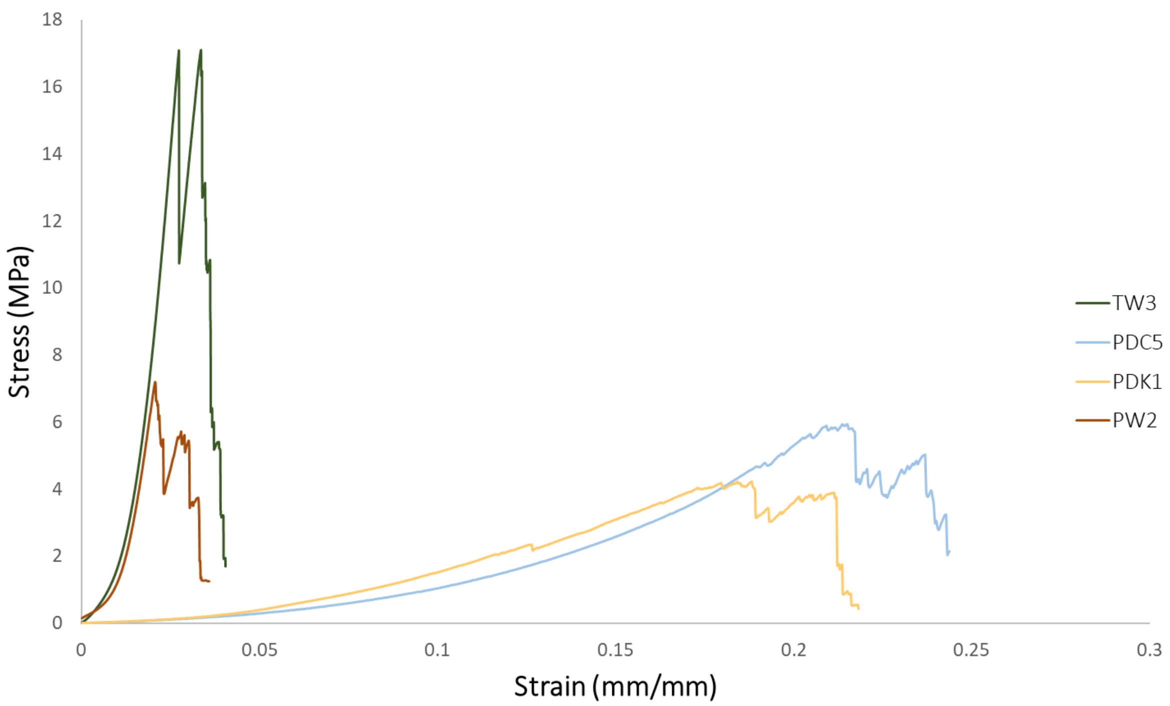

Figure 21. Representative Stress/Strain behaviour of the four different weaves: TW, PW, PDC and PDK.

The twill weave was found to be stronger than the plain weave in these tests and while there is some disagreement in the literature about what woven textile should be stronger, justification for these results can be found in published work. It is likely that the twill is stronger due to it having lower crimp meaning there are more yarns orientated in the direction of the loading [81]. The plain weaves are weaker since they have more crimp which decreases the amount of yarn in the direction of loading. Malik et al describe contact friction caused by high interlacement as being the key contributor to a plain weaves strength over twill weaves [80]. However, the looseness of the hand-woven samples used in this project may not have created enough friction between yarns to strengthen them in this way, causing them to be weaker than the twill samples.

These results are interesting because the hand woven *rau* textiles behave in a way that is anticipated of industrially woven textiles. As well as being hand woven, the *rau* used as yarns are not similar to the yarns that would be used in industrial textiles which are spun and entirely fibrous. The *rau* has fibres but they are encased in the *para*.

Both plain diagonal weaves, PDC and PDK, display different behaviour than the twill and plain weaves. They both have lower slopes due to their 45° bias weave as the yarns reorientate themselves into the direction of loading. The yarns cannot reach a 0° orientation though, so these weaves are not as strong as the PW or TW samples, even when they are stretched to their maximum. Due to their bias, they extend more than the TW and PW as seen in Figure 23 which shows the average stress at ultimate tensile strengths of the weaves. Due to their extension, the PDC and PDK weaves have higher strain at ultimate strength.

Interestingly, PDC samples were on average stronger than PDK samples. However, the standard deviation in PDC (1.12 MPa) is much higher than PDK (0.26 MPa) due to the experienced weaver being more consistent than the novice weaver. The consistency of weave structure is shown in Figure 22.

Figure 22. Consistency of weaves compared. Experienced weaver (top) and novice weaver (bottom).

Using the available data, a hypothesis can be drawn that the novice weave samples were stronger due to their looser, less consistent weaves. The looseness of the weave reduces the crimp angles so that there are longer sections of float in the *rau* yarns, increasing strength in the axis of loading [81]. This looseness which allows for the *rau* yarns to move more freely in the weave might also be the reason for the higher strain at ultimate strength since more movement in the weave caused a higher strain before load began breaking the fibres.

Table 8. Mechanical Properties of tensile tested weaves

Weave:	Ultimate Strength (MPa):	Standard Deviation:	Strain at Ultimate Strength (mm/mm):	Standard Deviation:
PDK	3.841	0.260	0.182	0.035
PDC	4.599	1.120	0.210	0.023
PW	5.636	1.430	0.021	0.006
TW	13.431	2.800	0.027	0.005

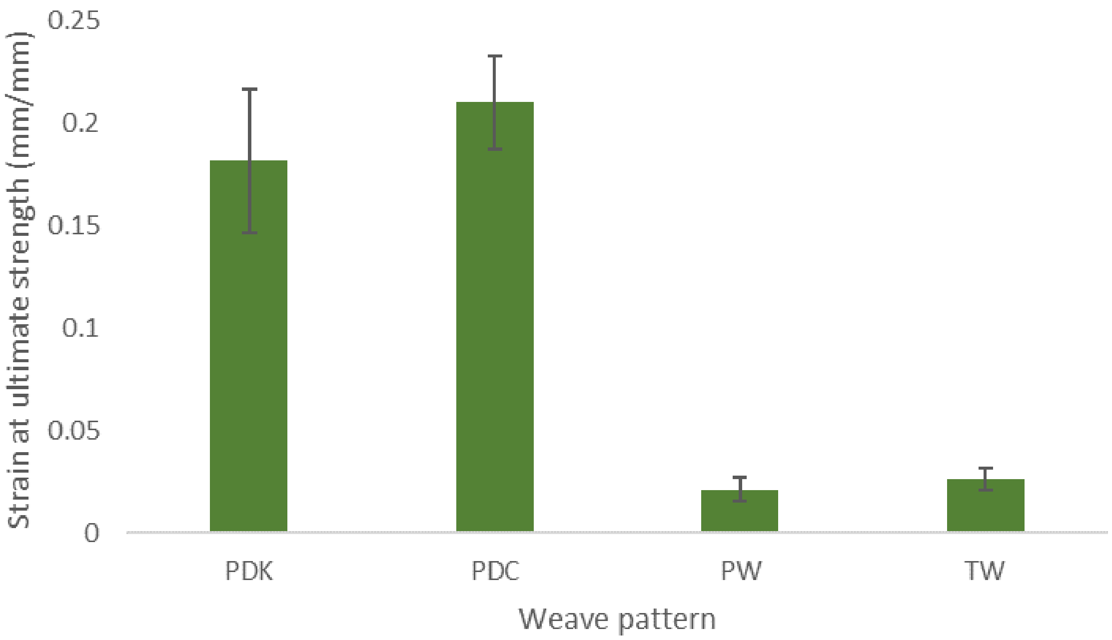

Figure 23. Average stress at maximum strain of each weave series. Error bars represent one standard deviation.

The textile weaves broke along the *whenu* or warp fibres which lie vertical in the weave. This can be seen in Figure 24 showing a *whakatutu* weave after break where the vertical *rau* have split along their length indicated with a blue arrow. This breaking mechanism can be used to help understand the shape of the stress/strain graphs where multiple peaks are seen in the curve. This is individual yarns breaking, followed by the other yarns taking on load. The first break is often at the highest stress point since after it breaks there are less yarns still intact and therefore less available *rau* to contribute to carrying load.

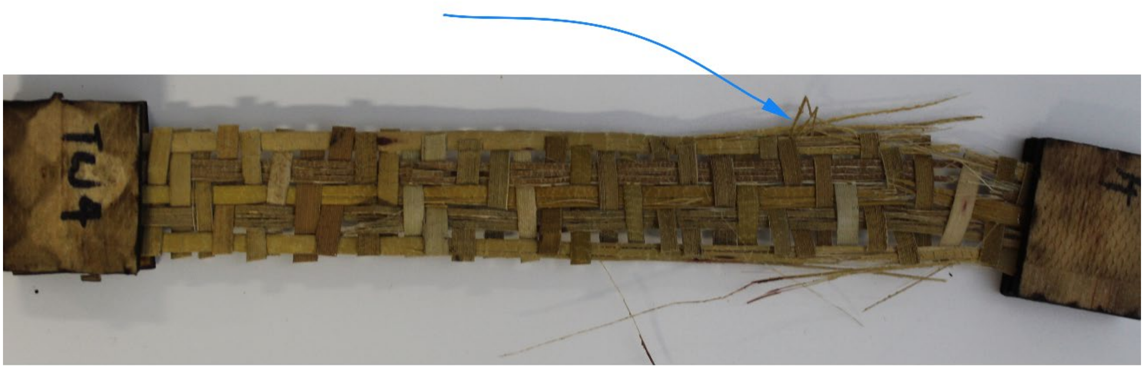

Figure 24. TW after break. Blue arrow indicates broken rau.

The *takitahi pāraerae* samples broke in the same areas after deformation. By the time these weaves broke they had been stretched and had therefore decreased in width as the *rau* yarns aligned themselves in plane with the load and got closer together. The *takitahi pāraerae* samples suffered gradual breaks in the weave which caused early peaks in the graph as the load was transferred between *rau* as they broke. The break is shown in Figure 25.

Figure 25. Takitahi pāraerae breakage.

4.2.2. ACC Samples

The behaviour of each of the textile weaves was translated similarly in the ACC samples, where the weaves behaved much the same. The ACC samples showed similar shapes in the graphs but were much weaker than the textile weaves. This is due to the fact that the cellulose matrix did not bond well to the *rau* due to the waxy hydrophobic nature of the *para* [103], as described earlier [104, 105]. Consequently, the matrix did not behave as it should and load was not transferred between the *rau* and matrix. Stress was not evenly transferred through the *rau* weave by the cellulose matrix, despite it adding volume to the samples which resulted in an overall decrease in strength. This can be seen in Figure 26 where the *whakatutu* weave is far stronger than its ACC equivalent. Interestingly, the strain can be seen to be much larger in the ACC. The only difference between the *rau* of the woven textiles and the ACC impregnated *rau*, aside from the added cellulose to the ACC weave, was that the ACC *rau* were pre-treated in order to help bonding to the cellulose. This pre-treatment solvent must have penetrated deeper than the external *para* and affected the nature of the inner fibres, giving them more strain potential. This behaviour has been seen in literature where ramie fibres increased their strain drastically after mercerisation [109]. ACC values are shown in Table 9.

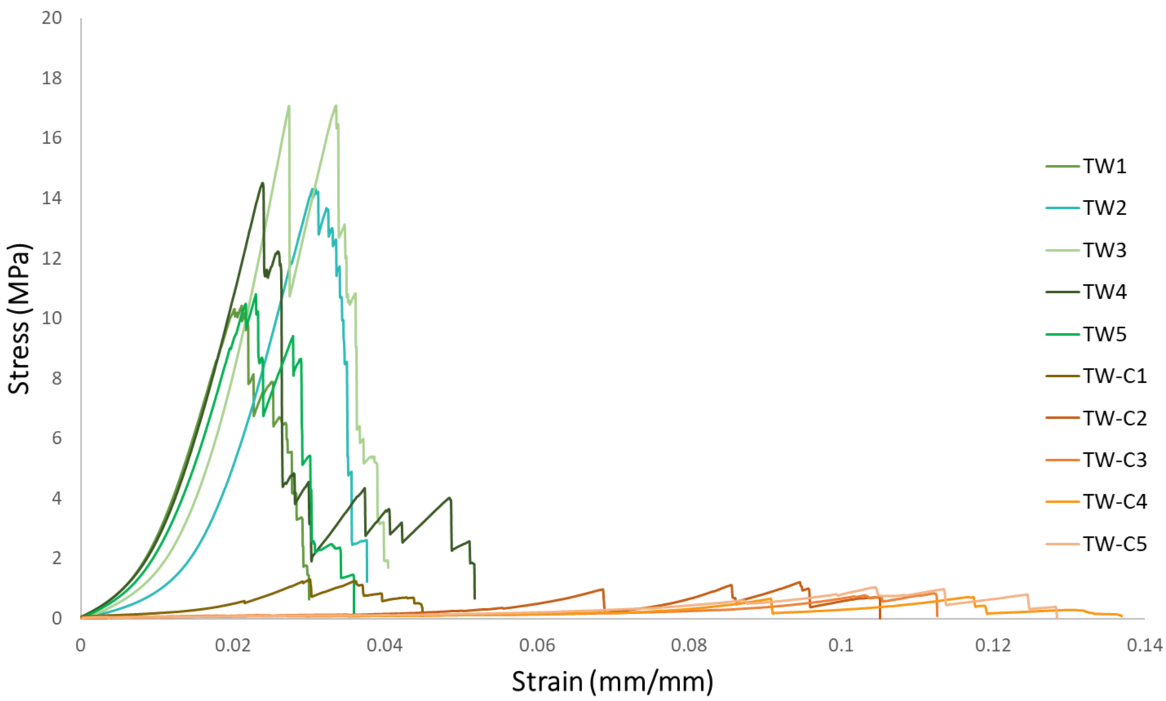

Figure 26. TW-C (Whakatutu ACC) compared with TW (Whakatutu weave) Stress/Strain graph.

Table 9. Mechanical Properties of tensile tested ACCs.

Weave:	Ultimate Strength (MPa):	Standard Deviation:	Strain at Ultimate Strength (mm/mm):	Standard Deviation:
PDK-C	0.986	0.238	0.222	0.026
PDC-C	0.493	0.220	0.307	0.028
PW-C	1.191	0.513	0.054	0.015
TW-C	1.019	0.240	0.092	0.035

Another reason that the ACC samples can be described as behaving similarly to the woven textiles is that they did not one area as one failure point but often at different places in the weave, further proving no load transfer occurred between *rau* and matrix. This behaviour is demonstrated in Figure 27 where there are breaks in the *rau* in the middle of the weave and at the base where a *rau* has been split. In the stress/strain graphs this behaviour is shown by the many peaks in the curve where the *rau* are breaking separately from one another instead of together as one unit, which would be expected in a composite where the matrix shares load between the fibres.

Figure 27. PW-C3, a plain weave ACC after break. Blue arrow indicates split at the base if the rau.

4.2.3. Epoxy and Glass Fibre Samples

The epoxy composite samples behaved quite similarly to one another in the shapes of their stress/strain graphs and the mechanical values they displayed. They did not behave like the textiles or ACC samples because the woven *rau* was not directly contributing to the sample's properties except for improving their stiffness. Due to the poor bonding between *rau* and epoxy described earlier [103-105], open cast moulds were used to encase the woven *rau*. This created composites that were predominately epoxy and had low mass fractions of fibre, with the mass fractions of the TW-E samples shown in Table 10. The average mass fraction for the TW-E samples was 0.137. This meant that the properties of the epoxy composites were largely influenced by the epoxy and hardly at all by the harakeke *rau*. The stress/strain curves of the TW-E composites, shown in Figure 28, resembled the behaviour of the epoxy rather than the curves expected from the textiles. The ultimate strengths where the composites broke were all similar to one another as seen in Table 11, despite the different weaves showing different behaviours in the textile and ACC forms. In Table 11 similar strengths are seen for the PDK-E and TW-E, and for the PDC-E and PW-E samples. The reasoning for this can be better understood when their *rau*/mass fractions are compared in the last column of the table. The strongest two samples, PDC-E and PW-E, have the lowest *rau* mass volumes at 0.12 and 0.11 respectively. The harakeke *rau* was actually weakening the epoxy so by having a lower fraction of harakeke, the composite was stronger. The only improvement that the *rau* made to the epoxy was to increase its stiffness by acting as a filler, since the harakeke is stiffer than the thermoset epoxy. The addition of fillers is known to improve stiffness in polymers [110-112]. The average stiffness modulus of the epoxy was found to be 1.424 GPa while the PW-E and TW-E samples had stiffness moduli of 2.15 GPa and 2.563 GPa. The Diagonal weaves in epoxy had an average modulus of only 1.6 GPa which was stiffer than the virgin epoxy but less than the other weaves, likely due to the diagonal structure of the weave which was less stiff as found in other tests with the ACCs and textile samples.

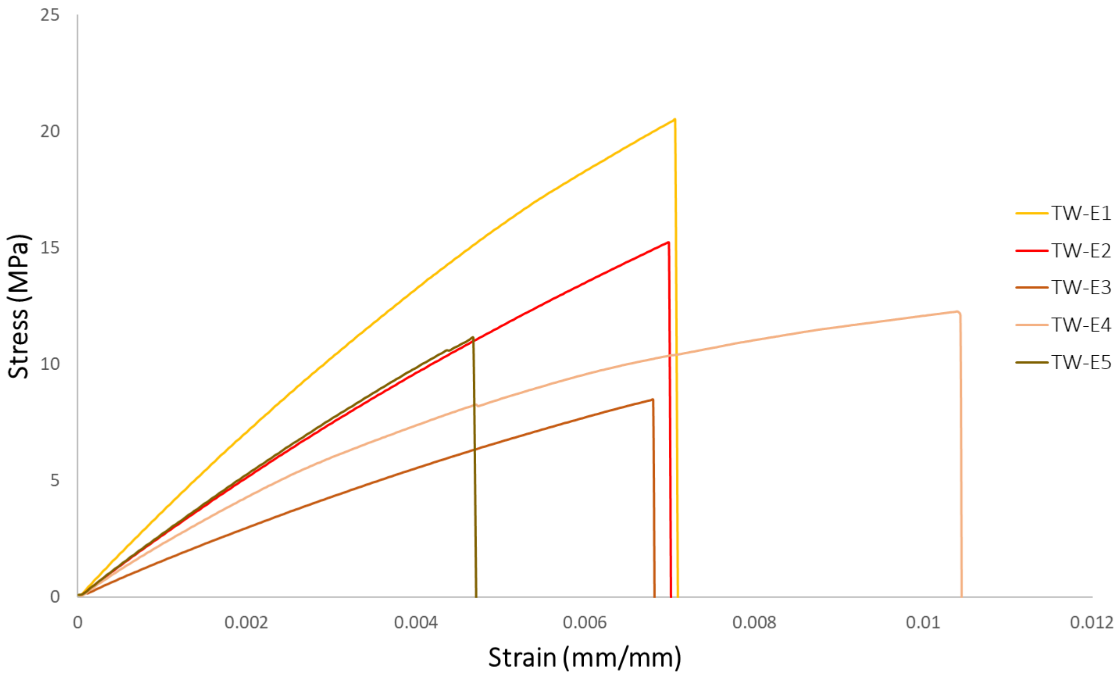

Figure 28. TW-E samples stress/strain curves.

Table 10. Rau mass fraction of TW-E samples

Weave weight (g)	Composite weight (g)	Mass fraction of *rau* in composite
1.982	17.974	0.110
1.566	11.452	0.137
1.708	10.865	0.157
1.667	11.008	0.151
1.692	13.267	0.128

Table 11. Mechanical properties and rau/mass fractions of tensile tested rau-epoxy composites.

Weave:	Ultimate Strength (MPa):	Standard Deviation:	Strain at Ultimate Strength (mm/mm):	Standard Deviation:	Average Fibre/*Rau* Mass Fraction
PDK-E	13.210	4.183	0.028	0.021	0.143
PDC-E	17.675	2.021	0.022	0.009	0.117

PW-E	17.430	1.957	0.011	0.001	0.114
TW-E	13.527	4.590	0.007	0.002	0.137

The matrix was not being strengthened by the *rau* due to issues with bonding as described previously [103-105]. Instead, due to the lack of bonding and therefore load transfer, the *rau* was acting like voids in the matrix. Breaks in the epoxy samples tended to occur across transversal *rau* due to this being the thickest part of the weave, as *aho* and *whenu* cross over, creating the largest voids in the epoxy. This is shown in Figure 29 below where X marks the largest gap created by the *aho/whenu* cross over. A transversal *rau* breakage that occurred in a PW-E sample is shown in Figure 30.

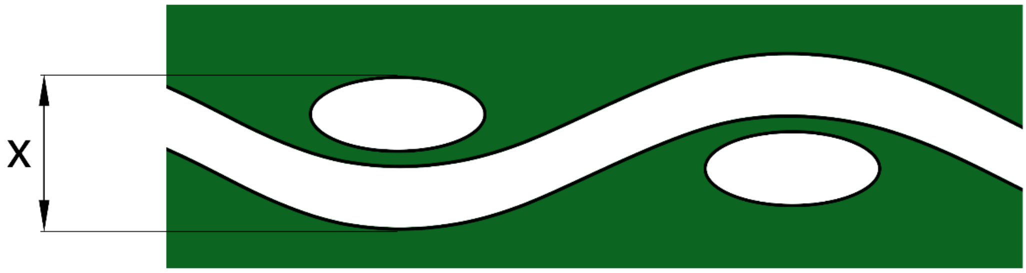

Figure 29. Epoxy matrix (green) with rau weave acting as voids (white).

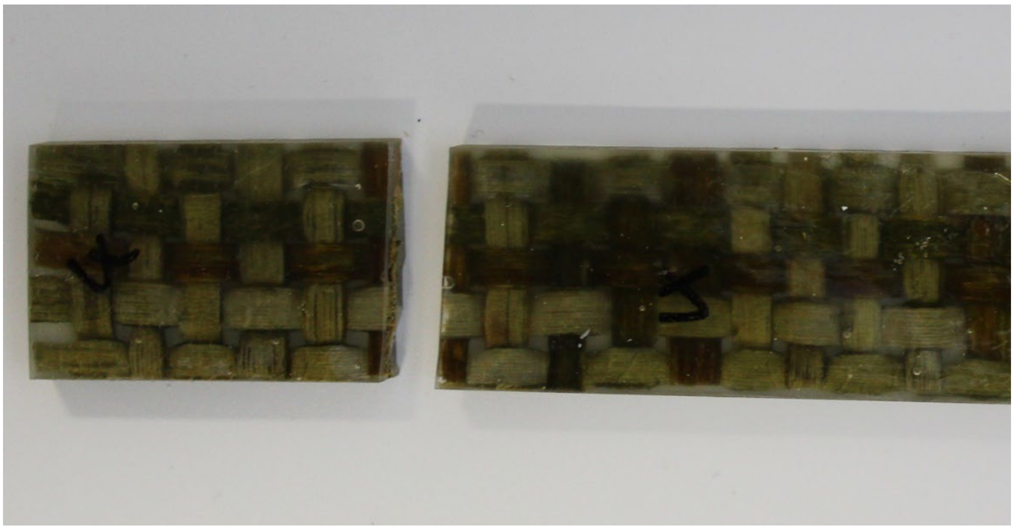

Figure 30. Breakage along the aho (transversal) rau in a Takitahi weave epoxy composite.

In Figure 31, one sample of each of the three weaves used to make the glass fibre composites are compared. In this graph, the three weaves clearly display their distinct behaviours and act as expected. The twill weave is the strongest of the three lending to its structure having longer areas of float and lower crimp as expected from published works [84-86]. The plain weave composites have lower strength due to higher interlacement which increases crimp, decreasing fibre alignment in the direction of loading. The diagonal weaves are seen to have the largest strain, due to their 45° bias structure stretching as the fibres realign in plane with the tensile force. All glass fibre graphs are shown in the Appendix. The glass fibre composites display behaviour that is expected based on the weave pattern reinforcing them and this is due to their good bonding with the epoxy which caused load transfer to be carried by the fibres. This distinction between weave patterns in composites would likely have been seen in the harakeke *rau*-epoxy samples, had the bonding been effective.

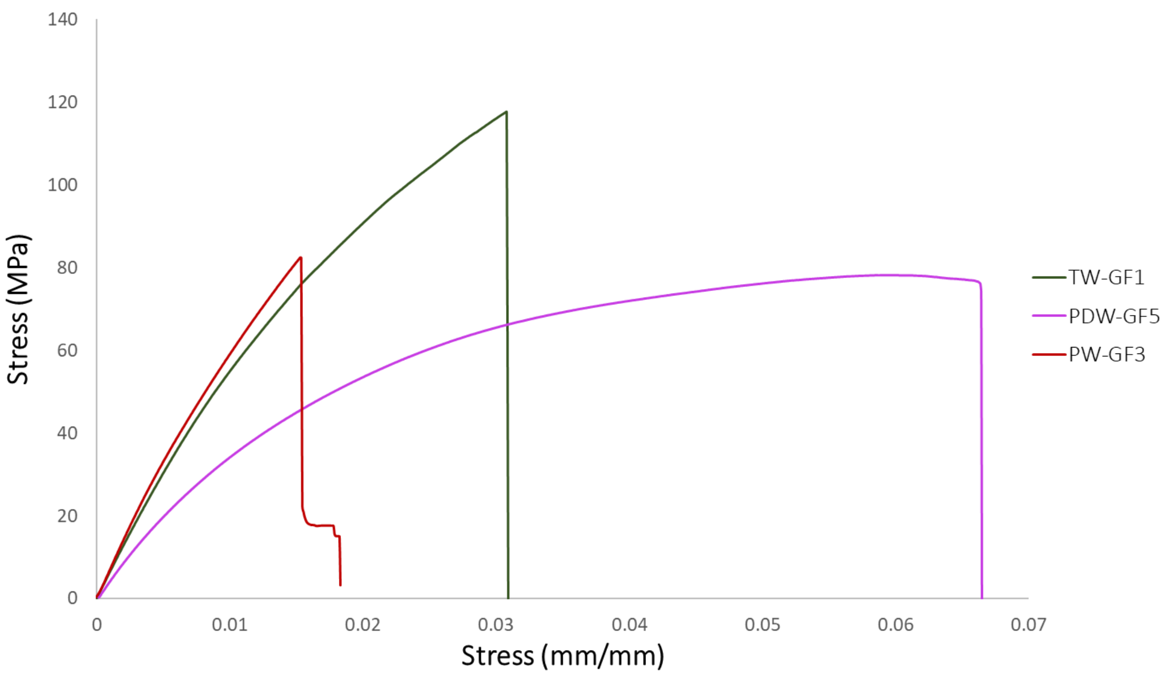

Figure 31. Representative sample of each of the three weaves used to make the glass fibre composites.

4.3. Model Weave Calculation

The stiffness modulus of the TW-E sample (2.563 GPa) was lower than the calculated TexComp value of 3.8 GPa. TexComp calculations assume full impregnation of the yarns, which was not the case for the *rau* since epoxy did not impregnate it at all. TexComp also assumes perfect bonding which did not occur between harakeke and epoxy due to the waxes on the *para*. In the case of the *rau*, which is made up of many parts, the spaces between fibre bundles are much larger than the spaces that would occur in an industrial yarn. Industrial yarns are made entirely of fibre, whereas the *rau* consists of *para* encasing the fibres. A volume fraction of 0.1 for fibres in the *rau* was calculated from the software which initially seemed low. However, when compared to the composites that were manufactured using the *rau*, this number is close to the values obtained for mass fraction (0.137) and when the low fibre volume fraction in the *rau* is considered, this calculation is likely to be too high. Still, it was used for lack of any other sufficient value. The *rau* is a chemically complex part of the plant and so separate testing would need to be done on the *rau* to get usable properties for making calculations in TexComp, or similar software.

4.4. Griswold's Method and Mathematical Modelling of Weaves

It was found that two Māori weaving patterns, *takitahi* and *whakatutu*, could be easily converted into binary arrays since they are the same structure as plain and twill weaves. *Takitahi* and *whakatutu* designs are described in a binary array below in Table 12. The "Test strip" array is only 5 yarns wide with no ellipses indicating that it continues further because this describes the test samples that were made for tensile testing.

Table 12. Takitahi and Whakatutu weaves described using binary array.

Takitahi	*Whakatutu*
General: 1 0 1 0 1 0 … 0 1 0 1 0 1 … repeat	General: 1 0 0 1 1 0 0 1 … 0 0 1 1 0 0 1 1 … 0 1 1 0 0 1 1 0 1 1 0 0 1 1 0 0 … repeat
Test strip: 1 0 1 0 1 0 1 0 1 0 repeat	Test strip: 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 repeat

There are some interesting mathematical aspects of this process which can be used to simplify and speed up the process. One such aspect is to consider the *cyclic permutation* of the rows of the binary array in the pattern. A cyclic permutation of a list of numbers means in each new row, each number moves one place to the left, and the first number cycles round to the last number. For example, here are three cyclic permutations of the list "1 2 3":

1 2 3
2 3 1
3 1 2
1 2 3

Where the “1” moves to the end of the sequence in the second row as the “2” and “3” move to the left. After three cyclic permutations of “1 2 3” the original sequence is repeated again. In the *takitahi* case, the second line of the unit motif, 0 1, is a cyclic permutation of the first line, 1 0. In the *whakatutu* case, the four lines each constitute subsequent cyclic permutations of the previous line, and in fact the same is true of the columns.

George Boole invented Boolean analysis to use logic to analyse the truth and falsity of statements. In his analysis, 1 corresponded to true and 0 to false. He broke down statements into a series of components which were connected by Boolean operators: OR, AND, NOT, and so on. Boolean analysis and Boolean operators are the theoretical basis for the logic gates used in modern computers.

The behaviour of these Boolean operators can be summarised in tabular form. For example, the compound statement "a OR b" is true if either statement "a" is true, statement "b" is true or if both are true. This is shown in Table 13.

Table 13. Boolean "a OR b" possible outcomes, where 1 = true, 0 = false.

a	b	a OR b
1	1	1
1	0	1
0	1	1
0	0	0

Table 14 shows the corresponding rules for the AND operator, which requires both statement "a" and statement "b" to be true independently before the compound statement "a AND b" is true.

Table 14. Boolean "a AND b" possible outcomes, where 1 = true, 0 = false.

a	b	a AND b
1	1	1
1	0	0
0	1	0
0	0	0

Griswold applied the operators to binary weave arrays in the following manner. First, it is noted that while the tables above correspond to Boolean operations on pairs of values, they can also be performed on whole binary arrays, such as the ones corresponding to drawdown diagrams of weave patterns. For example, here is the OR operation on the unit motif of the plain weave with itself:

```
1 0   OR   1 0   =   1 0
0 1        0 1       0 1
```

Where the operation results in itself. When the AND operation is used, the outcome is the same:

```
1 0   AND   1 0   =   1 0
0 1         0 1       0 1
```

A more interesting answer comes when considering a different Boolean operator, XOR, which is true if "a" or "b" is true, but false if both are true or both are false – that is, it is true when “a” and “b” differ. In that case:

```
1 0   XOR   1 0   =   0 0
0 1         0 1       0 0
```

All 16 Boolean operators can be considered and used to generate new unit motifs. This would show a connection between different weave patterns: they can be seen as being generated by Boolean operations of a unit motif with themselves.

But perhaps more interesting is to use Boolean operators to combine two whole weaves. For example, the first weave is a 5x5 *takitahi* weave which is combined with another 5x5 weave, shown in Table 10:

Table 10. Two 5x5 weaves which can be combined using Boolean operators.

1 0 1 0 1	1 0 0 0 1
0 1 0 1 0	0 1 0 1 0
1 0 1 0 1	0 0 1 0 0
0 1 0 1 0	0 1 1 1 0
1 0 1 0 1	1 1 1 1 1

If combined using OR:

1 0 1 0 1
0 1 0 1 0
1 0 1 0 1
0 1 1 1 0
1 1 1 1 1

If AND is used:

1 0 0 0 1
0 1 0 1 0
0 0 1 0 0
0 1 0 1 0
1 0 1 0 1

And when XOR is used:

0 0 1 0 0
0 0 0 0 0
1 0 0 0 1
0 0 1 0 0
0 1 0 1 0

This shows that the Māori weaving patterns *Takitahi* and *Whakatutu* can be described mathematically using Griswold's method of identifying the unit motif to create a binary array. Additionally, these binary arrays can then be used to identify patterns in the weaves, such as cyclic permutation, and can be manipulated using Boolean operators to create new patterns. However, the *takitahi pāraerae* weave cannot be described using this method due to the fact that it is orientated diagonally and the *whenu* and *aho* change direction by 90° every new row.

4.5. SEM

4.5.1. ACC Samples

To prepare samples for viewing under the SEM, they had to be broken into small pieces to fit into the machine. The pieces needed to have *rau* interacting with the matrix to view the bonding between them. The most ideal angle was a view in plane with the *rau*, showing the cross section of it inside the matrix. This is illustrated in Figure 32 where an ACC sample has the *rau* orientated in-plane. This would show best the bonding between the two phases, as opposed to angles perpendicular to the *rau* which could be affected by parallax. Due to the shape of some of the samples being quite flat, and the brittle nature of the cellulose producing rather unpredictable fractures, the most ideal cross section for viewing in the SEM was not achieved for all samples. Some samples were too flat in the cross-section plane to be placed in a stable manner into the SEM and were subsequently placed with the *rau* perpendicular to the microscope.

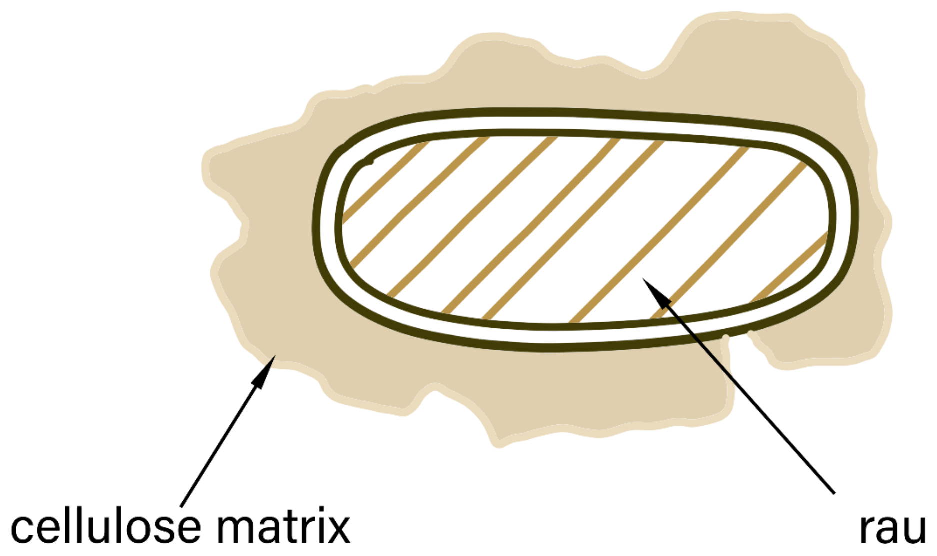

Figure 32. The most ideal view for viewing composites under SEM

Shown below is sample ACC-1 in Figure 33. The lighter region pointed out by a blue arrow is the *para* of the *rau* and the darker region indicated by a red arrow is the cellulose matrix. The bumpy deposits around the edge of the *rau* are also cellulose which has bonded to the side.

The bonding between cellulose matrix and *rau* is seen to be poor, with a gap between the cellulose and top of the leaf. However, there are areas near the edge of the *rau* where small sections of cellulose have stayed connected to it. In this case it is likely that the cellulose matrix is bonding with the cellulosic fibres that run through the cross section of the *rau*. These cellulose regions of the *rau* are only available for the matrix to bond to along the edges and tips of the *rau*, where there is no *para* blocking them. Of note is a fibre circled in green that can be seen protruding from the matrix with small deposits of cellulose bonding with it. This confirms that the cellulose matrix will bond readily with the other cellulose-based components of the harakeke plant, but not well with the *para*. The *para* prevents the matrix and cellulosic midsection of the *rau* from bonding as it is hydrophobic [103-105].

In Figure 34, a different angle of the *rau* is shown. This view shows that underneath the *rau*, there is a deposit of cellulose matrix that is attached. No bonding can be happening here between *rau* and matrix since the only *rau* exposed underneath is coated in *para*, which will not bond with cellulose. This section is remaining in place due to the bonds up around the cross section of the *rau*, where the cellulosic *muka* is bonding to the matrix. This means that matrix regions can appear to be bonded with the *para*, when in reality they are bonded with a cellulosic region but have formed around the *para* and have stayed there due to the cellulosic bond.

An example of this happening is shown in Figure 35 where a section of cellulose appears to be bonded around a *rau*. It is likely that the bonds between exposed *muka* and cellulose matrix on the sides of the *rau* were strong enough that the cellulose was able to remain in place and form around *rau*.

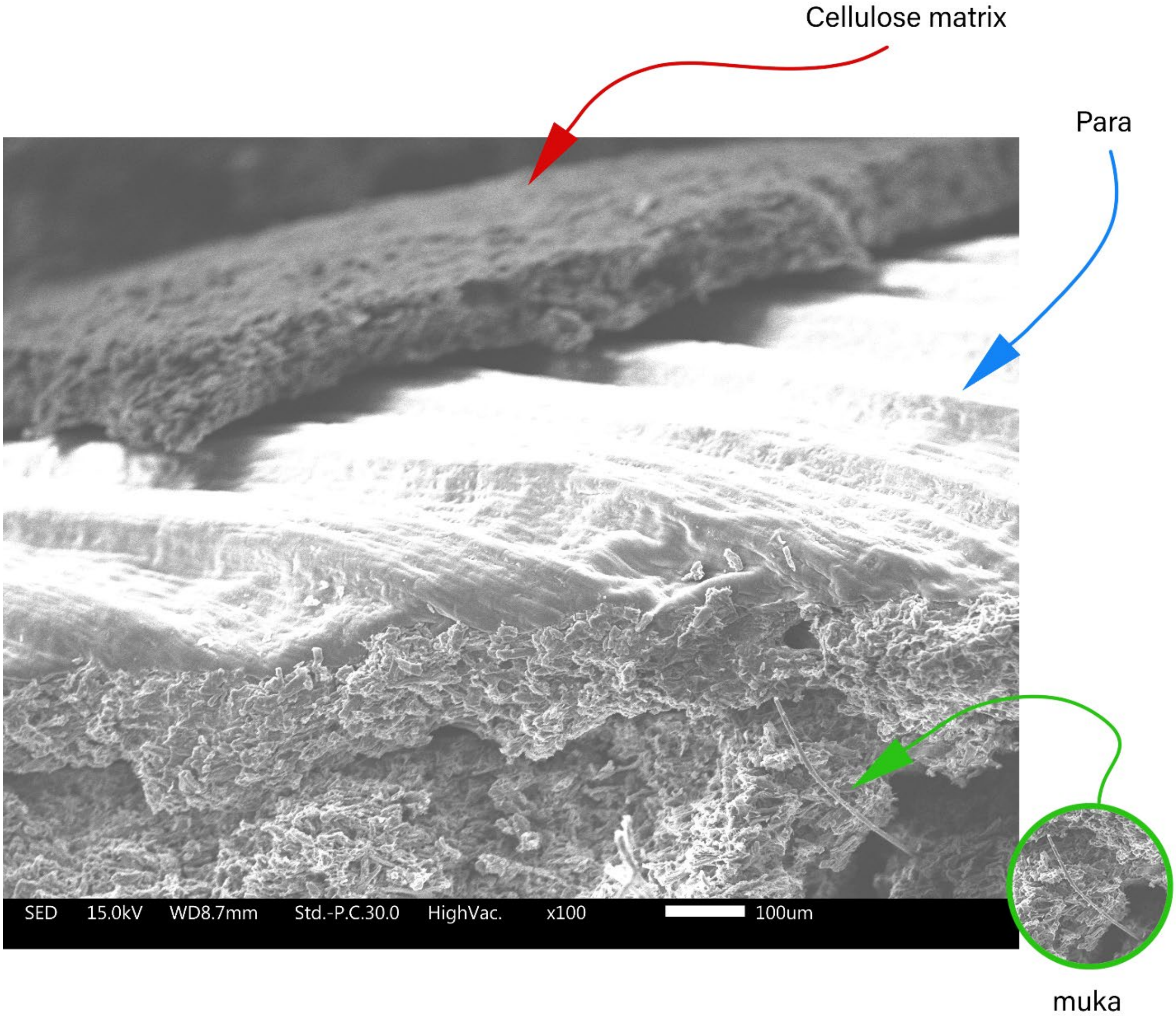

Figure 33. Cellulose-rau bonding in a short rau 30 wt.% cellulose ACC, sample ACC-1. The red arrow identifies the cellulose matrix, the blue arrow shows the para and the green arrow magnifies a fibre with cellulose bonded to it.

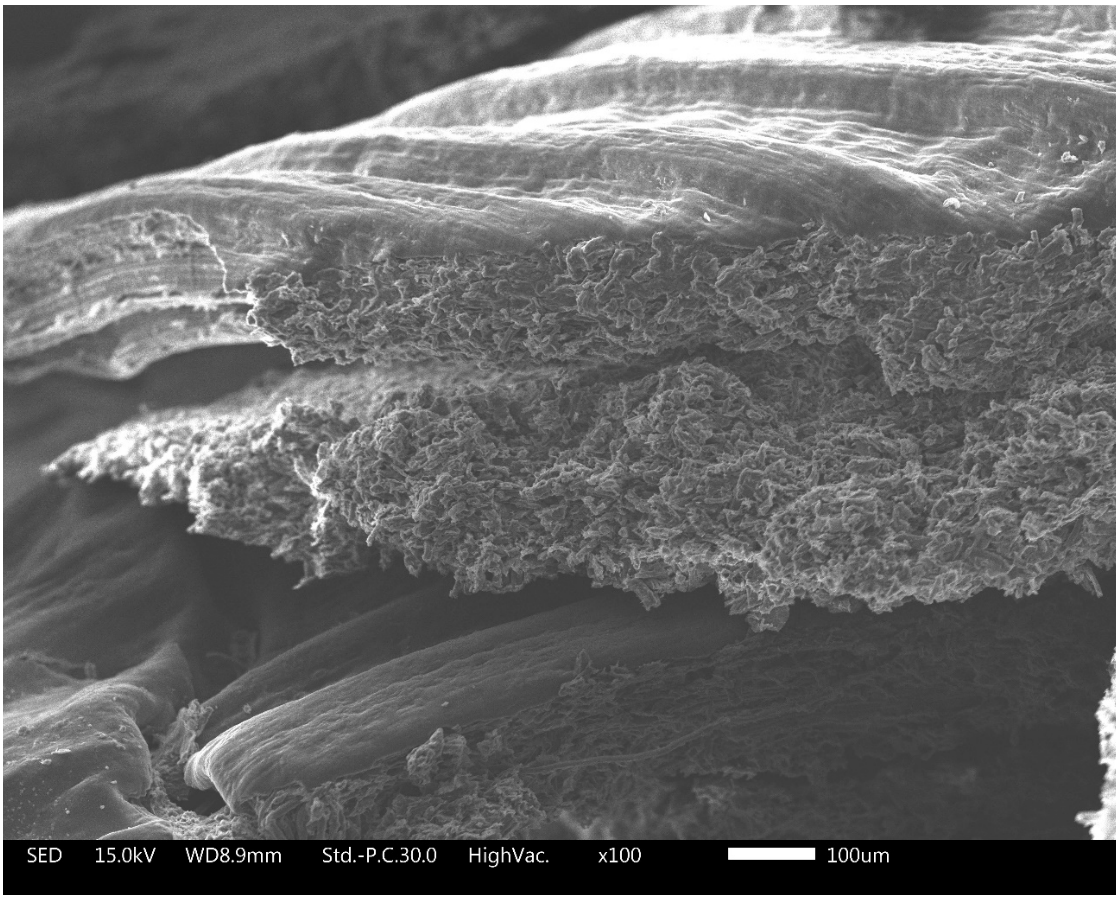

Figure 34. Cellulose matrix deposited underneath the rau.

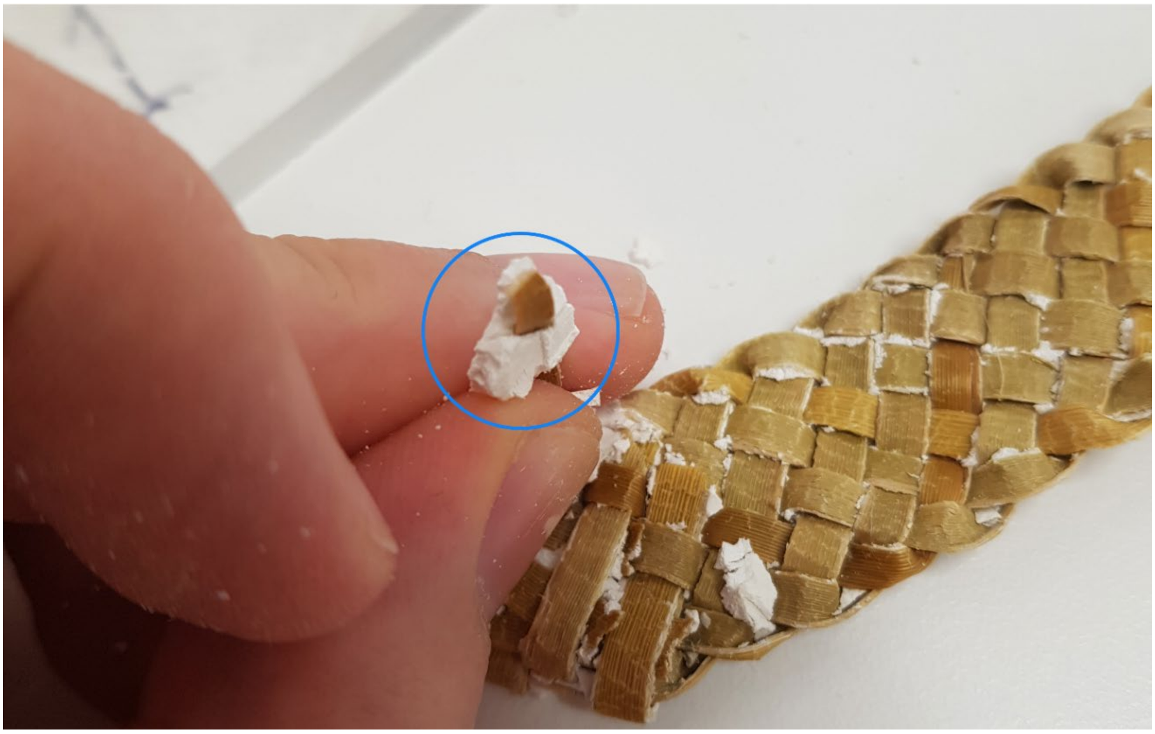

Figure 35. Cellulose matrix wraps around rau.

In sample ACC-2, the angle of the *rau* is perpendicular to the camera so the nature of the bonds is not as clear as in samples with a cross section view but the bonding can be compared with ACC-1. Figure 36 and Figure 37 show regions of *rau*-matrix interface in sample ACC-2.

In Figure 36 A there is a region of cellulose matrix on the left of the image. It looks to wrap around the *rau* and is likely bonded with cellulosic fibres of the cross section of the *rau*, as was seen in sample ACC-1. As the *rau* were cut into strips for use in these samples, there are exposed elements of the inside of the leaf with no *para* covering them on the sides of the *rau* strip. This uncovered cross section offers length-wise access for the cellulose matrix to hydrogen bond to the exposed fibres within. The wrapping effect seen of the cellulose matrix as it fits around the shape of the *rau* is being caused by mechanical interlocking of the matrix as it has formed as one solid piece of cellulose, keeping itself intact around the *rau*. On the smooth region of the *rau* on the *para*, small white pieces of material can be seen circled in blue. It is very unlikely that these are pieces of cellulose matrix, since the cellulose does not bond with the *para*. It is more plausible that these are waxes on the surface of the *rau*, the *para* is known to contain [103]. Their presence here displays the ineffectiveness of the NaOH pre-treatment against the *para* as it was not able to remove these waxes which prevent the cellulosic matrix from bonding with the *rau*.

At x1,500 magnification in Figure 36 B some small rough areas can be seen on the surface of the *rau*, circled in red. It is speculated that these areas may be where better bonding could occur between matrix and *rau*, if there is a deep enough hole in the *para*. The main bonding in these samples is likely to occur between the cellulose matrix and inner hydrophilic regions of the *rau*. Removing areas of hydrophobic *para* may provide a better surface for the matrix to adhere to the *rau* via chemical bonding by exposing cellulosic material beneath.

The *para* does not bond with the cellulose, which is seen in Figure 37 where a gap is apparent under the matrix, between it and the *rau*. The matrix, being a piece of cellulose, is being held in place by its bonds to the cellulosic regions of the flanks of the *rau*. This further demonstrates that the matrix cannot bond to the face of the *rau* due to the *para*.

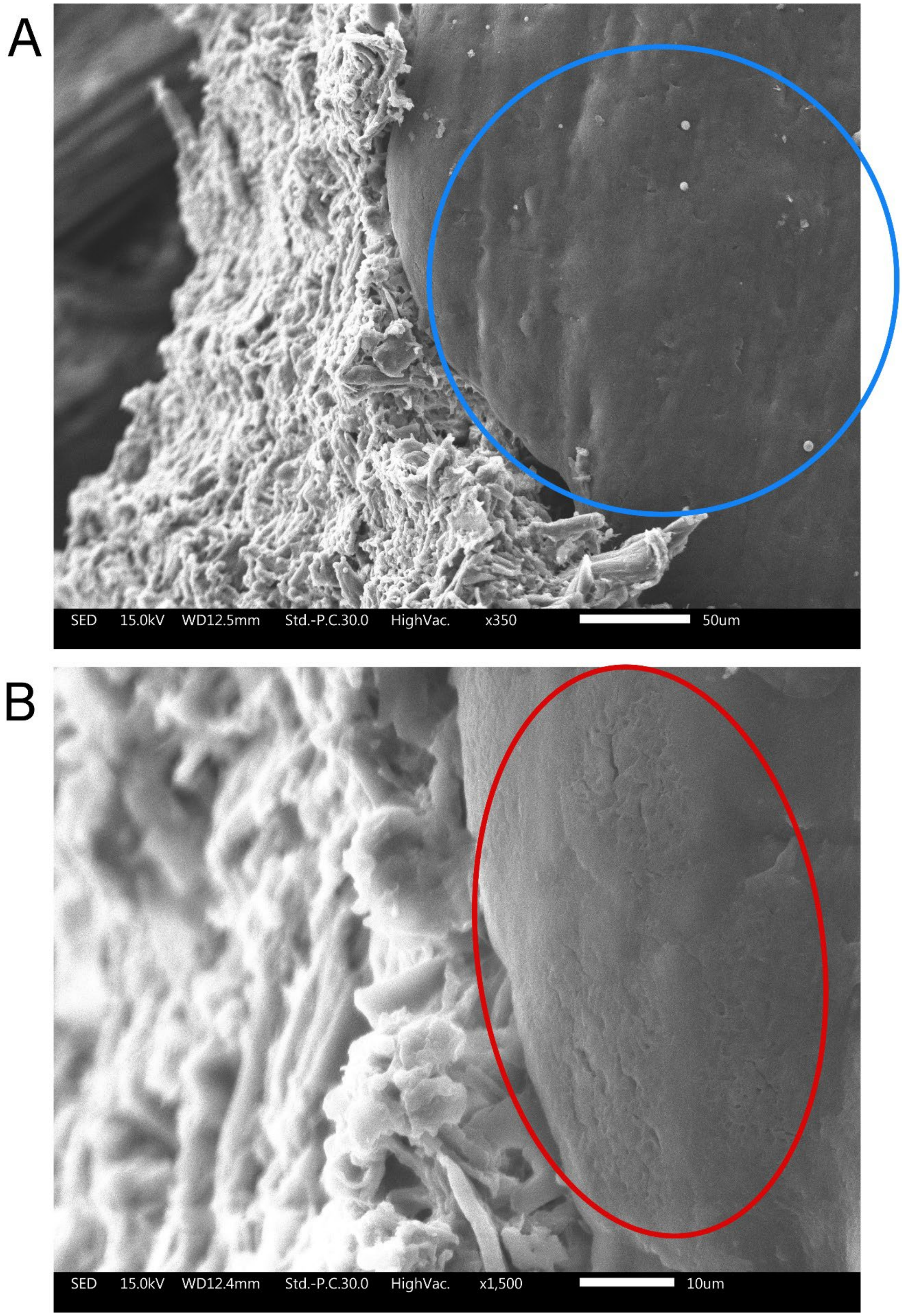

Figure 36. A: Cellulose matrix wrapping around the rau in sample ACC-2, waxes on the surface of the para circled in blue. B: Circled in red are regions of damaged para.

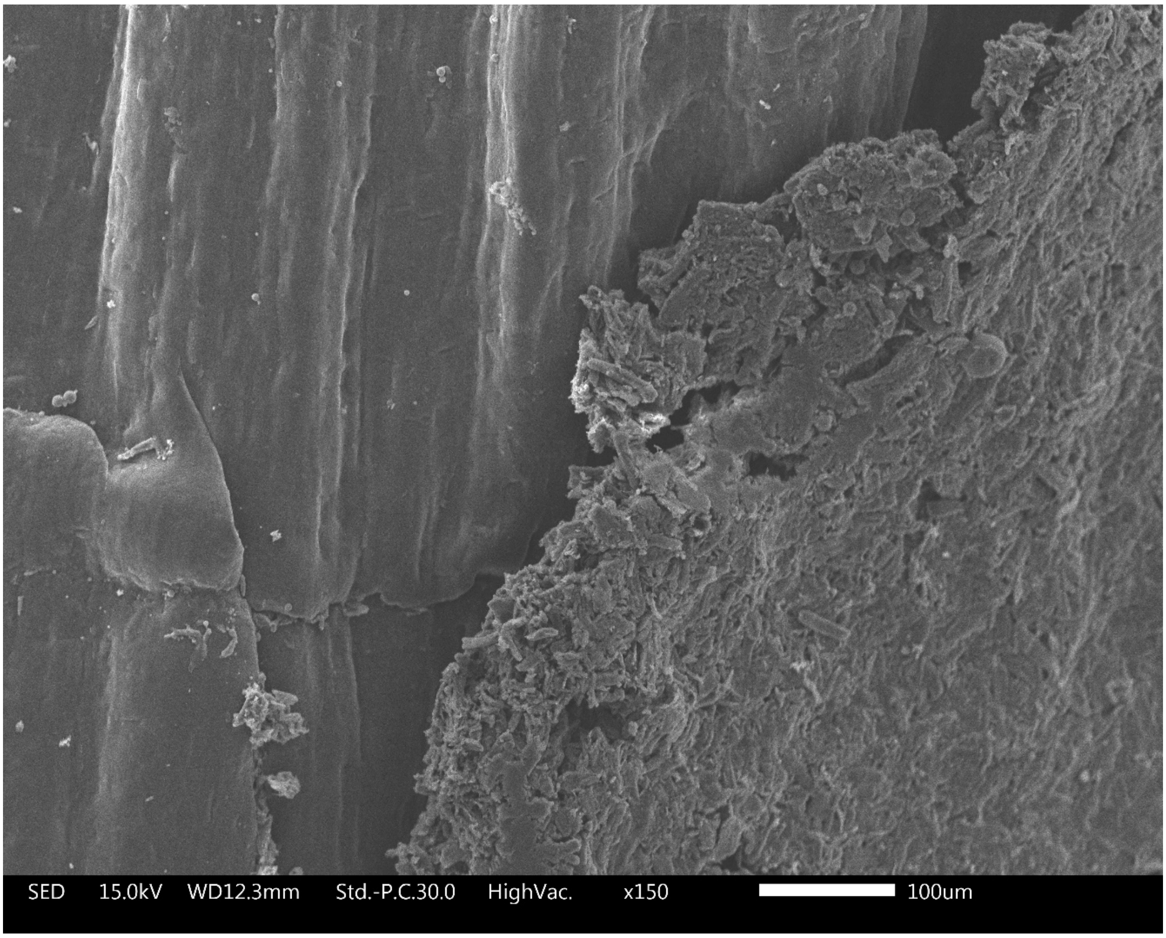

Figure 37. Cellulose matrix displaying poor bonding to the rau in sample ACC-2.

In addition to *hāpine*, *rau* were soaked in the NaOH/Urea solvent which was intended to remove outer layers of the *para* and improve bonding. Sample ACC-3 seen in Figure 38 underwent the same *hāpine* process as all other samples but was not soaked in the solvent before being processed into a composite. The SEM images show a much different surface on this sample's *para* which is textured and bumpy, whereas other samples are smooth. When handling the pre-treated samples, a small force was required to remove cellulose from the *rau*. But with the untreated samples *rau* and matrix separate far more easily requiring little force. The bonds were so weak that holding a small piece of short untreated *rau* in the ACC against gravity would separate the bond, while the pre-treated *rau* would not pull out under this same force.

Despite the change on the surface of the untreated *rau* which is bumpier than the smoother pre-treated *rau*, the differences in bonding are not likely to be caused by this physical change. The pre-treatment is not just affecting the *para* of the *rau*, but also the *muka* which, as described earlier, is the main bonding agent as it is the cellulosic region of the *rau*. Pre-treating *muka*/fibre improves its hydrogen bonding to cellulose [51] which is likely improving the bonding more significantly than any change to the surface of the *para*. If a more powerful solvent was used that could remove waxes and create holes in the *para*, then better bonding would occur between the matrix and the internal *muka* of the *rau*.

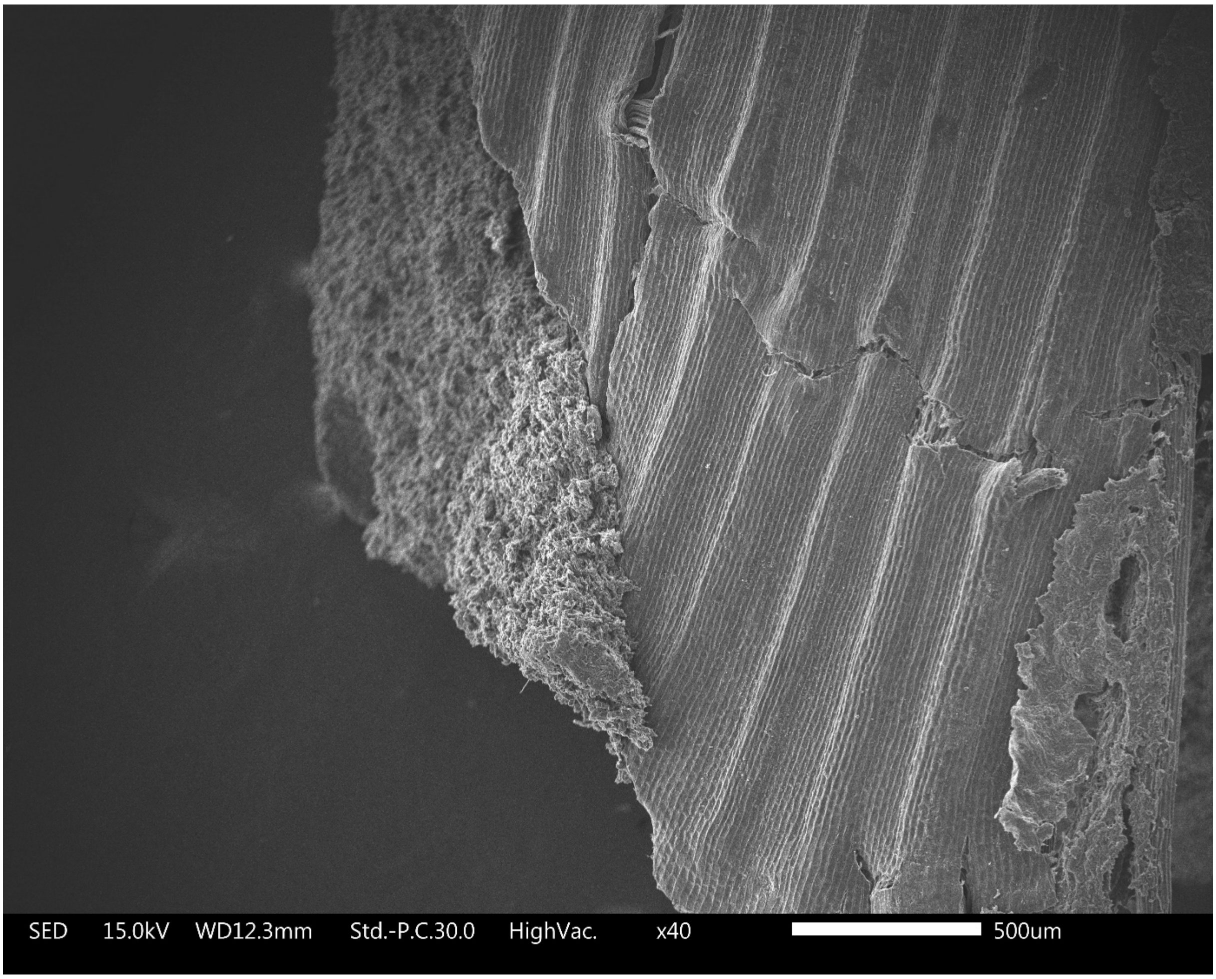

Figure 38. A textured surface on the para due to not being pre-treated in the NaOH/Urea solvent.

4.5.2. Epoxy Samples Under SEM

The Epoxy composite samples were also shown to have poor bonding. The *muka*-epoxy sample shown below in Figure 39 A had better bonding than the two *rau*-epoxy samples evidenced by the smaller gaps between fibre and matrix, referenced by a blue arrow in the figure. The gaps seen between the *rau* and epoxy are shown in Figure 40. The largest gap in the *muka* sample is 3 µm wide compared to the *rau* sample which has a gap of 6 µm. However, there were areas where there was no gap visible between *muka* and epoxy whereas gaps were consistently seen around the *rau* samples.

The bonding between *muka* and epoxy was not excellent as there were sections of fibre pull-out, shown in Figure 39 B. Fibre pull-out suggests that despite only having small gaps, there was no strong bonding between *muka* and epoxy since the fibres were still removed from the matrix under breaking [113]. Strong bonding in natural fibre reinforced plastics can occur when the matrix material enters inside the fibre and forms a strong adhesion via mechanical interlocking [114]. Poor interlocking occurred between *muka* and epoxy as evidenced by fibre pull-out.

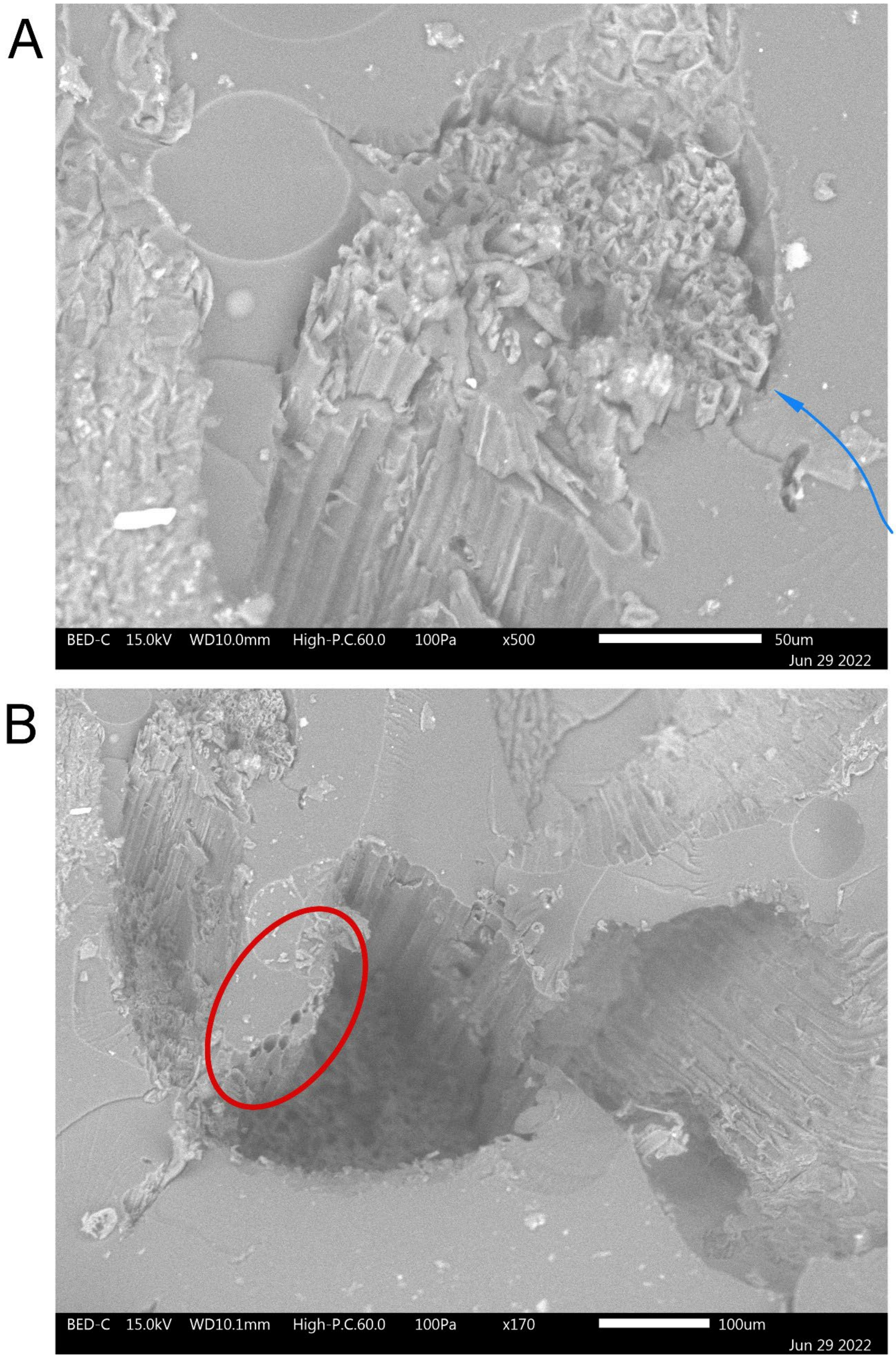

Figure 39. A: Small gaps between muka and epoxy. B: Fibre pull-out in the matrix, circled in red.

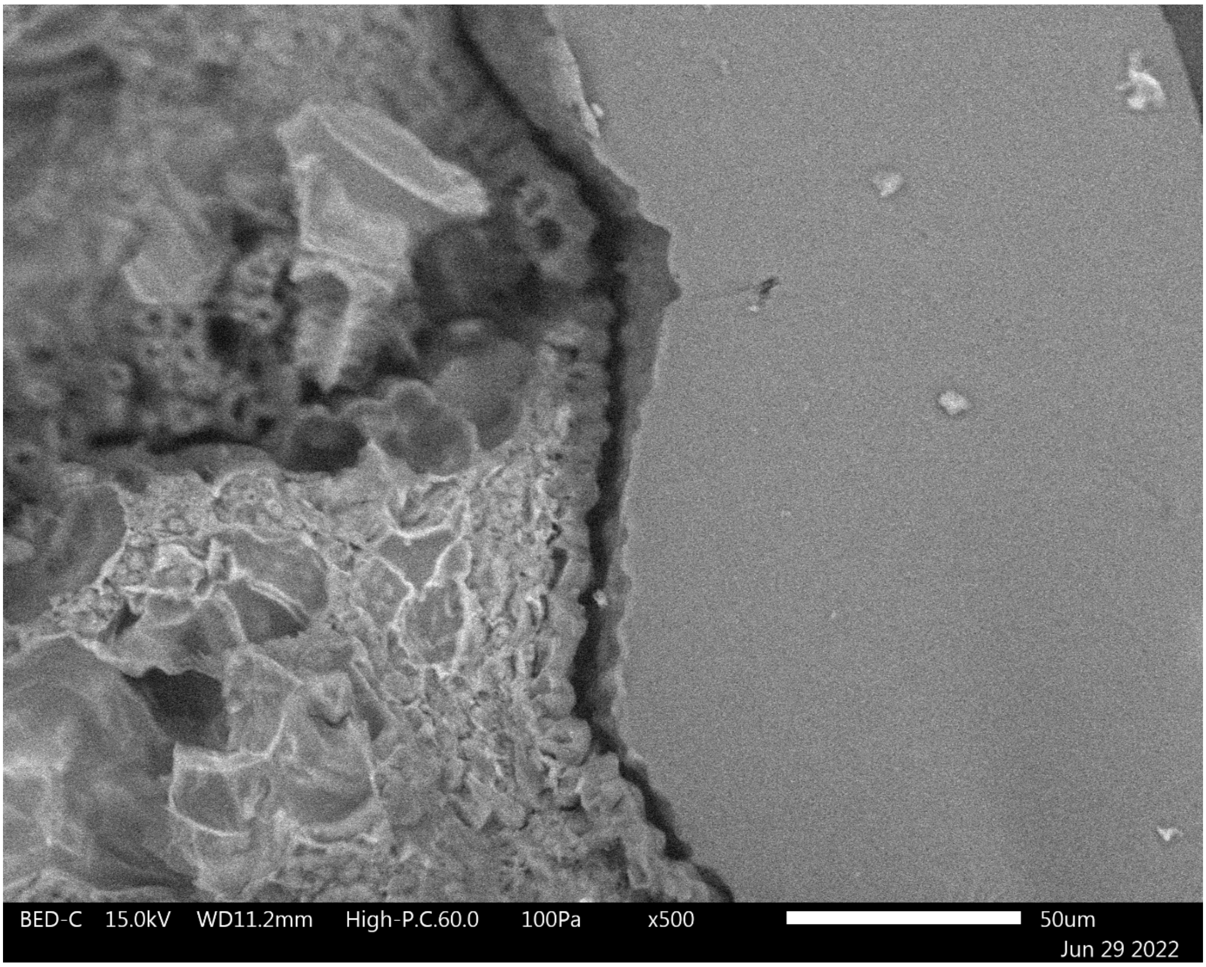

Figure 40. TW-x500-6 Epoxy and rau at x500 magnification showing a larger gap than seen in the muka-epoxy interface.

The gaps between *rau* and epoxy matrix are smaller than those seen between *rau* and cellulose matrix, however this doesn’t necessarily mean that the bonding is better between *rau* and epoxy but could be caused by the lower viscosity of the epoxy resin. As the epoxy flowed better than the cellulose paste, it may have been able to collect more closely to the surface of the *rau* despite its poor bonding. Liquid matrix forming is known to be more effective when a lower viscosity material is used [115].

At the same magnification of x500, similarly sized gaps between epoxy and *rau* are seen in the PDW open cast sample in Figure 41 and the vacuum formed sample in Figure 40 suggesting that there is no significant difference in bonding achieved by using a vacuum bag forming method or an open cast. The similarly poor bonding in open cast moulded composites compared to vacuum formed ones was anticipated since the bonding mechanisms were unchanged. The open cast method was employed to ensure a deposit of epoxy around the *rau*, which was not guaranteed when using vacuum forming. Vacuum forming had the issue of evacuating most of the epoxy while open cast moulding meant that the epoxy could not escape and would have to cure around the *rau*, creating a matrix. A consistent method was needed to ensure a matrix was formed for testing.

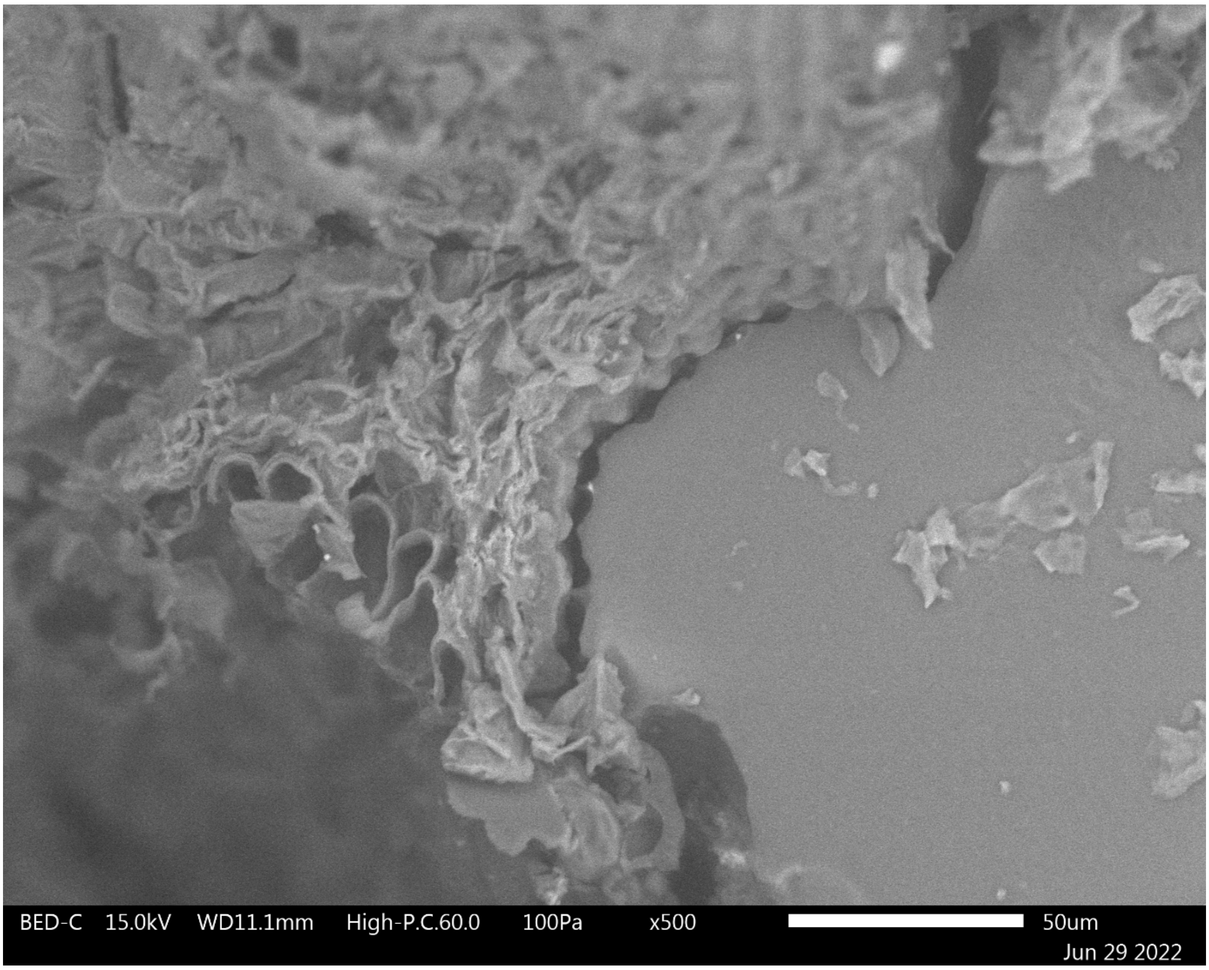

Figure 41. PDW-E sample showing gaps between matrix and rau.

4.6. Perception Study Results

56 participants contributed anonymously to the survey giving their opinions on the appearance of a selection of woven samples. 36 (64%) of the participants claimed that they perceive a material as having higher financial value if it has cultural significance. 20 participants (35%) said that they would not be willing to spend more money on culturally significant materials. This poses interesting possibilities for product design using woven composites in that higher financial value will be attributed to those that are made in a way that respects and highlights the cultural heritage of the material. Specifically for harakeke

composites, there is financial value to be added by following *tikanga* outlined by Māori weavers and making weaves by hand.

When ranking factors in a composite material, the most important factor was found to be sustainability with 25 participants (44%) placing it as most important, shown in Figure 42. Strength was found to be the second most important factor with 16 participants (28%) placing this as the highest consideration for a composite material. Only 8 participants valued cultural importance of a composite as the highest factor, and only 7 claimed aesthetic pleasantness as most important. This data shows that consumers are thinking about the environment and wanting to choose the best option in terms of sustainability and is in agreement with the literature stating that 47% of consumers desire sustainable products [74]. 47 respondents (84%) were below the age of 30 which may also have influenced the data in the favour of sustainability, considering younger people are more likely to purchase sustainably [116, 117]. This is a positive finding when considering use of natural fibres to create composites. Specifically for this project, the data would suggest that ACCs are the most desirable composite to manufacture from harakeke, although considering the second most important factor is strength, better processing techniques would be required in order to create stronger harakeke ACCs. According to these findings, marketing of the harakeke composites would not be able to rely on the cultural heritage of harakeke nor the fact that they were made using traditional Māori techniques and *tikanga*. The aesthetic nature of the woven composites would also be negligible in the marketing of such materials when compared to the importance of sustainability and strength.

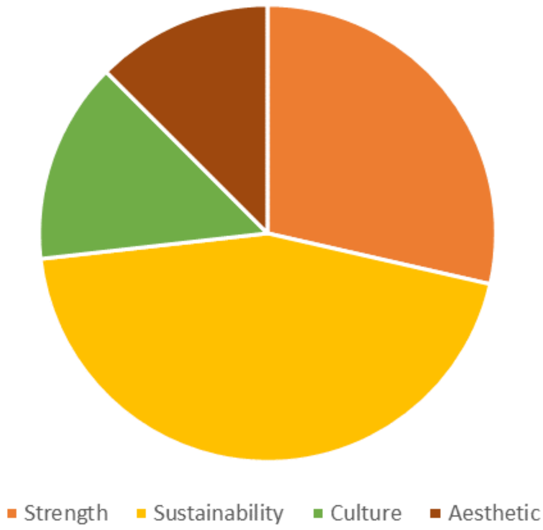

Figure 42. Attributes of a composite that participants valued the most highly.

Participants were shown images of a *rau*-epoxy composite, a *rau*-ACC composite and a glass fibre-epoxy composite and asked to rate them on a Likert scale against three categories: aesthetic pleasantness, cultural importance and sustainability. The *rau*-epoxy weave was the most highly rated for all three categories with 28 votes either agreeing or strongly agreeing it was aesthetically pleasant, 29 votes either agreeing or strongly agreeing it was culturally significant and 31 votes agreeing or strongly agreeing that it was sustainable. The explanation why the *rau*-epoxy sample was perceived as the most aesthetically pleasing was hypothesised by Morehu Flutey-Henare where samples were shown to her during a Zoom interview conducted on March 29, 2022. She stated that the epoxy matrix was her favourite since she could see the weave encased in it and it was the most pleasing visually. This is an interesting outcome as epoxy thermosets are not a sustainable material. However, the participants seemed to focus on the visible *rau* encased in the epoxy which influenced their perception that it was a sustainable material. This provides incentive for more eco-friendly transparent resin materials to be investigated as the visibility of the *rau* is important in perception of sustainability.

The ACC sample was perceived to be the second most sustainable composite with 27 votes either agreeing or strongly agreeing it looked sustainable. However, 25 participants felt neutral about its cultural significance and 19 either disagreed or strongly disagreed that it looked culturally significant. This is likely caused by the opaqueness of the cellulose matrix.

Because it is a white material, the weave inside the matrix cannot be seen and therefore consumers cannot tell it is a Māori weave. 27 participants agreed or strongly agreed that it appeared sustainable but 18 were neutral on this point. The fact that participants were not strongly convinced of the ACCs sustainability is likely due to the fact that the weave is not easily seen behind the cellulose matrix. Since the matrix was the only visible component to participants their perception of the ACCs sustainability was formed. Only 6 participants liked the aesthetic of the ACC. Aesthetics were found to not be an important factor in participants desires of a composite material, however it is likely that the ACC's appearance inhibits people's perception of how sustainable it is.

18 participants agreed that they found the glass fibre composite aesthetically pleasing with 17 being neutral and 21 disagreeing. Only 4 participants thought that the fibre glass composite was culturally significant with 37 disagreeing or strongly disagreeing. No participants strongly agreed that the glass fibre composite was sustainable but 15 did agree, with 18 being neutral and 23 disagreeing or strongly disagreeing. This agrees with findings that consumers have difficulty distinguishing bio-composites from synthetic composites [76] as participants did not strongly identify that glass fibre is unsustainable. The fibre glass composite was more aesthetically pleasing than the ACC however the ACC was perceived more sustainable. As sustainability was ranked more important than aesthetics in composites, this proves promising for the value perception of ACCs compared with fibre glass ones.

5. Conclusion

Three different weaves traditionally used by Māori were made, *whakatutu* (twill 2x2), *takitahi* (plain) and *takitahi pāraerae* (plain diagonal). These weaves were tensile tested to understand their behaviour and mechanical properties. These same weaves were then applied to composites using two matrix materials, cellulose and epoxy. Different processing methods were investigated to achieve good bonding in the composites including pre-treatment of *rau* and different moulding techniques. Ultimately, poor bonding was achieved between the harakeke *rau* and both matrix materials likely due to the waxy nature of the *para*. Glass fibre composites were made using industrial weaves to match the Māori weaves and provide insight into how composites with good matrix-fibre bonding would behave. The glass fibre composites behaved similarly to the woven harakeke textiles which was shown in stress/strain graphs.

Weaves made by a novice weaver and an experienced weaver were also tested alongside each other in all three forms – textile, ACC and epoxy composite. Surprisingly the looser and less consistent weaves of the novice weaver performed slightly better in terms of strength and strain, likely due to diminished crimp caused by lower interlacement and a loose weave.

SEM imaging was utilised to investigate the nature of the bonds in the composites. Confirmation that poor bonding had occurred was found in large gaps between *rau* and matrix in all samples. Good bonding was only displayed in small areas in the ACCs where cellulosic cross sections were exposed in the *rau* that allowed cellulose matrix to bond with it. The epoxy matrix was seen to fit the contours of the *rau* more closely than the cellulose but poor bonding was achieved, evidenced by fibre pull-out in the *muka* sample.

Mathematical patterns in Māori weaves were found to translate from drawdown diagrams to binary code in a similar fashion to how industrial weaving patterns are converted to binary arrays. Boolean operators were found to work with these patterns too which allowed for new patterns to be created by combing existing ones. However, diagonal weaves with 90° interlacement at the edges of the structure provide a complication to Griswold's method and cannot be described using a binary array.

Finally, a perception study was carried out to understand how people viewed hand woven harakeke composites. It was found that the participants of the study valued cultural significance and heritage in a material and were willing to pay more for this. However, in terms of ranking the most attractive factors in a composite material, sustainability was found to be most important, followed by strength. Interestingly, the harakeke composite with epoxy as the matrix was perceived to be more sustainable, more aesthetically pleasing and more culturally significant than the ACC and glass fibre samples.

5.1. Future works

Basic weaves were used for this project as the researcher was a novice weaver. However, more complex weaves used by Māori could prove interesting to research in the application of composites as more complicated weaves might show different performance than simple weaves due to their more varied crimp ratios and amounts of float in the weave structure.

The mathematical patterns established in the Māori weave patterns have potential to be explored in more detail. The *takitahi pāraerae* (plain diagonal) weave could not be described easily using the standard method since the warp and weft are constantly changing. A method of describing this might also unlock the ability to describe other patterns that see warp and weft shift in their structure.

If modelling and FEA are to be performed on harakeke woven composites, more data for the mechanical properties of *rau* would be needed to give accurate values. Alternatively, harakeke *muka* could be used to make these composites but this would require skilled weavers.

There is room in future study to investigate the awareness of Māori weavers of the codes and mathematical relationship found in their weaving patterns; particularly the ability to create new weaves by combining existing weaves using the Boolean code. Whether conscious or unconsciously, it would be interesting to see if Māori weavers do this with their weaves or if creation of weaves uses some other mechanism.

More market research could be carried out to build upon the short anonymous survey performed in this research project. Of interest would be how consumers behave when given the choice to purchase Māori woven composite materials at different prices to see if the perceived increase in financial value actually takes effect in their purchasing habits.

Future work into bio-based or eco-friendly thermoset resins would be fitting for the application of open cast moulding harakeke composites, which seemed to benefit from the transparency of the matrix material allowing consumers to see the *rau* weave.

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B. Appendix

Appendix 1: WiseTex and TexComp data.

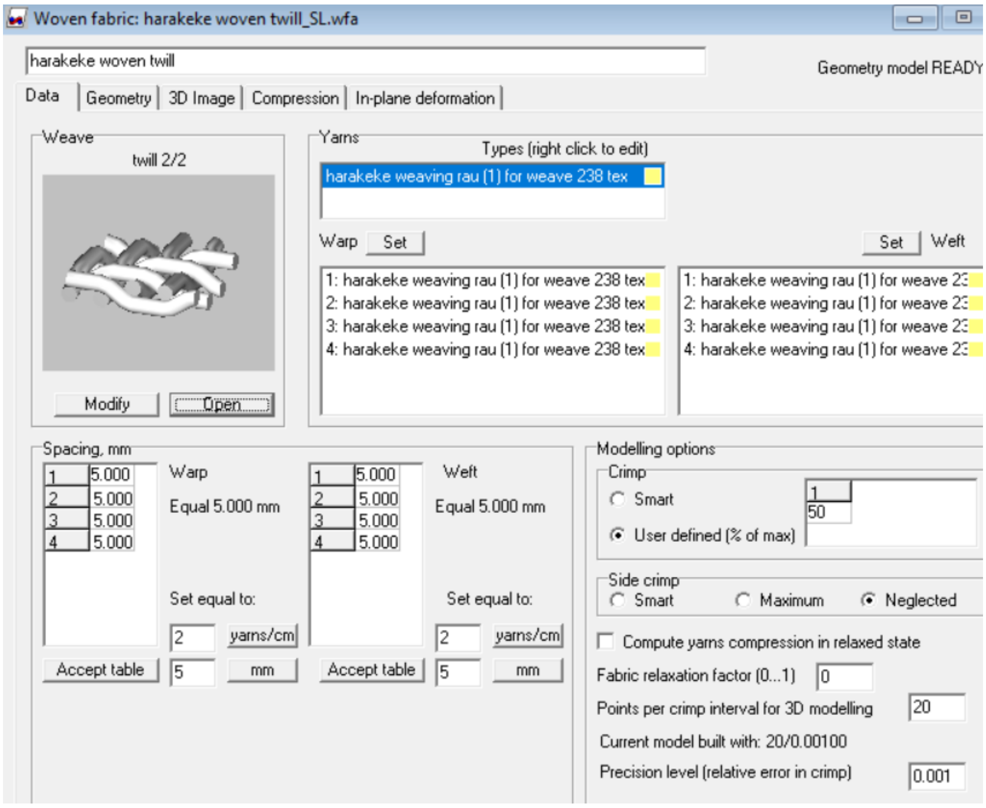


Figure A 1. A screenshot of the WiseTex software setting up a weave.

Appendix 2: Survey Questions.

Harakeke Composite Perception Study

Start of Block: Block 6

Introduction

Kia ora,

You are invited to participate in a research study on the perceived value and interest in Māori weaving patterns. This study is being conducted by Caleb Philps from the University of Canterbury | Te Whare Wānanga o Waitaha. Other research team members include Tim Huber and Nick Emerson. The study is being carried out as a requirement for a Master's Degree in Product Design.

What is the purpose of this research?
You are invited to take part in a survey where you will give your opinion on different materials. You will be asked about how they look, your judgements on how sustainable they appear to be, and how they compare in financial value to one another. I am interested in finding out how people perceive composite materials that are made with Māori weaving patterns. The information from this study will be used to advise where this material could be used commercially.

Why have you received this invitation?
You are invited to participate in this research because you have shown interest in being a participant.

Your participation is voluntary (your choice). If you decide not to participate, there are no consequences.

What is involved in participating?
If you choose to take part in this research, please complete the online survey that follows this information page. The survey involves answering questions about how you feel about a selection of materials. Completing the survey should take around 5 minutes.

Are there any potential benefits from taking part in this research?
We do not expect any direct benefits to you personally from completing this survey. However, the information gathered will potentially benefit research into a new type of material.

Are there any potential risks involved in this research?
We are not aware of any risks to participants in the research

What if you change your mind during or after the study?
You are free to withdraw at any time. To do this, simply close your browser window or the application (App) the survey is presented on. Any information you have entered up to that point will be deleted from the data set. As this is an anonymous survey it will not be possible to withdraw your information after you have completed the survey.

What will happen to the information you provide?
All data will be anonymous. All data will be stored on the University of Canterbury's computer network in password-protected files and will likely be used in published work. All data will be destroyed after publication of study findings. I will be responsible for making sure that only members of the research team use your data for the purposes mentioned in this information sheet.

Will the results of the study be published?
The results of this research will be published in a Master's thesis. This thesis will be available to the general public through the UC library. Results may be published in peer-reviewed, academic journals. Results may also be presented during conferences or seminars to wider professional and academic communities. You will not be identifiable in any publication.

I will send a summary of the research to you at the end of the study, if you request this. If you provide an email address for this purpose, it will not be linked with your survey responses.

Who can I contact if I have any questions or concerns?
If you have any questions about the research, please contact: Caleb Philps: cap89@uclive.ac.nz, Nick Emerson: nick.emerson@canterbury.ac.nz or Tim Huber tim.huber@list.lu (Note: questions should go to the student and concerns to the supervisor for student projects).

This study has been reviewed and approved by the University of Canterbury Human Research Ethics Committee (HREC). If you have concerns or complaints about this research, please contact the Chair of the HREC at human-ethics@canterbury.ac.nz .

What happens next?
If you would like a PDF version of this information sheet, please email Caleb Philps at the email address above.

Please read the following statement of consent and start the survey below:
I have read the study information and understand what is involved in participating. By completing the survey and submitting my responses, I consent to participate.

○ I consent and wish to take part (3)

End of Block: Block 6

Start of Block: Demographics

Age What is your age?

____

Sex/Gender

○ Female (1)

○ Male (2)

○ Please Specify (3) ____

○ Prefer not to say (4)

End of Block: Demographics

Start of Block: Block 1

Q1 Composites are a class of materials made up from multiple parts. Most often composites are made of a fibre which is coated in plastic, to protect the fibre and make it stronger. Some composites you may have heard of are fibreglass or carbon fibre. Composites are often used in high performance applications where both strength and lightweight properties are needed - often these are sporting applications or automotive uses.

This project is looking at using NZ Flax/Harakeke in the application of composites. These Harakeke composites are also made using traditional Māori weaving patterns.

Please rank these factors by dragging them to show how important you see them being in a composite material from most important (top) to least important (bottom):

______ Aesthetics (1)

______ Cultural significance (2)

______ Sustainability (3)

______ Strength (4)

End of Block: Block 1

Start of Block: Block 2

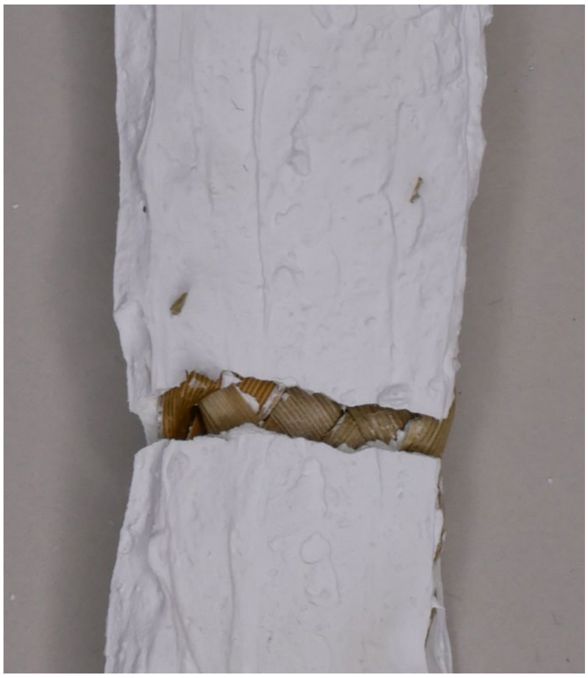
Q2 In this section, you will rank composite materials by: how aesthetically pleasing they are to you, how culturally significant you think they might be, and how sustainable they look.

Q2 Harakeke & Epoxy composite

Q2. a Please rate the above composite by these factors based on how it looks:

	1 (Strongly disagree) (1)	2 (Disagree) (2)	3 (Neutral) (3)	4 (Agree) (4)	5 (Strongly agree) (5)
Aesthetically pleasing (1)	○	○	○	○	○
Culturally significant (2)	○	○	○	○	○
Sustainability (3)	○	○	○	○	○

Q2 Harakeke & Cellulose composite



Q2. b Please rate the above composite by these factors based on how it looks:

	1 (Strongly disagree) (1)	2 (Disagree) (2)	3 (Neutral) (3)	4 (Agree) (4)	5 (Strongly agree) (5)
Aesthetically pleasing (1)	○	○	○	○	○
Culturally significant (2)	○	○	○	○	○
Sustainability (3)	○	○	○	○	○

Q2 Glass Fibre composite

Q2. c Please rate the above composite by these factors based on how it looks:

	1 (Strongly disagree) (1)	2 (Disagree) (2)	3 (Neutral) (3)	4 (Agree) (4)	5 (Strongly agree) (5)
Aesthetically pleasing (1)	○	○	○	○	○
Culturally significant (2)	○	○	○	○	○
Sustainability (3)	○	○	○	○	○

End of Block: Block 2

Start of Block: Block 3

Q3 Certain designs and ways of making things have been developed by cultures over time and have become significant to the peoples and cultures that have used them. some examples include traditional clothing with strong identity, like Japanese kimono, or handmade pounamu items made by Māori carvers.

Does the history of a material or method of crafting (e.g hand weaving) have any influence on how much you might pay for products made from such materials?

- ○ I would be willing to pay more for a material due to its history and cultural context (1)
- ○ I would not be willing to pay more for a material just because of its history and context (4)

End of Block: Block 3

Start of Block: Block 6

Q4 Would you like to be updated with a summary of the results of the survey?

- ○ Yes (1)
- ○ No (2)

End of Block: Block 6

Appendix 3:

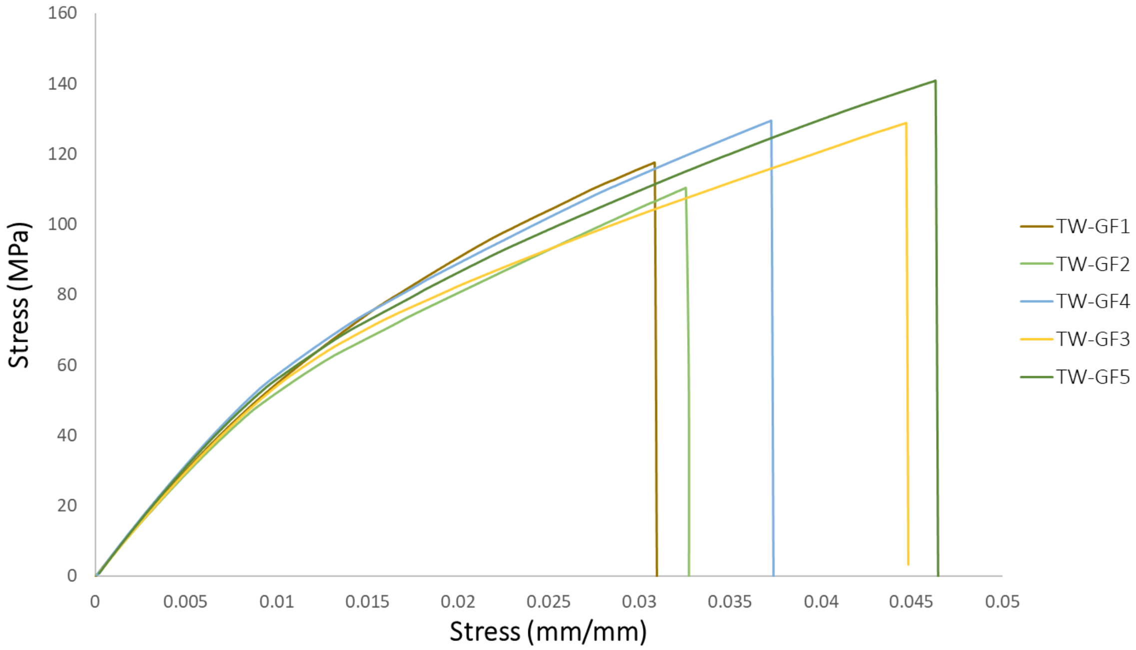


Figure A 2. Stress/strain curves of twill weave glass fibre composites.

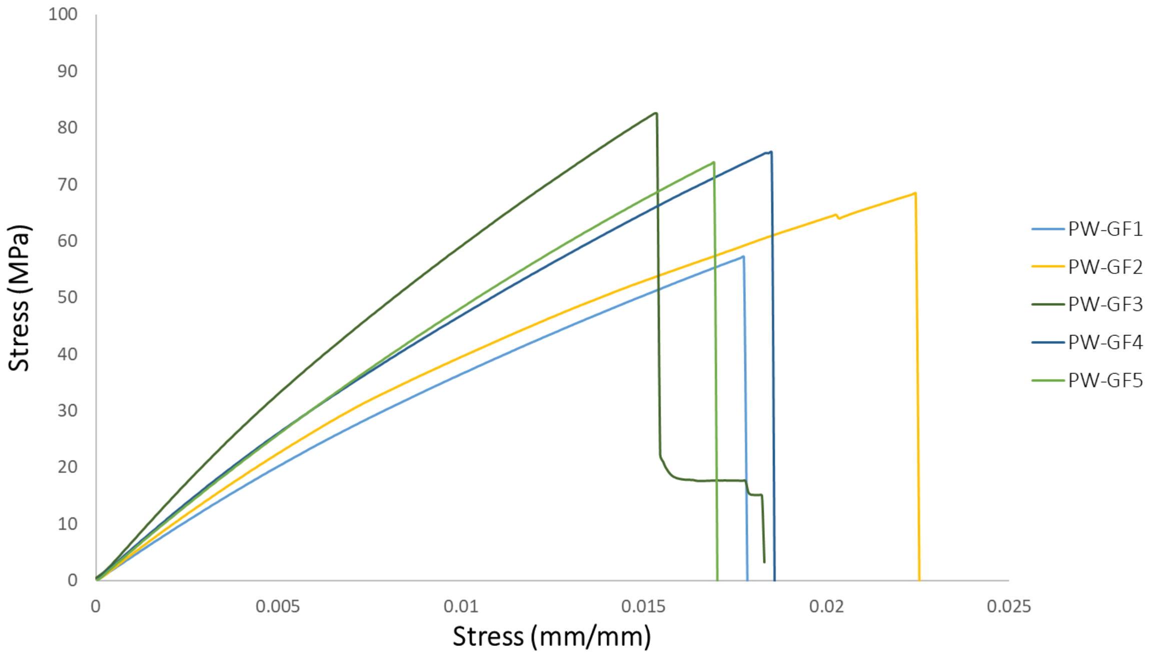


Figure A 3. Stress/strain curves of plain weave glass fibre composites.

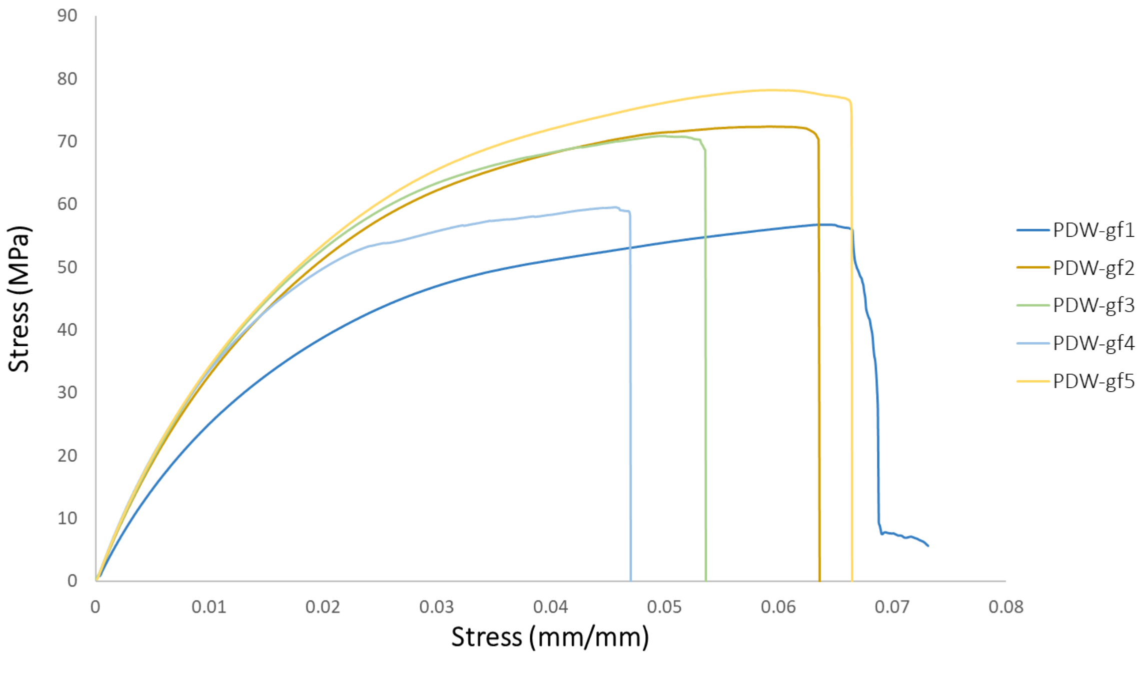


Figure A 4. Stress/strain curves of plain diagonal weave glass fibre composites.