

THE REALLY CLEVER BIOMATERIAL

TECHNICAL GUIDE

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INTRODUCTION

Purpose

Really Clever has invented, developed, and scaled up a novel biomaterial. This material is unique in meeting valid criteria for sustainability, performance, and cost efficiency. The technology behind the composition and production process for the material is patent protected. As a bio-based, natural biopolymer nanocomposite, the material balances environmental impact and high-level properties, without compromising on either. The structural framework of the material is set by naturally occurring polymers – long-chain molecules with repeating units found in plants, fungi, algae, and other natural sources – while the composition also incorporates smaller molecules and nanoparticles within its structure. With viscoelastic properties – being able to stretch as well as maintain firmness – this design has enabled continuous refinement of the formulation and enhancement of the material’s properties to meet customers' specific requirements, by leveraging the vast array of sustainable resources provided grown by nature. Importantly, the material has been developed without reliance on animal products, non-renewable plastics, petrochemicals, or their derivatives. The primary purpose of the material is thus to replace harmful materials – plastic and leather – with a viable alternative. Scalability and price point being key, the mission of Really Clever is to enable truly sustainable products, accessible to all.

Composition

In structural terms, the material assembles and completes the formation of a novel network through the production process. The final composition of the material is a biopolymer network, containing two core features: (i) a rigid carbohydrate-based

scaffold and (ii) a flexible biomatrix, with a molecular ratio of approximately 1:20 respectively (figure 1). Alongside the polymer network core, small molecules are integrated in a stable manner during the formation process. The complex behaviours of both the scaffold and peripheral parts of the whole material allow its highly adaptable uses and stability. By having this “recipe with ingredients” -like formulation, the material lends itself to diverse modifications and continual development to new specifications.

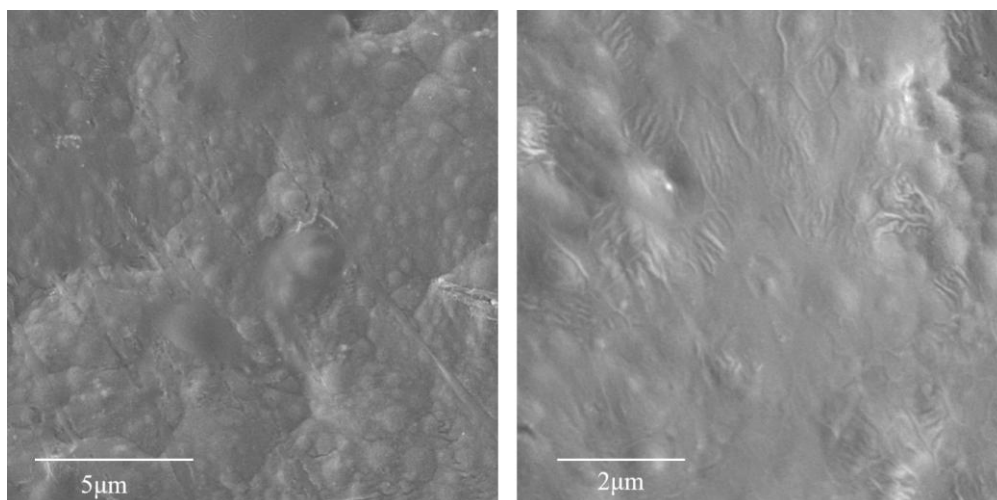
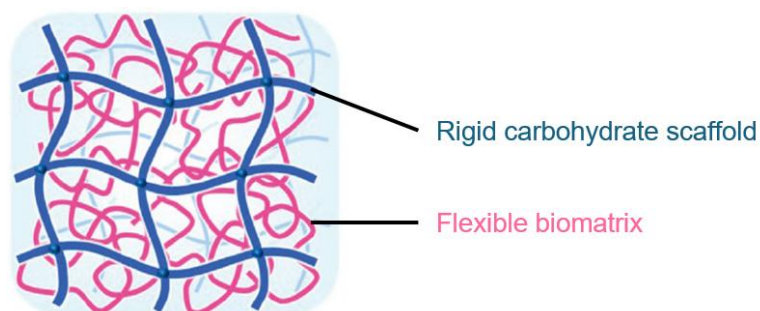


Figure 1: Material Structure. Schematic of the core biopolymer network structure present in the material (above); scanning electron microscopy images of the material surface (below).

The inputs going into the production process in which the material is formed are primarily taken from fungal and plant resources. The inputs used by percentage are displayed in figure 2.

A major component is fungal stalk waste slurry, which is harvested from the waste portion of lower stalks produced by mushroom growers. These peat-embedded stalks undergo a scientific but scaled proprietary extraction process developed by Really Clever in which the slurry is formed (59%). The plant extracts used to create the material (40%) include sources of natural polymers as well as smaller molecules which act as stabilising agents in the production process as well as affecting a multitude of specific material properties. The biobased and natural minerals used in the process provide further interactions with chemicals in the slurry and plant extracts required to complete the formation process.

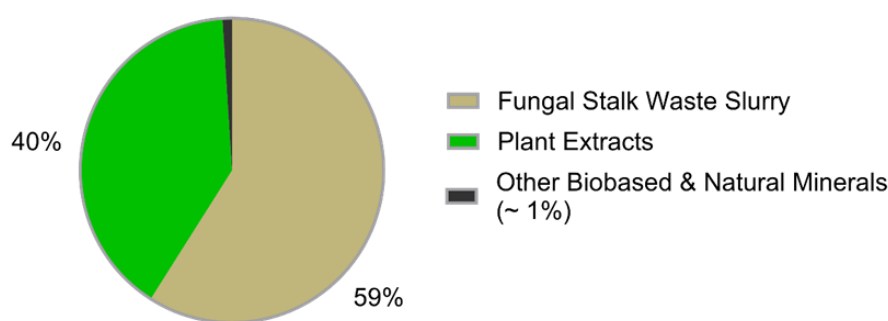


Figure 2: Inputs used by percentage to create the Really Clever biomaterial.

The material is certified with V-label, having no animal products involved anywhere in its production as confirmed by Really Clever as well as suppliers. Additionally, the material has USDA certification as 100% biobased in itself and 99% biobased overall after the application of coating. This states, according to a third-party laboratory carbon source test procedure, the level of carbon in the material from biological sources as opposed to that from petrochemicals.

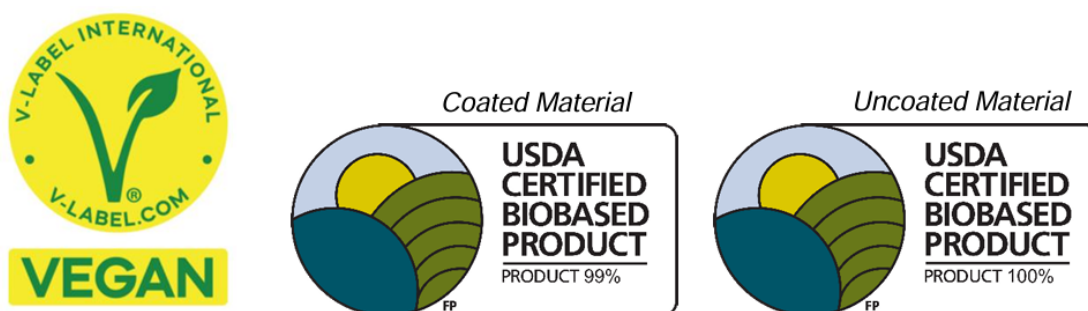


Figure 3: V-label vegan and USDA biobased certifications.

Production Process

The compositional feed inputs to the material are subjected to a range of temperature and mixing conditions in the formation of the material under the scale process. Having been developed first under laboratory conditions and a manual experimentation process, the successful transfer of the process to full scale production has been predicated on the overall simplicity of the steps. Broadly the material is processed as a liquid mixture and then cured into solid sheets, which are then finished with a coating provided by an external partner.

At scale, the feed inputs are first mixed in a bioreactor under conditions which are controlled to ensure homogeneity of the mixture and begin the chemical processes. The temperature steps and mixing programmes allow full integration of the diverse array of natural chemicals in the material's liquid form into what will ultimately form the structure of the dried material. The liquid is then transferred into a tray using a robot dispensing head that can be controlled in its movement and flow rate. These parameters are controlled to ensure consistent material deposition on the tray and to give the required material thickness, which is proportional to volume of the liquid. The material is then transferred into an oven for curing where the temperature, air flow rate and humidity are controlled to enable water removal and finalise the formation of the polymer network and composite material structure. Finally, once this step is complete, sheets of material are peeled from the trays.

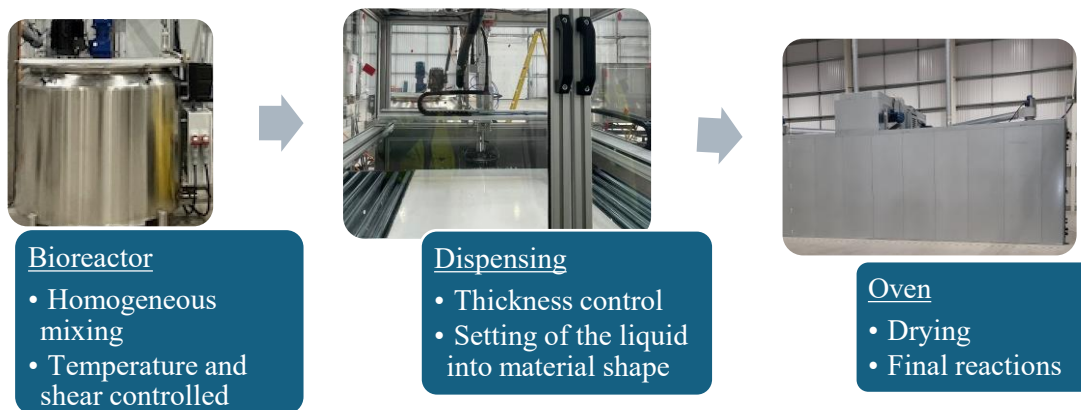


Figure 4: The Scale Production Process

A continuing area of research focusses around improvements in efficiencies of the material production process, as well as confirmatory analysis of the effects of material formulation changes on the scale process. As such the research and development facility in Nottingham is equipped all levels of material dispensation and process modelling equipment at lab scale, including an in-house oven, scaled-down mixing bioreactor, and trays to best appropriate to the full-scale production facility in Oxford.



Figure 5: The tray dispensation production line in Oxford, left; laboratory preparation of samples, right.

Rigorous quality control takes place within two main categories at the scale facility in Oxford and supported by the research team in Nottingham. Firstly, incoming feed inputs from suppliers are tested against an array of standards for consistency and to monitor their contribution to the material formation process. Secondly, the quality of manufactured material is assessed by visual surface inspection, measurement of thickness consistency, and performance standards for strength and flexibility in line with customer expectations.

Sustainability

Carbon Footprint. The industry standard for declaration of carbon emissions tied to any product is a full life cycle analysis (LCA). Due to the complex considerations of this assessment, it requires a year's data from full production at scale. This will be undertaken in the near future. The current understanding of the carbon emissions (CO₂e) of the Really Clever is based upon calculations performed on the basis of best

knowledge of the emissions from the inputs, transport of these, energy use at the production facility, and the impact of coatings. These figures are displayed in table 1, alongside those from bovine leather and faux leather (PU).

Table 1: Carbon footprint in terms of CO₂e equivalent of Really Clever Material compared to bovine leather and polyurethane based faux leather.

Bovine Leather			Faux Leather [1]	Really Clever [3]
Published Value [1]	Best Case Estimate [2]	Hide Processing Only [1]		
110 kg/m ²	19.7-22.4 kg/m ²	17 kg/m ²	15.8 kg/m ²	1.39 kg/m ² *

* Total made up of feed materials 0.65 kg/m²; energy 0.51 kg/m², and transport 0.23 kg/m² and coatings.

Biodegradation. Biodegradability observed over several months is in progress, according to the standard ISO 14855 which involves an aerobic biodegradation test under controlled composting conditions at 58°C and measures carbon dioxide release as a proxy for degradation. So far, consistent development of degradation has been observed, albeit this is likely to be lower than the oft-cited recommendation of 90% degradation in six months. Microbial consumption, weight loss, and loss of integrity of material samples via in-house soil testing has also been observed, indicating biodegradability. A key consideration with biodegradability speed is the understanding of trade-offs needed with other customer requirements. In summary, in recognition that the material is biodegradable, there is an understanding of the limitation of the speed of the degradation process in order to provide the material with anti-putrefaction, spoilage, and water-resistant properties required by customers.

MATERIAL PROPERTIES

The Really Clever biomaterial is commercially ready for the footwear and fashion sectors. At every stage, the invention of, and research and development of the material has been led by four key considerations: sustainability, scalability, cost, and performance. Having corresponded with over 20 brands regarding the material across footwear, fashion, and automotive sectors, the science team has been led by the expectations of customers on performance. In many cases, material test reports, product use case feedback, and subjective opinions of customers has directly fed into research and the iteration cycles of the material.

Performance Summary

Performance expectations set by customers are detailed in terms of test standards. These inevitably vary between different sectors, due to different requirements for material in the context of products. There are also key nuances between different standards used by customers within the sectors, and between different testing houses. Table 2 details the performance properties of the material with respect to the typical requirements by sector.

Table 2: Material performance properties, detailed by sector and standard. Requirements listed are those which are typical for each property and of each sector. The scores listed have been provided by third party testing.

Material Property	Sector	Standard Example	Typical Sector Requirement	Really Clever Score
Tensile Strength	General	SATRA TM 43/ TM 29	10 MPa	10 MPa
Tear Strength (Baumann/ Double Edge)	Footwear	SATRA TM 162	50 N	60 N
	Fashion	ISO 3377-2	40 N	50 N
	Automotive		45 N	
Tear Strength (Trousers)	Footwear	SATRA TM 30	30-40 N	60 N
	Fashion		20-30 N	
Stitch Tear Strength	Footwear	ASTM D4705	30 N	65 N
	Automotive	DIN EN ISO 23910	40 N	
Strength Perpendicular to Needle Perforations	Footwear	SATRA TM 33	3.5 N/mm	5 N/mm
Lastometer Ball Burst Test	Footwear	SATRA TM 24	8 mm	25 mm
Shrinkage Temperature of Leather	Footwear	SATRA TM 17	No shrinkage up to 100°C	No shrinkage up to 100°C
	Automotive	IQ00149, §11.2.2	5% or less	2%
Hydrolysis (70°C, 95%RH, 7 days)	Footwear	SATRA TM 344	No observable change	No observable change
	Fashion			
Hydrolysis (50°C, 90%RH, 96 hours)	Fashion	ISO 17728	No observable change	No observable change
Hydrolysis (70°C, 50%RH, 72 hours)	Automotive	Customer Standard	No observable change	No observable change
Presence of Harmful Chemicals	General	REACH Regulations	None present	None present
Bally Flex – Dry	Footwear	SATRA TM 55	100,000 cycles, no damage	100,000 cycles, no damage
	Fashion	ISO 17694/ 5402-1	50,000 cycles, no damage	
	Automotive	UNI/EN/ISO 5402	100,000 cycles, no damage	
Bally Flex – Wet	Footwear	SATRA TM 55	50,000 cycles, no damage	70,000 cycles, no damage
	Fashion	ISO 17694/ 5402-1	20,000 cycles, no damage	
Bally Flex after Hydrolysis	Footwear	SATRA TM 344 + TM 55	80,000 cycles, no damage	80,000 cycles, no damage
Adhesion of Coating – Dry	Footwear	SATRA TM 410	2 N/mm	2.5 N/mm
	Fashion		1.2 N/mm	
	Automotive	UNI/EN/ISO 11644	0.4 N/mm	
Adhesion of Coating – Wet	Footwear	SATRA TM 410	1.5 N/mm	1.6 N/mm
	Fashion		1.0 N/mm	
Cross Hatch Test	Footwear	SATRA TM 406	Less than 5% area affected	No damage
Resistance to Scuffing	Automotive	SAE J365	200 cycles, no damage	200 cycles, no damage

Abrasion Resistance – Martindale Method – Dry	Footwear	SATRA TM 31	50,000 cycles, moderate wear	51,200 cycles, no damage
	Fashion	ISO 17704/ 105-X12	25,600 cycles, no damage	
		ISO 12947	50,000 cycles, no damage	50,000 cycles, no damage
Abrasion Resistance – Martindale Method – Wet	Footwear	SATRA TM 31	12,800 cycles, no damage	25,600 cycles, no damage
	Fashion	ISO 17704	6,400 cycles, no damage	
		ISO 105-X12	12,800 cycles, no damage	
Abrasion Resistance – Taber Method, 1000 grams, CS-10 wheels	Footwear	SATRA 163	300 cycles, no damage	1,000 cycles, no damage
	Automotive	Customer Standard	Grade 3 after 600 cycles	Grade 3 after 600 cycles
	Automotive	SAE J948	1000 cycles, no damage	1000 cycles, no damage
Crockmeter Test – Dry	Footwear	SATRA TM 167	4 GS after 516 cycles	4.5 GS after 516 cycles
	Fashion	ISO 17700/ 11640	3 GS after 50 cycles	
Crockmeter Test – Wet	Footwear	SATRA TM 335 + TM 167	3 GS after 256 cycles	5 GS after 256 cycles
	Fashion	ISO 17700/ 11640	3 GS after 20 cycles	
Colour Fastness to Circular Rub – Dry	Footwear	SATRA TM 8	3 GS after 256 cycles	5 GS after 256 cycles
Colour Fastness to Circular Rub – Wet	Footwear	SATRA TM 8	3 GS after 128 cycles	4 GS after 128 cycles
Veslic Rub Test – Dry	Fashion	ISO 11640/ 105-X12	3 GS after 150 cycles	5 GS after 150 cycles
Veslic Rub Test – Wet	Fashion	ISO 11640/ 105-X12	3 GS after 150 cycles	5 GS after 150 cycles
Colour Fastness to Rub – Dry	Automotive	UNI/EN/ISO 11640	4 SG after 1000 cycles	5 SG after 1000 cycles
Colour Fastness to Rub – Wet			4-5 SG after 500 cycles	4-5 SG after 500 cycles
Colour Fastness to Rub – Alcohol			3.5 SG after 10 cycles	5 SG after 10 cycles
Colour Fastness to Rub – Sweat			4 SG after 25 cycles	5 SG after 25 cycles
Colour Fastness to Perspiration, Petri Dish Method with Alkaline and Acid	Footwear	SATRA TM 335-2, 3	3 GS	4+ GS
Colour Migration to Solvent	Footwear	ISO 17701	4 GS	5 GS
Resistance to Water Spotting	Footwear	TM 185	3 GS	4-5 GS
Light Fastness	Footwear	TM 160	4-5 GS	4-5 GS
Colour Fastness to UV	Fashion	ISO 105-B02	Score 3	Score 3.5

Sun Test, White Material (70°C, 550W/m ² , 2 hours)	Footwear	ASTM D1148	4-5 GS	5 GS
Resistance to Phenolic Yellowing	Footwear	SATRA TM 260	4.5 GS	5 GS
Staining to PVC	Footwear	ISO 15701	4-5 GS	5 GS
Odour Test	Automotive	VDA 270	Grade 3 or lower	Grade 3
Fogging Resistance	Automotive	UNI/EN/ISO 17071-B	5 mg or lower	3.83 mg
Weather & UV Resistance, 220 kJ/m ²	Automotive	SAE J2412	4 GS	4-5 GS
Resistance to Heat Ageing (80°C, 500 hours)	Automotive	Customer Standard	4 GS	4-5 GS
Resistance to Heat Ageing (95°C, 500 hours)	Automotive	Customer Standard	4 GS	4-5 GS but stiffening*
Resistance to Heat Ageing (105°C, 168 hours)	Automotive	UNI/EN/ISO 20150-A02	4 GS	1-3 GS*
Humidity Exposure (Atomised, 72 hours)	Automotive	Customer Standard	4 GS	5 GS
Resistance to Combustion	Automotive	UNI/ISO 3795	< 100 mm/min	Self-Extinguishing
Susceptibility to Soiling and Cleanability	Automotive	Customer Standard	4 GS	4 GS

* Automotive customer requirements which are not met in the classic version of the Really Clever material. Specialist automotive specification of the material is in development.

Type of Material

Table 2 summarises the properties of the material with regards to typical performance requirements set out by customers in the footwear, fashion, and automotive sectors. There are important factors to appreciate when testing the Really Clever biomaterial against these properties, which will be described in detail. Before this, there are considerations to made of the type of material it is.

In doing so, it is also important to note the extent of contradictory or often opposing features which the material needs to have, to be suited to use by customers and to fit the criteria against which it is judged. With the strength and flexibility required for products, it also has to be malleable enough to be moulded in construction processes, and retain its given shape following this. It needs to be heat and water resistant to a degree, but also interact with water such that damage does not occur and yet the material allows some penetration. The material is demonstrably biodegradable but does not spoil. Finally, the material is entirely biobased, with a low carbon footprint, and yet is able to take plastic (PU) coating according to existing finishing processes as mandated by customers for a product context.

The material has a density of approximately 970 kg/m³ – i.e. 0.97 kg for a sheet of material of an area of 1 m² and of 1.0 mm thickness. The density remains the same and therefore weight increases proportionally with both area and thickness (i.e. volume). The approximate early stretch young's modulus (measured up to 20% elongation) for the material ranges from between 5 and 10 MPa (0.005 and 0.01 GPa). By some

assessments (e.g. [4]), this can therefore be classed near to the elastomers in terms of material type, and away from the scope of other natural materials, such as the commercially as-yet unsuccessful mycelium-based materials, and the scope of polymers – which it serves to replace.

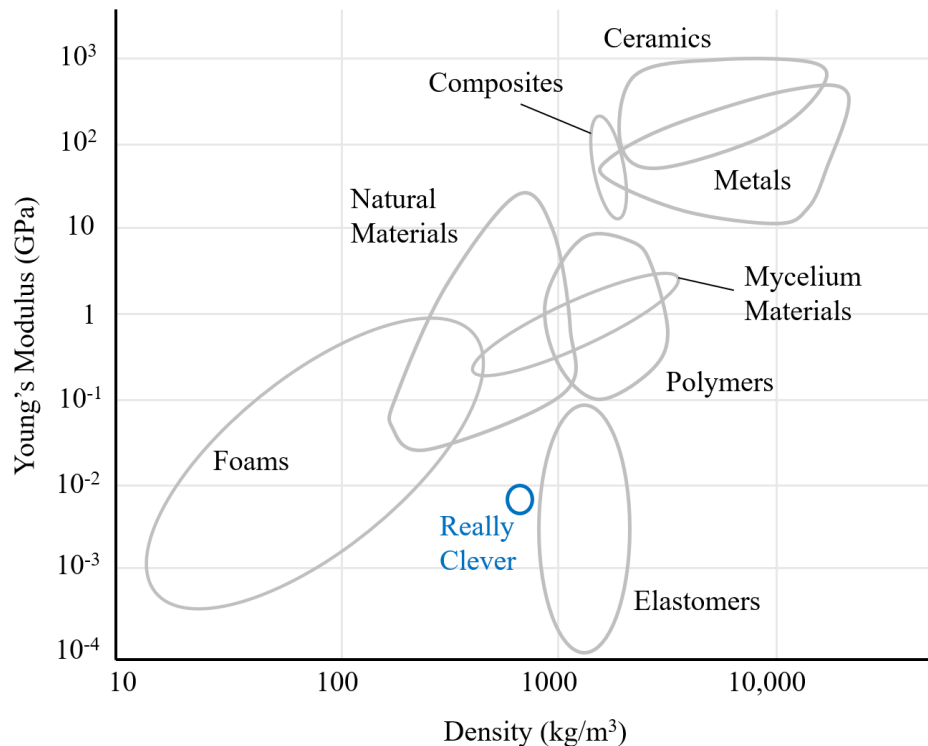


Figure 6: Materials property chart (Ashby chart) featuring various materials. To note, despite containing fungal content, the Really Clever biomaterial does not bear similarity to (unbacked) mycelium materials.

This similarity to elastomeric materials does in part owe to the presence of a notable plant extract (part of the 40% of inputs featured in figure 2) – that being natural rubber latex, from *Hevea brasiliensis*. It should be noted that the biomaterial however is not a form of rubber, and in no part of the process or supply chain are vulcanisation or other synthetically-derived rubber processes deployed. Rather, the material incorporates as an input a maximally-natural and unprocessed form of the plant extract (i.e. the latex) which also acts as the starting raw material for rubber products. Key changes to the behaviour and role of the polyisoprene polymer are made via the use of the other inputs to the production process for the material. Outside of the material properties visited in the following sections, this can be appreciated by looking at rheological curves along a frequency sweep depicted in figure 8. The angular frequencies at which variants of the Really Clever biomaterial transition between “viscous liquid” and “elastic solid” differ substantially to those of solidified natural rubber. These unique rheological properties contribute to the bigger picture of the material’s performance in the product context.

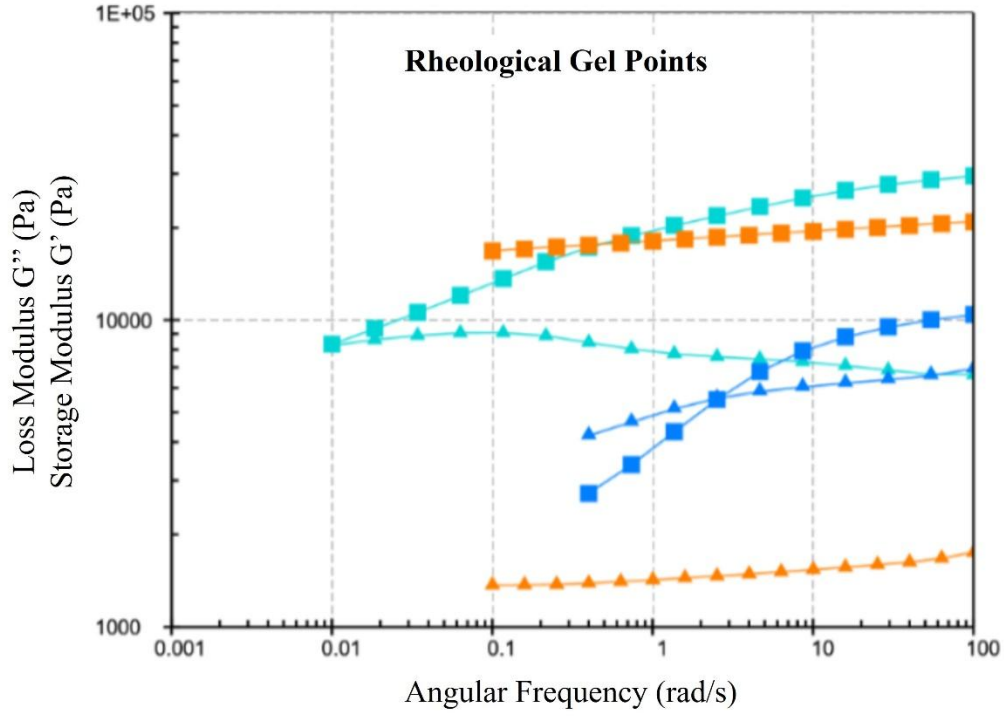


Figure 7: Rheological gel points for variants of the Really Clever biomaterial (blue), and G'' and G' plots along the same frequency sweep for solidified natural rubber (orange). G' plots: triangle points and G'' : square points.

Third Party Testing

Having worked with over 20 brands and customers from across the footwear, fashion, and automotive sectors, multiple material testing houses and scientific testing authorities, and finishing/ coating providers, the Really Clever technical team have become aware of discrepancies and variations in testing practices, standards, and results. As such, from large datasets relating to internal and external tests of the Really Clever material, over 1000 variations of which have been tested since 2022, a probability distribution for the internal vs external validated performance has been modelled. This Unified Properties Score $f(\sigma_t)$ is demonstrated in figure 8. This is a recognition of the differences that can occur between different testing sources, and accounts for these with predictability. It is important to set expectations against the understandings made from this.

$$f(\sigma_t) = \frac{1}{1+e^{-k}} \text{ where } k = \frac{100(\sigma_d - |\sigma_d|)}{\sigma_m^2} + \frac{4(\sigma_d + |\sigma_d|)}{\sigma_m} \text{ and } \sigma_d = \sigma_t - \sigma_m$$

σ_t represents test value, σ_m represents minimum requirement value from the customer.

$f(\sigma_t)$ represents the probability of passing external assessment based upon the comparison of the test value by internal assessment and the minimum requirement value.

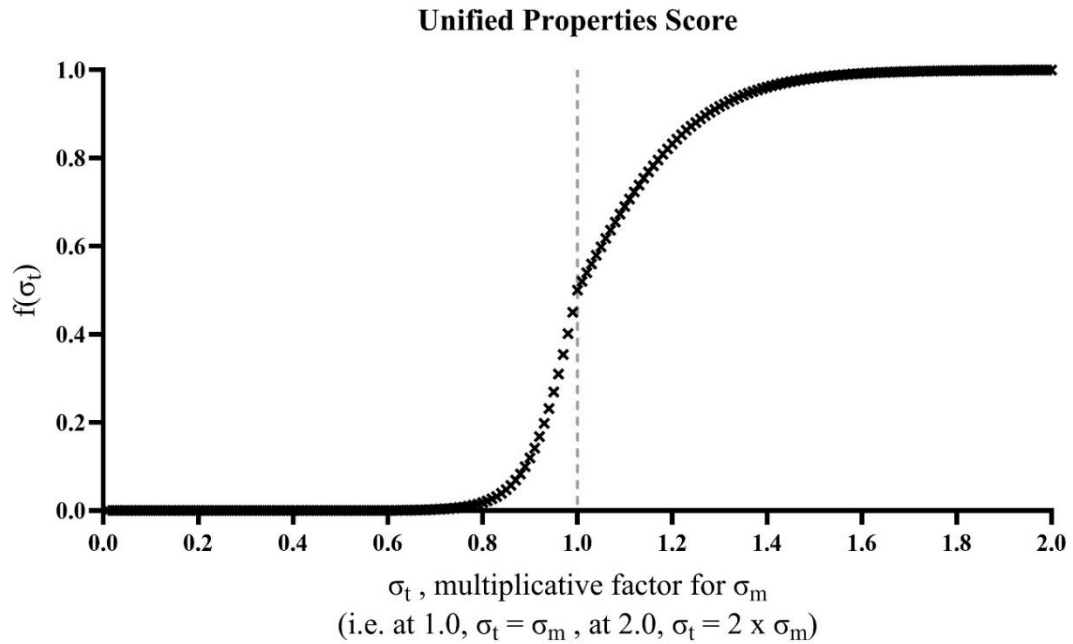


Figure 8: The Unified Properties Score probability distribution – formula and graph against multiplicative test value factor for minimum requirement value.

With an appreciation of both (a) the type of material and (b) the predictive considerations for third party testing – the following sections on strength, flexing, durability and resistance, and coating properties can provide further context and inform fuller understanding of the genuine properties and behaviour of the Really Clever biomaterial.

Strength

Tensile strength. Test methods for determining the breaking tensile strength, or ultimate strength of materials have been described in several standards, relating to leather, plastic, and other types of material. These include various dimensions of testing strips, and shapes varying from dumbbells/ dog bones to straight rectangles.

It is essential to note that the definition of tensile strength considers the original thickness of the sample prior to stretching, and has the following formula:

Tensile strength (MPa) = maximum load (force) (N) / cross-sectional area (mm²).

The ultimate tensile strength is the maximum stress that a material can withstand while being stretched before breaking. In the biomaterial, this maximum stress occurs close to moment of break. Therefore, to obtain the value for ultimate tensile strength, during testing a sample of the material must be stretched to break.

Testing Considerations. Standards such as SATRA TM 43, SATRA TM 29, ASTM D2209, ISO 527-3, and ISO 3376 are often cited for the assessment of tensile strength, breaking strength, or similar. In many cases, proprietary in-house standards are used. Really Clever provides the following recommendations for consistent testing of the biomaterial. If necessary, the material must be pulled twice on a tensiometer (stretched after the first extension, if the column of the tensiometer is not sufficient to break the material – which typically occurs at 900% elongation). A tensiometer jaw/clamp gap of 25 mm, test piece width of 10 mm or greater, and an extension speed of 500 mm/min and recommended. A lower extension speed results in greater error of recorded results. Finally, the material is noted to show consistent tensile strength up to a thickness of 1.5 mm, after which a minor decrease is observed. Effects of these considerations are shown in figure 9.

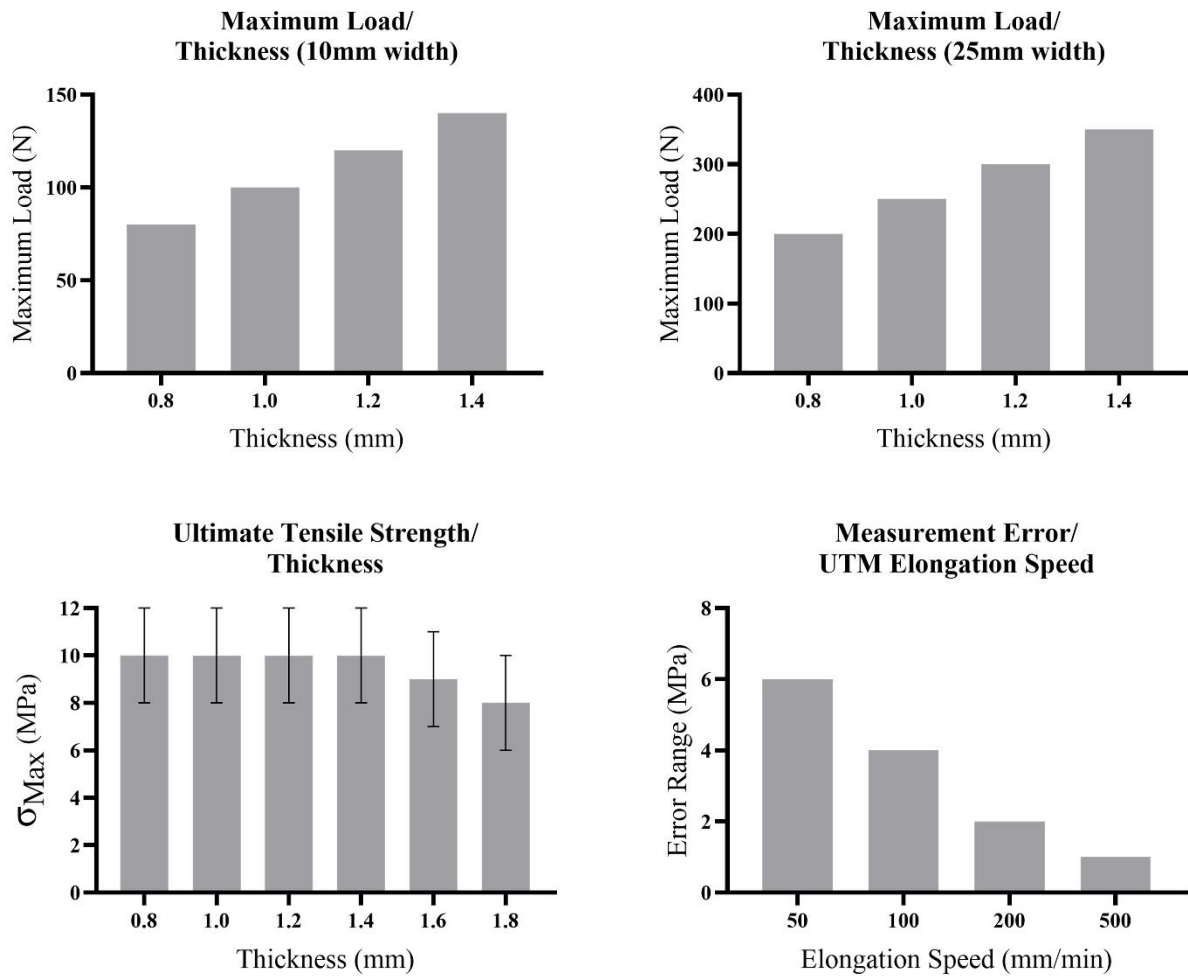


Figure 9: Factors relating to measurement affecting maximum load and ultimate tensile strength scores of the biomaterial.

Stress vs. Strain. The Really Clever biomaterial exhibits a stress-strain relationship with elastic and non-elastic behaviours dependent on elongation (strain) extent. Due to this, elongation at break may vary, but typically occurs around 900%; of course, stress increases with strain, but in a non-linear manner (figure 10). It is essential to note that the correct maximum load, and therefore ultimate tensile strength of the material only can be measured by breaking it, and that therefore this is not shown in the graph. Based on the variability of the elastic portions of stress-strain relationships for the biomaterial, a key metric for material strength is the tensile strength (adjusted load for thickness) at 100% elongation. Figure 11 shows typical load at 100% scores for the material with different test piece dimensions.

Strength and Humidity. Temperature and humidity conditions recommended for testing of material strength are 23°C and 50% RH, in line with standards. Effects of humidity on tensile strength scores both ultimate and at 100% elongation are shown in figure 12. Thus, there are also observable and reversible differences in stress-strain relationship graphs for samples of the biomaterial after exposure to drier and more humid environmental conditions (figure 13). This is related to water uptake levels caused by changes in humidity, as can be observed by subtle weight changes in the biomaterial (figure 14). These effects do not lead to compromises on functionality or performance requirements.

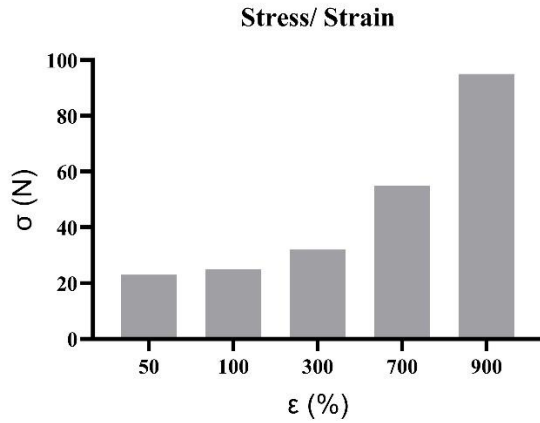


Figure 10: Stress(σ) vs. strain (ϵ) relationships for the biomaterial, with data shown for a typical test piece of 10 mm width and 1 mm thickness.

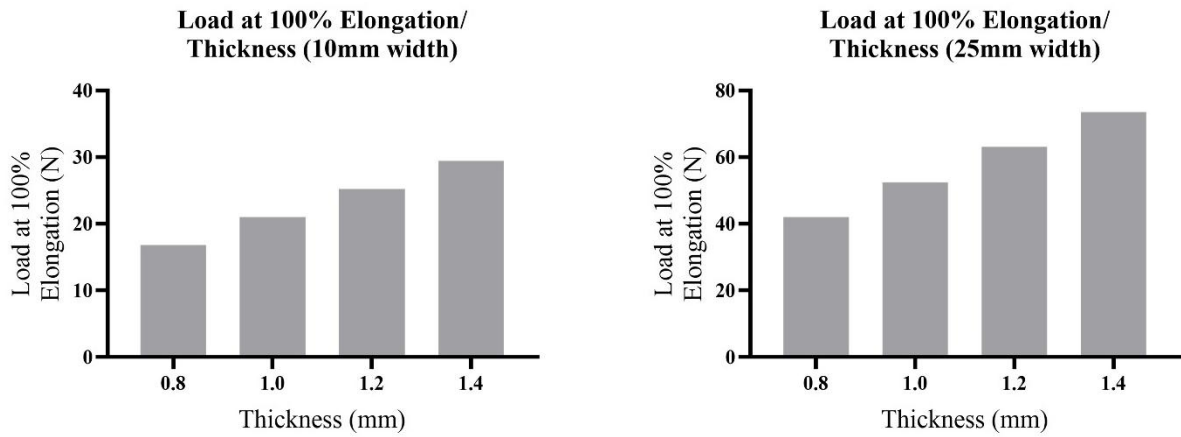


Figure 11: Scores for load at 100% elongation, for different test piece dimensions of the biomaterial.

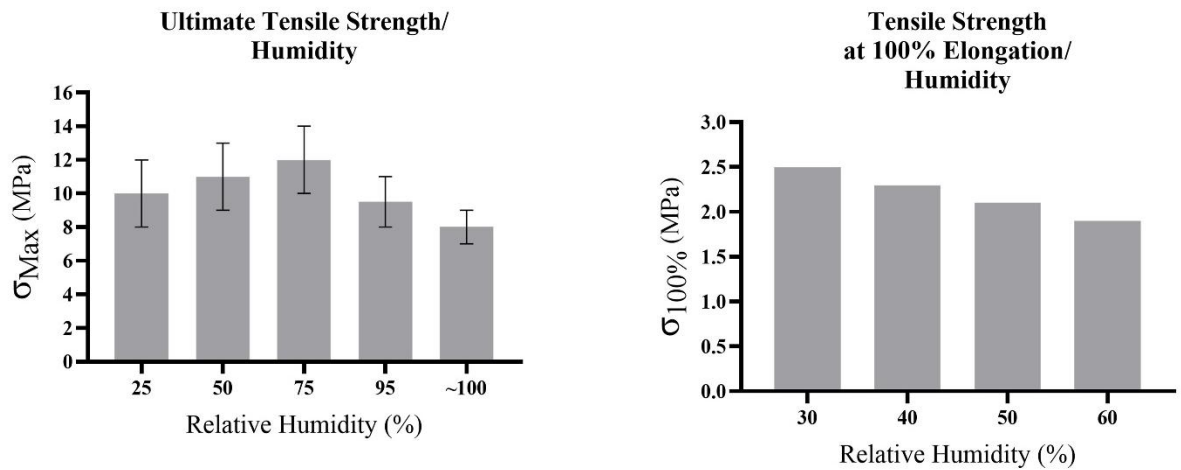


Figure 12: Ultimate tensile strength and tensile strength at 100% humidity for samples at varying humidity and of 10 mm width and 1 mm thickness.

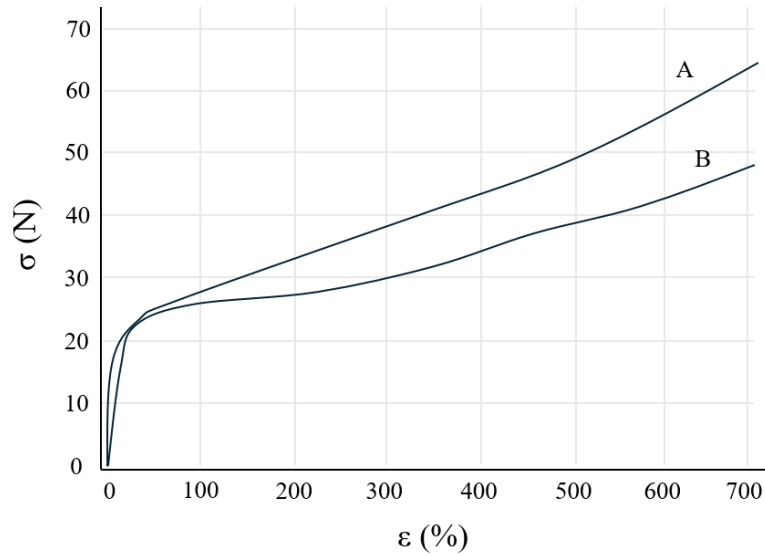


Figure 13: Stress-strain graph showing material following exposure to relatively dry (A) and humid conditions (B). The material does not have different maximum load or tensile strength values under the different conditions (not shown).

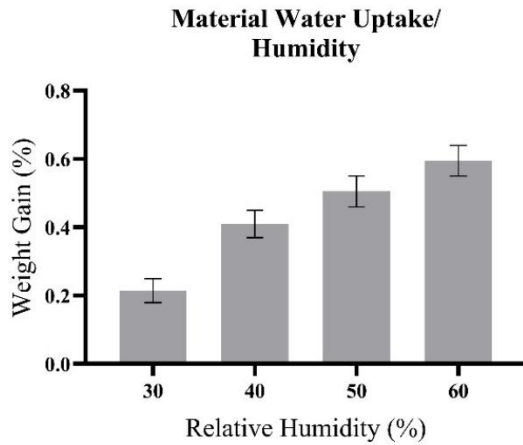


Figure 14: Water uptake levels as observed by weight gain with changing relative humidity.

Tear and Stitch Strength. Various standards and forms of testing for tear strengths have been used to assess the biomaterial, including for trouser (SATRA TM 30) and Baumann (SATRA TM 162, ISO 3377-2) tear tests, and others such as trapezoidal (ASTM D5733). For strength testing relating to stitching and seams, several standards are used – such as ASTM D4705, ISO 23910 (double hole method), SATRA TM 33 (perpendicular to needle perforations), SATRA TM 180 (seam strength), ASTM D5733 (trapezoid stitch tear), and others.

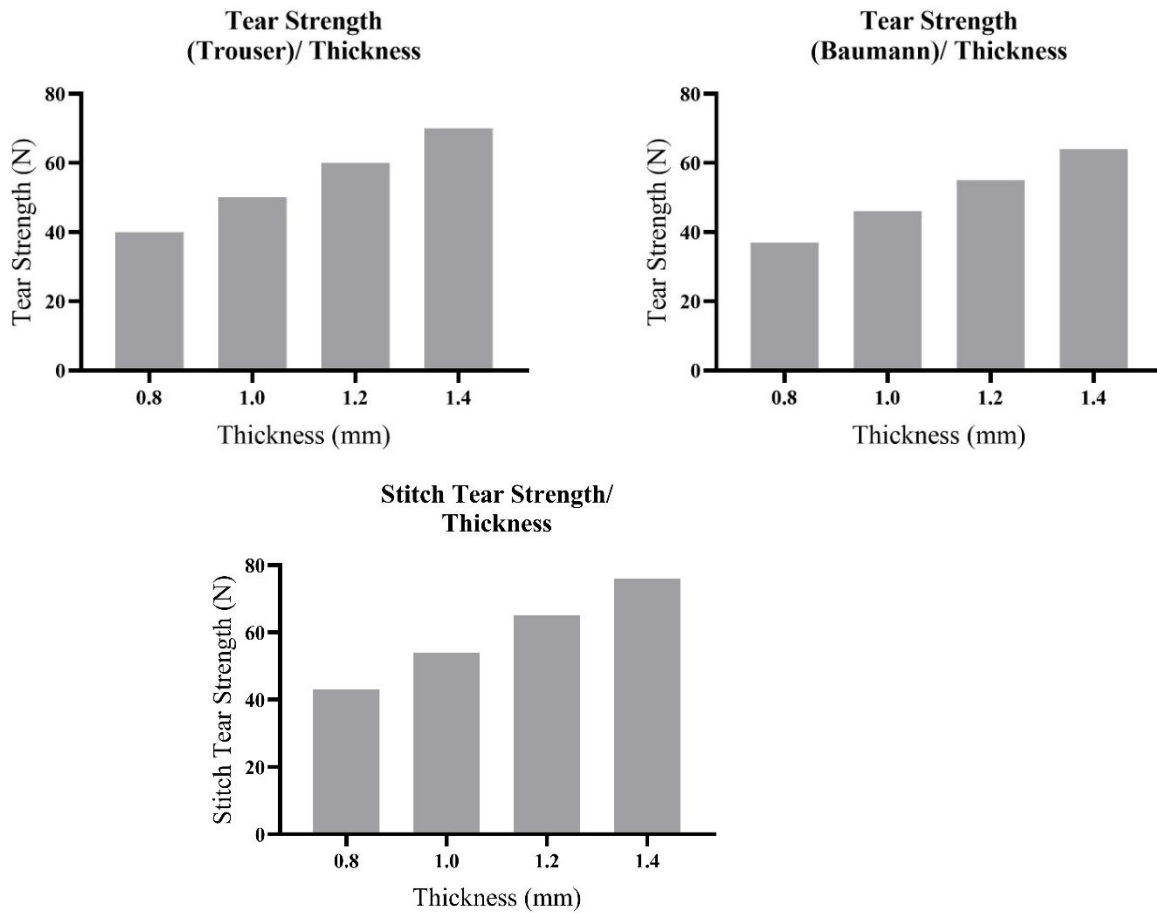


Figure 15: Tear (trouser and Baumann) and Stitch Tear (double hole test) strength scores at different thicknesses of material, of 10 mm test piece width.

Lastometer and Stretching. The biomaterial has been demonstrated on multiple occasions its readiness for lasting and the required manipulation for shoes and other products. Additionally, satisfactory lastometer test results (e.g. SATRA TM 24) have been recorded. Regarding the intrinsic properties of the material, a linked hysteresis behaviour can be noted, with “strain memory” shown from multiple stress-strain graphs when repeated stretching of the material is performed (figure 16).

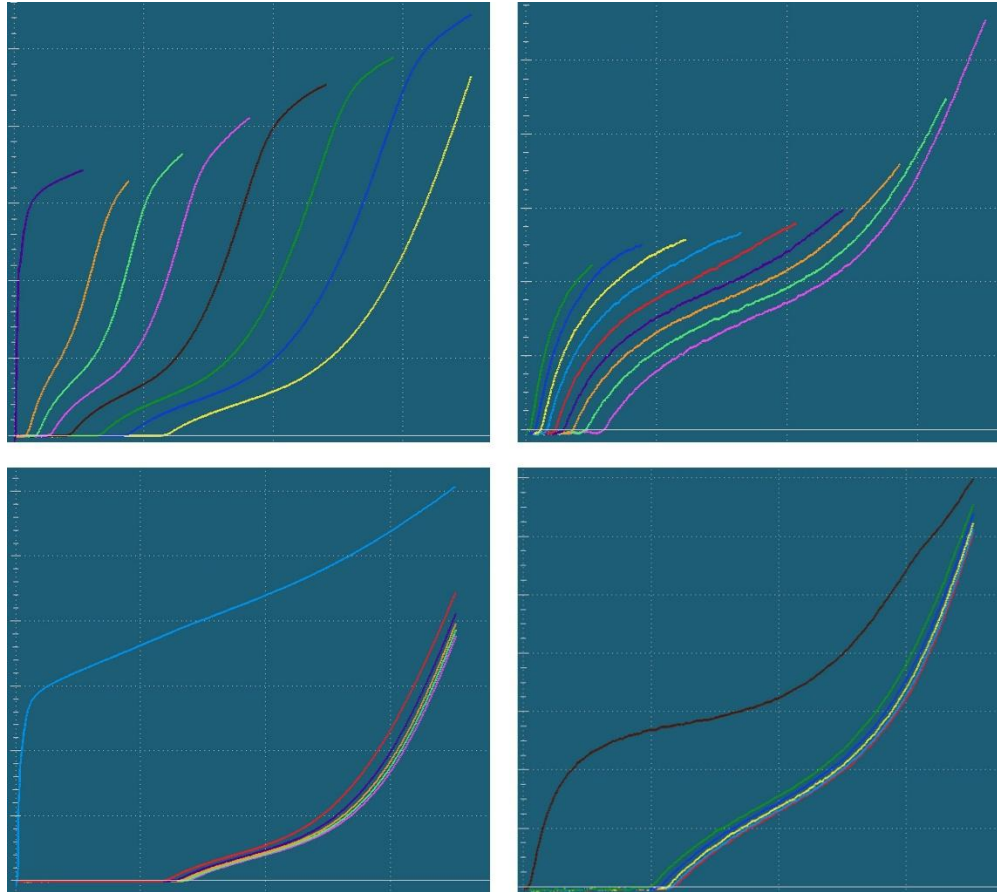


Figure 16: Stress-strain graphs, showing multiple repeat stretches of the same materials (one in each panel) to varying extents.

Flexing

Bally Flexometer. The flexing resistance of materials in shoe uppers, as well as in other applications, is widely assessed using the bally flexometer, according to standards SATRA TM 55, ISO 17694, ISO 5402-1, as well as proprietary and varying internal methods. These can also be combined with condition variations – for instance dry, wet, and hydrolytic (e.g. such as set out by SATRA TM 344, ISO 17728 or similar). Test standards describe the placement of a rectangular piece of material in an upper clamp, folded back and then securely fixed into a lower clamp such that a perpendicular arrangement is achieved. There is to be no slipping of material from the clamps, excessive bulging from the sides of the material, or additional stress placed along the axis of the material. As such, the material must be observed to flex in the correct manner, repeated to a given number of cycles, and then inspected for cracking or other types of failure.

The biomaterial can withstand up to 100,000, 70,000, and 80,000 bally flexing cycles without significant damage in dry, wet, and following hydrolytic conditions respectively. When failure occurs, this is observed initially as minute cracking on the surface of the flexed material, with cracks gradually deepening and increasing in length over repeated cycles. When coated samples are tested, creasing is observed. These observations are depicted in figure 17.

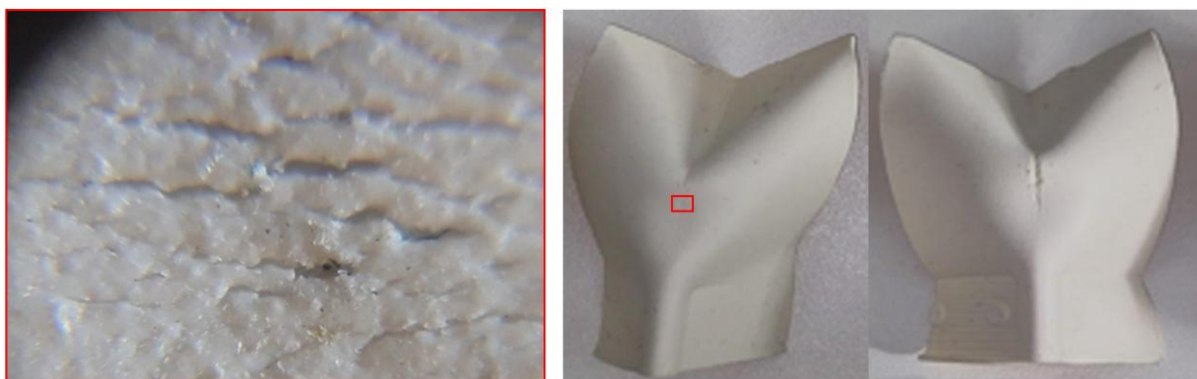


Figure 17: Bally flex damage observations. Sample with minor cracking (centre) with magnified image (left); sample with severe cracking (right).

Other Flexing Test Types. Other types of flexing tests can be performed on the biomaterial. These include vamp flex (standards SATRA TM 25, ISO 5402-2), and flexing tests associated with rubber-like materials (e.g. standards SATRA TM 60, ISO 132). It is essential to contextualise use case of the material in the end product when considering these tests – hence informative inferences around material function can be made. These optional tests are understood to be less indicative of the flexural strength and resilience of the material, and its subsequent functionality in products. More specialist test requirements may be addressed with tailored new specifications of the material where necessary.

Durability and Resistance

A broad range of tests and standards assessing general durability resistance to varying environmental conditions have been considered for the biomaterial and are of keen interest for product applications. Many of the relevant tests apply to both coated/finished material and unfinished material. Some of the tests take into account the resistance to damage of the material. Tests assessing the integrity of the coating itself and/or the quality of its adherence to the material as a substrate are considered in the next section. There is often considerable overlap, with conditions of humidity, temperature, and other factors placed together, alongside physical testing, appearance, or other more subjective observations.

Hydrolysis and Water Resistance. A key overall property of the material is its propensity to uptake and soak water, albeit at a limited rate compared to alternatives, as covered earlier. Interaction of humidity and with liquid water noted, a compromise is met between an entirely water-impenetrable and unbiodegradable material and one which retains moisture to the extent of encouraging putrefaction, leading to compromised physical properties and other downsides such as malodour.

Hydrolysis testing (e.g. SATRA TM 344, ISO 17728) involves the placement of material into a chamber of elevated temperature and humidity for a given period of time – typically up to 70°C at 95% relative humidity, for seven days. After this period, when re-conditioned to testing requirements, the material exhibits no observable damage. Wet testing, by contrast, involves the immersion of material in liquid water, which most often used in combined testing of finish/coating standards. Practices vary, but in some cases (e.g. as specified in ISO 11644) there is application of pressure for a given time and level. The material passes the necessary requirements when wet testing is used.

Heat Resistance. According to various test standards involving elevated temperatures as well as other modified environmental conditions relevant to footwear and fashion

applications (e.g. SATRA TM 344, ISO 17728, ASTM D1148) – the biomaterial is highly resilient, meeting requirements. For tests involving elevated temperatures for extended periods of time, such as those required for automotive products, development of material readiness is an ongoing pursuit. Modified/ custom additions to the formulation may address these.

Finishing the Material

Finishing Considerations. The material may be coated/finished according to customer expectations, using the same techniques (such as spray and roller coating) as typical of the industries. In order to obtain the best performing and adhered polyurethane finish to this unique biomaterial, the following recommendations are understood. Rubber primers may be used, and without during the adhesion process conditions exceeding 80°C. Additional steps of preliminary spray of chlorinating agents – such as sodium hypochlorite – can be deployed to enhance adhesion. The material also takes and holds embossed patterns. Greater than 1500 psi pressure is recommended.

Coating Properties. Relevant test standards for coating properties concern in some cases the properties of the coating in isolation, in others the adhesion between the material and coating, and in further examples the properties of the coated material as a whole. The most relevant standards are listed in table 2.

REFERENCES

[1] UNIDO (United Nations Industrial Development Organization), 2017. Leather Carbon Footprint; Review of the European Standard EN 16887:2017. Leather – Environmental footprint – Product Category Rules (PCR).

[2] Bovine best-case estimate includes an allocation for farming the animal based on 2019. Recommendation on the use of Environmental Footprint methods and published values one for leather website <https://www.one4leather.com/article/the-real-carbon-footprint-of-leather>

[3] Calculation is an estimate for the pilot facility based on the expected energy requirements of the manufacturing line, published values on the carbon footprint of feed materials, published values for carbon footprint of road transport and shipping, and published values for coating. The breakdown of this is as follows:

[4] Peeters, E. *et al.* (2023): Growing sustainable materials from filamentous fungi. *The Biochemist*. 45(3): 8-13.