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Predicting Penetration Performance in Current and Novel Sustainable Tissue Simulants Using Quasi-Static Compression Data

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ABSTRACT

Historically, ballistic gelatine has been used as the industry standard when conducting experiments associated with survivability, ammunition lethality, and wound ballistics. This biopolymer is used to replicate human tissue and examine permanent and temporary cavitation. However, previous works have highlighted a promise in using foodstuffs gelatine to provide economic benefit to research programmes and reduce the environmental impact caused by a single source supplier. This work compares alternative foodstuffs' porcine gelatine to vegan alternatives using quasi-static compression testing to investigate differences in performance, repeatability, manufacturing considerations, and a comparison on transparency when compared to 10% ballistic gelatine. Vegan alternatives were identified as suitable candidates to reduce the ethical and environmental issues associated with traditional gelatine manufacture. It was found that both porcine and vegan alternatives can provide increased performance, transparency, and repeatability at a lower strain rate when using 10% ballistic gelatine as the control. The work reported within this study highlights that at a lower strain rate, researchers can use an alternative material to produce the same results as 10% ballistic gelatine; however, dynamic testing revealed no correlation between datasets, generated as part quasi-static and dynamic research programmes, can be made, with significant differences in global and local response to impact.

1 | Introduction

Ballistic gelatine has historically been used as a bulk tissue analogue for assessment of wound ballistics and both lethality and survivability assessment [1–26]. This viscoelastic material has been proven to be a reliable model for comparison against human muscle and associated tissue [2, 3, 27].¹ Acceptance as a suitable tissue surrogate has required extensive characterization to fully understand the materials' microstructure, with mechanical testing being used to investigate material performance [22, 28, 29, 24, 30–33]. The field of mechanical testing contains a

vast number of methodologies; therefore, selection of the correct tests is crucial in understanding how a material performs within a given environment or scenario [14, 34–40]. As ballistic gelatine is primarily used to understand temporary and permanent wound tracts and injury from Behind Armour Blunt Trauma, the main areas of focus are mainly tensile and shear testing, compression testing, puncture, and friction tests [22, 24, 28–31, 33, 41]. However, the question of strain rate is also of importance to ensure differentiation between lethal and less lethal kinetic impact material response and, therefore, materials use in a wide range of scenarios [14, 29, 33, 42–44].

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As no industry has accepted the single model currently exists to accurately reproduce the characteristics of human anatomy, numerous tissue surrogate models are used (such as the skin and bone) to ensure the research community is provided with a comprehensive understanding of the injury mechanisms [45–53].

Ballistic gelatine is delivered in powder form and is incrementally mixed with hot water to provide either 10% or 20% ratios, which can be easily tuned and used in most ballistic applications [5, 6, 54, 55, 56]. To ensure any manufactured material is validated correctly, a calibration method exists that primarily focused on the depth of penetration of a 4.5 mm projectile fired from a fixed distance and velocity [57]. This is extremely important to ensure the materials have been proven to perform satisfactorily, reported as such and therefore enable experiments to be repeated easily.

However, this material has been reported to be subjected to limitations that could affect its performance and shelf life [1, 58]. Of note are the temperature dependence [2, 10, 28] of ballistic gelatine and the inconsistent manufacturing methods that are available within the literature [5, 6, 54, 55, 56]. Temperature dependence in this instance refers to the dissolution temperature, which has been evidenced to change protein structure, gel strength, and viscosity that results in differing responses to physical impact [54]. Each of the five manufacturing methods reviewed for this study was also found to contain inconsistencies or missing information regarding manufacturer, block sizes, and dissolution temperatures. The variations between methods and the absence of critical information have the potential to compromise datasets and increase the probability of not being able to replicate previous works with sufficient accuracy.

Additionally, previous works have shown that environmental impact, especially during manufacturing and supply chain assessment, can be minimized by utilizing products already within existing markets [59].

With societal drives toward more sustainable and ethically advantageous approaches [1, 60–62], it is paramount that the literature starts to explore alternative material options. A recent study has shown that there are both economic and environmental advantages of using materials that have high elastic modulus and can exhibit responses similar to that of the human body under laboratory testing conditions [59]. While ballistic gelatine is the industry standard to which a comparison must be assessed [1, 63], there are opportunities for utilization of alternative raw material products and reductions in “post processing” material, thereby reducing economic and environmental burden. Once such material was identified by previous works as foodstuffs gelatine.

Gelatine has been used for decades as a trusted substance for the creation of many materials used within the Food, Pharma, and Technology industries [64]. What is known today as gelatine was first conceived 8000 years ago, as a substance to bond two materials together [65]. Analysis by the Weizmann Institute in Israel has shown that forms of crude gelatine were used during the New Stone Age, and later during the reign of the Egyptians used to aid the construction of various pieces of furniture [65]. Collagen glue was produced by using the hides of animals and is still manufactured for applications most widely used in medical

industries [66–69]. However, some Egyptians also used bones to prepare various food sources, which when cooled, resulted in a form of foodstuffs gelatine [65]. This has been further evidenced at the banquets of King Henry VIII, in which dishes of “Pickled Glittering Calves” Foot Jelly was served as a delicacy and by the French Navy during the Napoleonic Wars upon having their supply chain cut off by the Royal Navy, reducing food supply (meat) and thereby requiring a protein rich food source [65, 70].

In today’s world, numerous different types of gelatine are available, traditionally made from pig or cow skins and animal bones that have been demineralized (reduced or eliminated calcium content) [71]. Following delivery from the slaughterhouse, the raw materials undertake a quality inspection and deep cleaning using either an acidic or alkaline based procedure, producing either Type A (acid) formed gelatine or Type B (basic) gelatine.

- a. Acidic processing (Type A)—This procedure is most common with pig skin, where the raw material is subjected to a 24-h conditioning process, involving an acid treatment to render the collagen soluble. The 24-h processing time is reported to be due to the tissues of the skin not yet cross-linked due to the young age at which pigs are slaughtered [72, 73].
- b. Alkaline processing (Type B)—Both cowhide and ossein (95% collagen—extracellular matrix of bone) raw materials favor this procedure, as the raw materials have crosslinked the collagen content. Here, the raw materials are subjected to 2–3 weeks of treatment with calcium hydroxide, allowing the collagen structure to be softened (by destroying the collagen bonds) and ready for extraction [72, 73].

Once the collagens have been extracted from the pre-processing procedure using warm water, purification is required to eliminate any residual traces of fat or insoluble particles. This follows several filtration cycles that increase in severity until a final ion exchange purification step is employed to remove any salts. The final processing step is to remove any additional water, which is completed using a series of vacuum evaporators before being subjected to a set of cellulose polishing filters to remove any fine particles that remain. The material that remains is heat-sterilized, cooled, and allowed to set before being dried with sterile and filtered air.² The material, brittle in nature, is sent to storage until requested by the customer. Customer needs can be achieved by post-processing of the material in processes such as milling, blending, and sieving before being packed and transported [74].

It is of note, however, that with an increase in sustainable and ethical focus, plant-based gelatine has become increasingly popular. Some reported advantages of plant-based alternatives are the higher melting point and, therefore, increased duration in which the mixture can remain stable (not melt) [75] and quicker setting time [76].³

Vegan alternatives such as Agar Agar and Carrageenan are widely accepted as alternatives for traditional porcine variants; however, their manufacturing methods are different and do not require the volume of pretreatment required. Carrageenan is harvested from the ocean before being washed in a hot water and alkaline mixture to soften its material matrix and ready for extraction.

This is followed by thoroughly washing the seaweed with water before entering either a semi-refined (carrageenan is cut into small pieces and dried in a closed dryer before being milled to become powder) or fully refined (water pushed down on top of the seaweed to sieve out the solids, leaving only the carrageenan and water. The carrageenan is then recovered from the water and follows the same cutting, drying, and milling procedure as the semi-refined variant) product stage [77, 78].

Similarly, Agar Agar is made from the seaweed (Red Sea Algae) that has the carbohydrates extracted to form the raw product. This is achieved by first harvesting and drying the material to reduce the moisture content. The material is then bleached in an alkaline solution before moving to extract the Agar in boiling water as following a very similar manufacturing process as fully refined carrageenan before being moved to be filtered, gelling/freezing, drying, milling, and packaged for dispatch [79].

Regardless of content, material entering the foodstuffs market must abide by rigorous standards [80] to maintain both the quality of product but also the safety of consumers. Gelatine produced for edible purposes is subjected to food law [81] and regulations [82, 83] on edible gelatine. Additionally, manufacturers can obtain the Food Safety Systems Certification (FSSC) 22000 [84] international certification which builds on ISO 22000 declaring manufacturers follow robust quality, safety, and industry approved processes [85] to which gelatine should be manufactured. Each country will also provide additional quality standards (ISO 9001 and ISO 14001). In addition, the UK also has procedures in place for manufacturers to declare health certificates for their produce before it is allowed into Great Britain [86].

Increasing environmental awareness has encouraged manufacturers to carefully consider their production techniques alongside supply chain impact [87, 88]. The two main metrics worthy of attention here are the potential for reductions in carbon footprint and both water consumption and wastewater generation [59].

A recent series of studies commissioned by the Gelatine Manufacturers of Europe investigated the progress made toward reductions in carbon footprint between 2006 and 2021 [89]. However, due to the sheer amount of water used during manufacturing, a separate study examining the water footprint of GME members was commissioned in 2016, covering the same 2006–2021 period [90]. The water footprint assessment shows that there has been a 9.7% reduction since 2006; however, during the period 2020–2021, a marginal increase was observed, which has been reported to be concerned with adaptations in manufacturing technique, utilization, and adaptations to further reduce the carbon footprint of manufacturing [90].

When considering carbon footprint, the GME assessment was undertaken using internationally recognized standards [91] and focused on both Gate-to-Gate and Cradle-to-Gate assessment principles. This report shows that there has been a 10.2% reduction in carbon footprint and a 17% reduction in energy consumption across the GME member organizations showing encouraging signs that gelatine manufacturing and processing techniques are progressing toward the EU 2030 climate objectives [61, 62] and the long-term 2050 carbon neutral status [1, 60].

This report did, however, note that when the Cradle-to-Gate principle was observed, concerns were raised with the total greenhouse gas emissions (CO₂e) from the supply chain. The results show that “*the agricultural supply chain for raw materials is responsible for a significant part of the overall carbon footprint of gelatine and collagen peptides*” [89].

Examination of the environmental implications of rearing livestock and raw materials used for plant-based gelatines also requires attention. In recent times, traditional animal-based farming practices have been scrutinized for producing excessive amounts of methane, which has been reported to have a global warming potential of more than 28 times that of carbon dioxide (CO₂) [92–97]. Scientific research in this field has started exploratory work to reduce and aim to eliminate the methane produced by cows [98] as directed by plans released by the UK Government [99, 100]. Equally, although more sustainable, farming of plants to produce plant-based gelatines is also predicted to cause concern. This method relies heavily on nutrient-rich soil for the plants to grow rapidly enough to make the farm economically successful. Where this is not possible, fertilizers may be required alongside the use of herbicides and pesticides to accelerate and manage plant growth, but at an environmental cost [101–103]. In addition, increased usage of farm equipment used to prepare the fields for growth and harvesting when ready will also contribute to increased CO₂ output.

As this research focuses on the quantification of foodstuffs gelatine for use in wound ballistics and survivability assessment, the environmental impact of raw material production is outside the scope of this research. It has been mentioned above to ensure that sufficient breadth of environmental considerations is known prior to physical material testing, and an enhanced desktop qualitative environmental and economical assessment is undertaken, as well as providing strands for further work.

Previous works have suggested that foodstuffs gelatine could provide both economic and environmental advantages to the field of survivability assessment, provided that the performance of the material should be improved [59]. To further explore this material’s viability within this field, a series of manufacturing-based experiments were derived to explore material viscosity in relation to material response when exposed to low strain rate compressive experimentation, with the aim of better characterize foodstuffs gelatines against the well-established and proven 10% ballistic gelatine baseline. In addition, a series of materials was produced by combining the top three best-performing materials initially exposed to quasi-static testing. These were subsequently exposed to the same testing regime to evaluate performance, and all samples were placed under dynamic test to investigate where higher strain rate impacts correlate to quasi-static results.

2 | Materials and Methods

2.1 | Materials

Moulds of dimension 25 mm internal diameter and 25 mm height (± 0.25 mm) were manufactured from polyoxymethylene (POM), also known as acetal. This thermoplastic material was selected

TABLE 1 | Material summary.

Material summary	
Material	Supplier
GELITA 10% ordnance gelatine	GELITA [6]
Foodstuffs gelatine (cubed)	Asda [106]
Foodstuffs gelatine (powder)	Amazon UK—MM Ingredients [107]
Carrageenan Kappa	Amazon UK—Special Ingredients [108]
Agar Agar	Amazon UK—Special Ingredients [109]

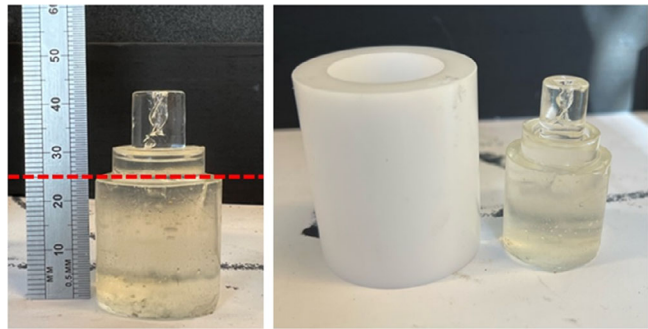


FIGURE 1 | Left: Decanted material 25 mm height with sacrificial material highlighted above the dash line. Right: POM mould alongside decanted gelatine mould.

due to its dimensional stability under varying temperatures and low-friction applications [104]. A key requirement for the gelatine moulds was to ensure that the surface of the material undergoing test remained defect-free, thereby reducing any inconsistencies in data capture. A 19 mm hole was machined at the base of each mould, which was then filled with a plastic bung to ensure no leaks were present during manufacture of the materials. Once filled with material and cured, the plastic bungs were drilled out using a 3.5 mm drill, and a small quantity of compressed air was passed through the hole to safely remove the materials without comprising the sides of each sample. The sacrificial material shown in Figure 1 was carefully removed using a sharp blade and disposed of safely.

For dynamic testing aluminum moulds were used to create material sizes of 9" × 4" × 4". Aluminum was used as a readily available, cost-effective solution with good temperature stability within the ranges required for this study [105]. $n = 3$ was used to ensure sufficient data analysis could be conducted post-test and ensure no anomalies in the dataset.

Table 1 provides a summary of all materials used in this study. Further information on each material can be found within the following sections for small-scale tests, with the larger mould sizes detailed above. All materials were manufactured individually and poured into the moulds before either being placed within a fridge set to 3–5°C or left at room temperature to set. Prior to any material manufacture, the sides of the mould were sprayed with DWR plastics liquid wax release agent to reduce the probability of the material from becoming damaged during decanting.

2.2 | Ordnance Gelatine

2.2.1 | Ballistic Gelatine

Hundred gram of Gelita Ballistic 3 Ordnance gelatine powder was incrementally mixed with 1 L of fresh water, which was preheated to 70°C [5]. A liquid wax release agent was applied to the sides of the mould before the gelatine mixture was poured into 12 moulds. Twelve moulds were initially made to ensure a minimum of $n = 6$ was achieved successfully, due to the risk of damage during decanting. Once rested, the moulds were placed inside a fridge set to 3–5°C for 48 h [5, 6, 56, 110, 111].

Three differing resting methods were explored within this study to reduce the quantity of bubbles within the material. This has been highlighted as a key issue, yet not studied within the existing literature. The following conditions were chosen to investigate how sample rest duration and temperature influence the reduction in bubbles when compared to performance:

1. Rest at approximately 21°C for 2 h (six successful samples).
2. Rest at approximately 18°C for 6 h (room temperature—12 successful samples).
3. Rest within a bowl of 70°C hot water to match the temperature of the gelatine mixture and left to cool to room temperature (20°C) for ~2 h. This prevented the gelatine from curing too fast and allowed for 100% of the bubbles to escape the material, resulting in nine successful samples).

Material used within dynamic testing was conducted using the 18°C methodology, which was proven to be more advantageous during quasi-static testing.

2.3 | Traditional Foodstuffs Gelatines

2.3.1 | Cubed (Ready-Made) Food Stuffs Gelatine

Nine packets of Hartley's Lemon Jelly were sourced from a major UK supermarket [106]. Two ratios of 1:1 and 1:2 (jelly:water) were initially investigated. These ratios were selected due to the promise seen during a previous study [59] that concluded that the mixture recommended by the manufacturer did not produce the required density or elasticity to both deform under load and recover from a low-velocity projectile impact; however, post-cure it was observed that the material did not contain the required viscosity for test and was therefore negated from the experimental



FIGURE 2 | 25 mm diameter Hartley's Jelly sample highlighting tearing to the outside surface during decanting.

work. It was, therefore, concluded that a 1:0 (jelly:water) ratio should be investigated.

To generate a ratio of 1:0 (jelly:water), three packets of jelly cubes were placed into a 1 L beaker and heated using an 800 W microwave for 60 s. This was stirred and left to rest for 10 min. The rest period was crucial to enable any bubbles within the mixture to rise to the surface and burst. Once complete, the mixture was poured into 15 moulds and placed inside a fridge to set for 24 h at 3–5°C.

Decanting of the 15 moulds resulted in five samples containing excessive damage to the outer surface of the material (Figure 2). This is assumed to be due to the material's sugar content acting as a binder, which was in greater quantity compared to the release agent, which was applied to the internal surfaces of the mould before each sample was poured. For this reason, only 10 samples were of sufficient quality to be tested.

2.4 | Powder Form Food Stuffs Gelatine (Manufacture Required)

Two hundred forty bloom pork gelatine powder was sourced from an online marketplace [107]. This was mixed in ratios 1:4 and 1:6 (powder:water) to better explore how the viscosity of materials can affect their performance. 1:4 was selected as the minimum viable ratio due to viscosity concerns during manufacture. Gelatine powder mass was measured using a calibrated scale (± 0.5) before adding boiling water and stirring by hand. The gelatine:water mixture was placed inside an 800 W microwave for 60 s and stirred before allowing to rest. Like other materials within this study, the rest period allowed for any bubbles to rise to the surface, thereby allowing for greater transparency and reducing the probability of degrading material performance by inducing localized weak spots [5]. The mixture was poured into 15 moulds per ratio and placed within a fridge set to 3–5°C for 24 h.

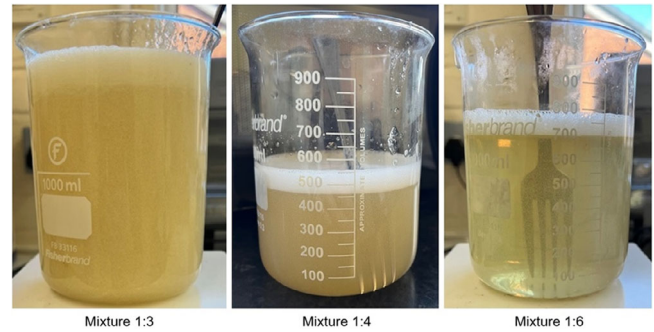


FIGURE 3 | Powder gelatine ratios (left 1:3, center 1:4, right 1:6) highlighting variations in mixture quality.

A ratio of 1:3 (jelly:water) was trialled using the same process listed above. It was noted that due to the density of the mixture, the bubbles could not rise to the surface, thereby hindering transparency and introducing an increased probability of early failure (Figure 3). For these reasons, this mixture was discounted from the test series reported below.

2.5 | Plant-Based/Vegan Gelatines⁴

3 | Agar Agar

Originally developed from Red Algae, Agar Agar's uses within the foodstuffs market are well known and used in a variety of food and beverage products. Delivered in powder form from Special Ingredients [109] ratios of 1:10 to 1:60⁵ in 0:05 increments were investigated to explore the influence water content may have on mechanical performance ($n = 5$). Ten gram of Agar Agar powder was added to the water volume required for the ratio being manufactured and left to bloom for 10 min as per the manufacturer's instructions. Once the gelatine had rested within the water, this was gradually heated to 100°C ($\pm 1^\circ\text{C}$) using a Bibby Sterlin CB162 hot plate, stirring constantly to ensure a homogenous mix was achieved [109]. On reaching the required temperature, this was poured into five moulds per ratio and left to set at room temperature (18°C).

Visual inspection during decanting confirmed all moulds manufactured using the method detailed above confirmed that the samples had cured correctly and did not contain defects. This confirmed the sample's viability for the test, the results of which are reported on within this paper (Figure 4).

4 | Carrageenan

Carrageenan is a dried red seaweed extract that has historically been used as a thickener in products requiring enhanced stabilization or gelatinization [112]. Delivered in powder form from Special Ingredients [108], initial ratios of 1:4 and 1:6 were explored to match that of commercial porcine gelatine despite the manufacturer's instructions stating that 0.2%–2% mixture should be used per constituent part. This mix was diluted gradually adding 100 mL boiling water and stirred vigorously until a final ratio of 1:30 was deemed viscous enough to pour into 15 moulds and placed within a fridge set to 3–5°C for 24 h. At 1:30



FIGURE 4 | Agar Agar ratios. Front: 1:60, rear: 1:20. Ratios decreasing in 0:05 increments from the front.

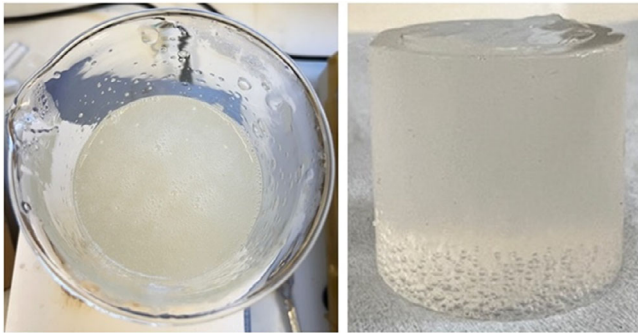


FIGURE 5 | Carrageenan Kappa. Left: Mixture of 1:60. Right: Decanted material at 1:60 ratio.

ratio the percentage of product per constituent part was 3.13% highlighting that within food-based products, the mixture would have required further dilution further emphasizing that this was the minimum viable pour achievable. Five further moulds of 1:15–1:60⁶ in 0:05 increments were made, respectively, to provide a greater understanding of how increased ratios may increase material performance (Figure 5).

5 | Set Up and Method

5.1 | Quasi-Static Testing

Figure 6 shows the Zwick Materialprüfung 1445 universal testing system was utilized to undertake the work presented within this study. The machine was configured to measure force (N) against displacement (mm) in compression testing with the bottom platen remaining fixed and the 1 kN load cell (top platen) allowing for a small degree of movement using a ball joint to ensure load was applied uniformly across the sample.

To ensure statistical analysis could be conducted post-test, six repeats per material were undertaken and the results were recorded using TestXpert II software. A constant crosshead speed

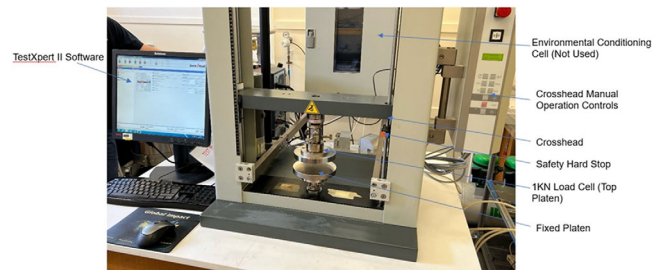


FIGURE 6 | Zwick 1445 universal testing machine set up.

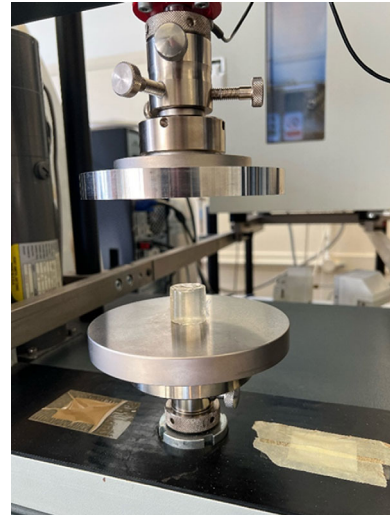


FIGURE 7 | Gelatine sample located centrally within the 1 kN load cell prior to testing.

was set to 5 mm/min. Initially, 25 mm/min was selected, however, on completion of three tests using control samples, this was discounted due to insufficient definition on the output graphs.

All samples were tested within an ambient temperature laboratory (18°C). The samples were located centrally between the platens (Figure 7) prior to starting the test. Any material defects or points of interest were noted prior to test. Before beginning the test, the top platen was brought within 1–2 mm of the top surface of the material before adding the input value as the start position. This minimized the need for pre-load and accounted for any sample size variability. Post start position identification, the force was zeroed to ensure the initial point of contact could be easily identified. During the test, the data were captured using the TestXpert II software and once completed, exported to Excel for analysis. To increase the understanding of the material's response to the applied load, a 10Mp Velbon CV Mini video camera was located centrally in front of the sample and set to record using a 320 × 240 resolution and 30 fps. The camera was linked to the TestXpert II software and programmed to start/finish recording on test start/completion.

5.2 | Dynamic Testing

A single 4.5 mm AISI420 stainless steel ball bearing was housed inside a plastic sabot that had been pre-stressed to increase to



FIGURE 8 | 4.5 mm ball bearing inside plastic sabot.

TABLE 2 | Phantom V12-12 settings.

Phantom V12-12
Resolution = 896×352
Frames per second = 28 000 fps
Exposure = $5.00 \mu\text{s}$
Calibration = 0.337 mm/pixel
0.304 mm/pixel (Day 2)

probability of separation at 180 ms^{-1} (Figure 8). The ball bearings each weighing 0.4 g were visually inspected before being placed inside a plastic sabot to minimize the amount of lost energy caused by air passing over the surface of the projectile. This was loaded to the single stage ELVIS gas gun breach before the target sample was placed on an elevated table within the target chamber and positioned to align centrally with the 8 mm diameter gas gun barrel. Once content with sample location, a high-powered light was used to highlight the samples transparency.

The gas gun was pressurized to 3.5 bar of air ($\pm 0.5 \text{ bar}$) to achieve an output velocity of 180 ms^{-1} ($\pm 5 \text{ ms}^{-1}$) and fired from a remote position. The velocity of the projectile was calculated using an oscilloscope, which used two independent light gates to measure the projectile time of arrival between each gate.

To capture both projectile and material response, a Phantom V12-12 high-speed video camera was used, the settings of which can be found in Table 2. Post experimental campaign, analysis of the high-speed video footage was undertaken using PCC software at version 3.7.802.0 (Figure 9).

6 | Results and Discussion

6.1 | Material Dependence on the Manufacture Conditions

Figure 10 shows the results for the 10% gelatine samples rested at 21°C . It is noted that the displacement over time curves, and therefore stiffness, remain similar across all tests when compared to material exhibiting the highest maximum applied load at sample failure. Sample failure throughout this manuscript refers to the sudden decrease in applied load. All samples had good repeatability, however some variance was noted. Specimen 5 which reached a maximum force of 16.61 N at 12.33 mm displacement which suggests this result is an outlier and is proposed to be a result of microscopic defects within the material

triggering the early failure. Regardless of the load applied, during deformation materials exhibited a barrelling response which was not considered problematic during this study due to an evenly applied load and, therefore, reduced risk of failure from shearing. While no direct measurement of elastic recovery was considered due to previously being reported within the wider literature [28, 32, 33, 113–115], a high-level comparison based on visual observation was conducted. This approach was considered more advantageous as visual observation of both permanent and temporary cavitation is crucial in determining the severity of projectile impact and its trajectory throughout the medium [1, 59]. In addition, the approach enabled the researchers to understand both current and future material limitations to help inform further work in high-strain-rate impact are met.

Visual inspection during compression on Specimen 3 showed localized failure inside the material at 36.08 N (reducing to 35.53 N) before a maximum force of 41.14 N was applied. This is believed to be due to increased stress on a small area that was proud of the surface produced as a result of not removing the sacrificial material parallel enough during decanting of the material.

Similar to the 21°C samples shown in Figure 10, the samples rested at 18°C ambient temperature also exhibited a similar rate of displacement over time (Figure 11); however, a qualitative assessment showed these samples had a reduction in the quantity of bubbles, which was vital to increasing the material's strength. This finding is consistent with the various manufacturing methods within the literature [5, 6, 56, 110, 111]. The reported longer duration rest at temperatures within the literature are more consistent with the 18°C samples in this study, enabling bubbles to be removed in a controlled manner without the material setting at an excessive rate [5, 6, 56, 110, 111]. It should be noted, however, that the literature does contain variations such as cure temperature and durations that could alter the performance of the material [10, 28]. To evidence this, Figure 11 shows the applied load and deformation of samples at 18°C . Of highlight is that Specimen 1 was able to withstand a maximum force of 120.08 N before failure. This is an increase of 70.725% when compared to the highest performing (57.34 N) sample rested at 21°C . It can be seen that all samples rested at 18°C are able to withstand a higher applied load and deform more consistently (Table 3). By comparison, Figure 12 shows the results for samples that rested in 70°C water during manufacture. It can be seen that seven of the nine samples failed when a minimal load was applied.

During visual inspection of the samples, it was observed that a pitted surface (Figure 13) was present on one side of the sample, which is thought to be caused by the merging of the gelatine material and release agent applied to the moulds during time in the water bath. However, this pitting phenomenon was only present in 50% of the specimens that rested within the water bath and was not present in any other sample presented within this work. The extended duration at high temperature would have allowed the two liquids to mix and, therefore, cause an inconsistent surface. As the applied load was gradually applied, a different deformation pattern was observed (Figure 14) when compared to the more common barrelling deformation seen within this study and the wider literature [33, 44, 113, 115]. Further visual inspection of the top platen of the equipment



FIGURE 9 | ELVIS gas gun set up [59].

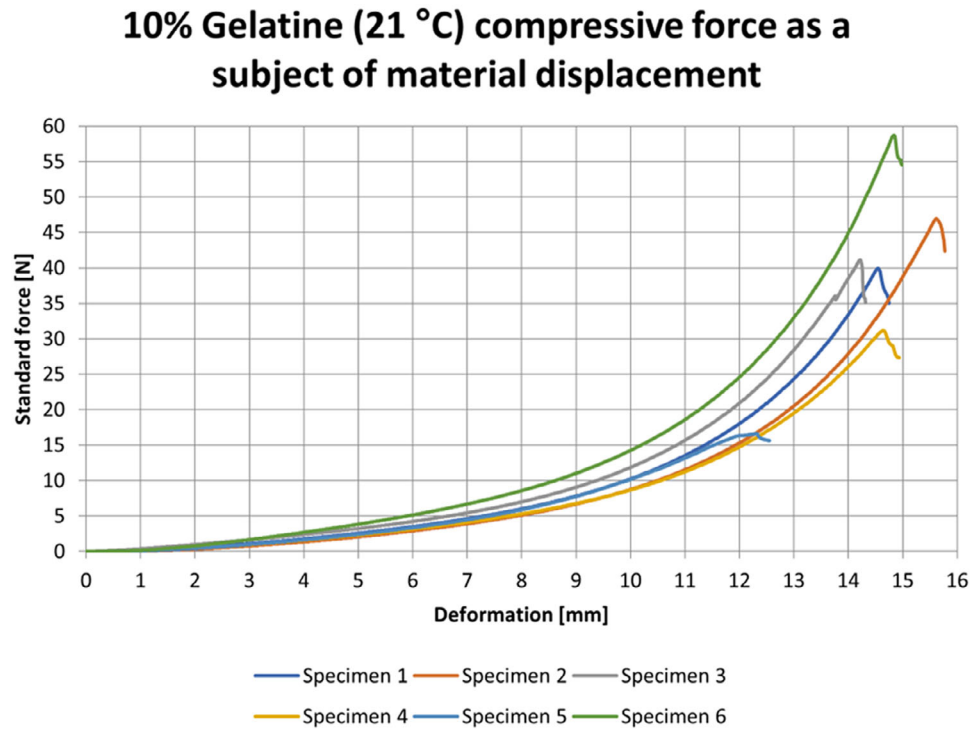


FIGURE 10 | 5 mm/min compressive force as a subject of material displacement on 10% ballistic gelatine (21°C).

TABLE 3 | Comparison of sample performance against the material manufacture's temperature.

Material	Average Fmax (N)	Std. Dev.	Average displacement (mm)	Std. Dev.
21°C samples	45.90	22.74	15.33	2.54
18°C samples	93.05	13.14	14.64	1.18
70°C samples	23.30	15.86	11.42	1.54

revealed machining marks present within the center. These minor inconsistencies will have contributed to excessive friction on the inconsistent face of the material, resulting in failure earlier than anticipated and an uneven distribution of force resulting in the abnormal deformation. To further explore this,

Specimens 4 and 5 were rotated to allow for the rough surface to be located on the bottom platen and smooth face on the top platen. Although similar failure modes were witnessed during test, the failure continued to begin around the pitted face regardless of orientation.

10% Gelatine (18°C) compressive force as a subject of material deformation

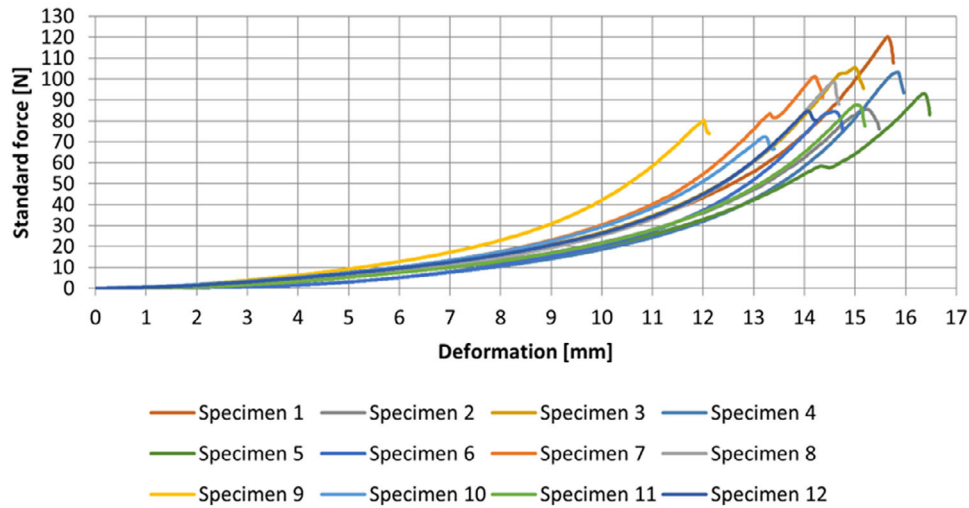


FIGURE 11 | Ten percent gelatine (18°C) compressive force as a subject of material deformation.

10% Gelatine (70°C water bath) compressive force as a subject of material deformation

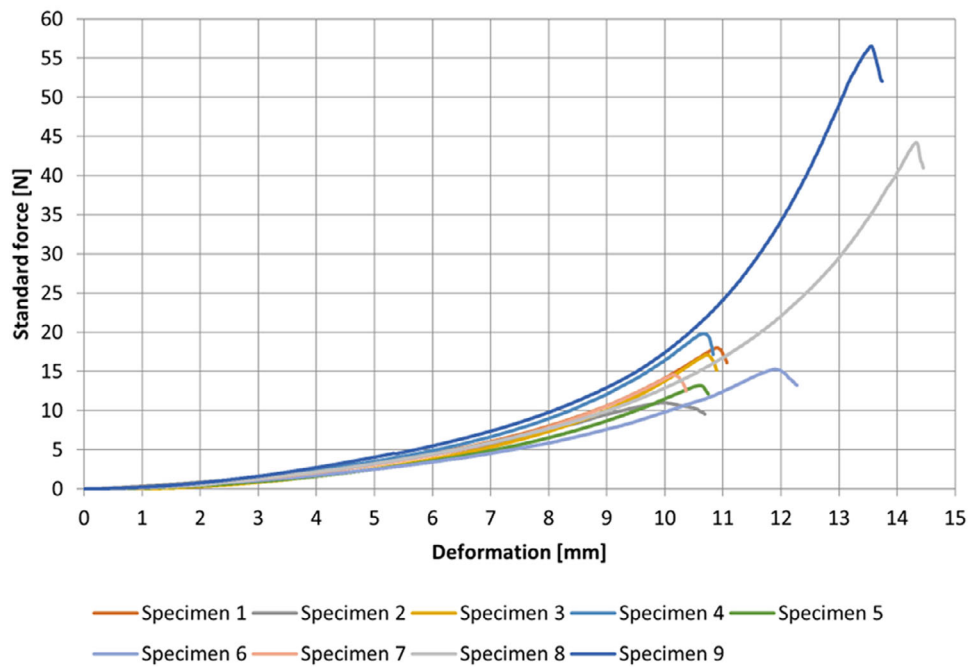


FIGURE 12 | Ten percent gelatine (70°C water bath) compressive force as a subject of material deformation.

Specimens 6–9 also explored orientation with regard to face deformation. These specimens did not contain pitted surfaces but did contain minor burring around the outside due to decanting and removal of waste post-decanting. Figure 12 shows that Specimens 8 and 9 exhibited an increase in performance when the face that contained burrs was facing the top platen. This phenomenon is proposed to be due to the freedom of movement in the top platen, which results in a more dynamic load application when

compared to the bottom platen, which is fixed. When considering highest performing pitted specimen from the samples rested in a water bath and the samples rested at ambient temperature, the difference in applied load is 143.3% (100.20 N) proving that temperature control during manufacture and the elimination of bubbles is key to material performance and thereby providing the research community with data that is not falsified by early failure of the test material. A qualitative assessment on the

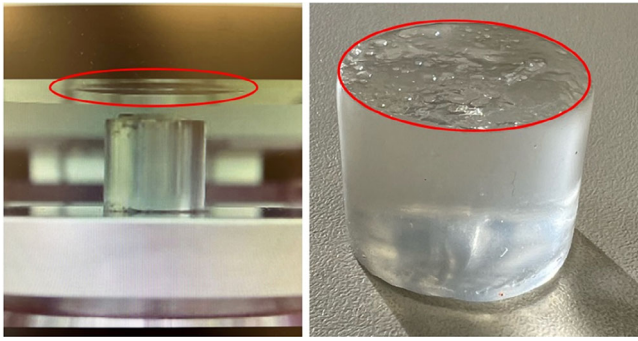


FIGURE 13 | Left: Top platen machining marks. Right: 10% gelatine pitted surface highlighted in red.

severity of bubble content of each sample ratio was conducted and confirmed that the higher the water content within the mixture, the higher the probability of reducing bubble content. It was observed that the denser materials will not enable bubbles to rise to the surface before the material begins to set, leading to voids within the material. As observed within this study, the more diluted ratios contain fewer bubbles. However, have been proven to perform less advantageously and, therefore, should be further explored to investigate the feasibility of additional constituent parts to increase the material strength and thereby ensure it performs as required. When carefully monitored, the temperature and mixture ratios ensure the probability of voids or defects within the material does not negatively impact on the material's performance through premature material failure, which may occur by sudden collapsing of the voids and thereby introducing a shearing failure.

6.2 | Quasi-Static Compression

Figure 15 shows the quasi-static compression of commercial foodstuffs gelatine powder, which was of porcine construction. The average applied load required to enable failure of the 1:4 ratio samples was 357 N compared to 135.16 N for samples at a 1:6 ratio, resulting in a 90.16% difference in compressive strength. However, when compared to the average F_{max} (93.5 N) measured at material failure for 10% ballistic gelatine (Table 3), it is shown that this material can withstand a higher load at these ratios. Additionally, the deformation was marginally different, with a coefficient of variation (CV) of 3.97 and 6.20 mm for 1:4 and 1:6 ratios, respectively. This highlights the materials' repeatability when compared to the 8.06 mm CV value for the 18°C 10% gelatine samples. During compression, the samples exhibited a similar compression mode to the 10% ballistic gelatine samples, barrelling which became increasingly pronounced as the load was applied. By contrast to the 10% ballistic gelatine samples, the 1:6 and 1:4 samples made from powder gelatine showed an ability to recover to their original height, highlighting their elasticity. This is desirable to enable researchers to study the expansion and contraction of both temporary and permanent wound tracks and, therefore, provides a measurement of how severe an injury is [1, 3, 10, 13, 59, 110, 116–118]. Visual inspection of the video camera footage and post-test sample inspection resulted in the conclusion that the main failure mode for powder gelatine samples was shearing. However, post-test observation showed that only ~70–

80% of the length of the sample had sheared, which may have assisted in its ability to elastically recover to its original height [115]. Samples at the 1:6 ratio showed a comparable level of light transfer as the 10% ballistic gelatine (Figure 16). Samples at the 1:4 ratio were slightly more discoloured but would still be comparable to 10% ballistic gelatine with an appropriate light source. This is due to the lighting for assessment coming from natural light, whereas ballistic test experiments traditionally use high-powered lighting to ensure the best possible high-speed video footage can be captured. An increased discolouration of the Hartley's Jelly samples was apparent during inspection; however, this is assumed to be down to the flavouring which was included within the samples. A method to remove the flavouring from the gelatine should be explored as part of future work.

Figure 17 highlights the Hartley's Jelly samples' ability to deform without failure, with an average deformation of 21.49 mm. In all instances, the samples exceeded the working limit on the 1 kN load cell employed within this study, proving the material can evenly distribute load throughout its matrix, and provide an enhanced ability to recover elastically when compared to the previous materials under test. It should be noted that although the material was able to recover to within ~10% of its original height, the samples did contain permanent plastic deformation that did not decrease with time (Figure 18). This is not of concern to ballistic applications so long as the material can capture ballistic impact, and any temporary and permanent cavitation. To further explore the materials ability to withstand applied load when compared to 10% ballistic gelatine, Specimen 1 was retested. The authors observed a similar barrelling effect from the material during compression; however, the data points within Figure 17 show a form of hardening of the material was present with a reduction in deformation of 1.15 mm (5.96 %) over the original result. This result should be further explored in further work to further validate the materials ability to be used within multiple ballistic events before disposal.

Two differing types of vegan gelatine were explored to investigate whether any benefit could be found to using materials that do not contain animal products enhancing more ethical research methodologies and the ability to both reduce environmental impact and increase value for money within research programmes [1, 59, 60, 119].

Carrageenan Kappa and Agar Agar were chosen after qualitative investigation revealed their highly praised use in commercial foodstuff setting, the results seen in Figure 19. It can be seen that the Carrageenan 1:15–1:20 ratio yields higher results compared to the other ratios under test. However, 1:15 and 1:20 sheared under loading due to lack of elasticity which is essential in ballistic experimentation [1, 2, 9, 59]. 1:25 was proven to be the most advantageous as elastic recovery was witnessed, providing greater returns to shape and size once load was removed. Figure 19 shows the rate of deformation (by material) being very closely matched across all samples regardless of ratio. Carrageenan and Agar samples both deformed uniformly before failure but did not barrel which is a contrasting result compared to the 10% gelatine baseline experiments. Figure 19 also highlights the Agar Agar material being considerably stiffer with more applied load at the early stages of deformation when compared to Carrageenan. This increase in stiffness resulted in the material being unable

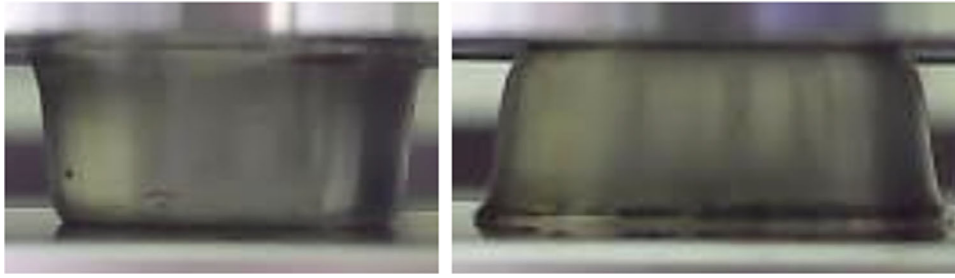


FIGURE 14 | Orientation influence on specimen deformation for 10% specimens with a single pitted surface.

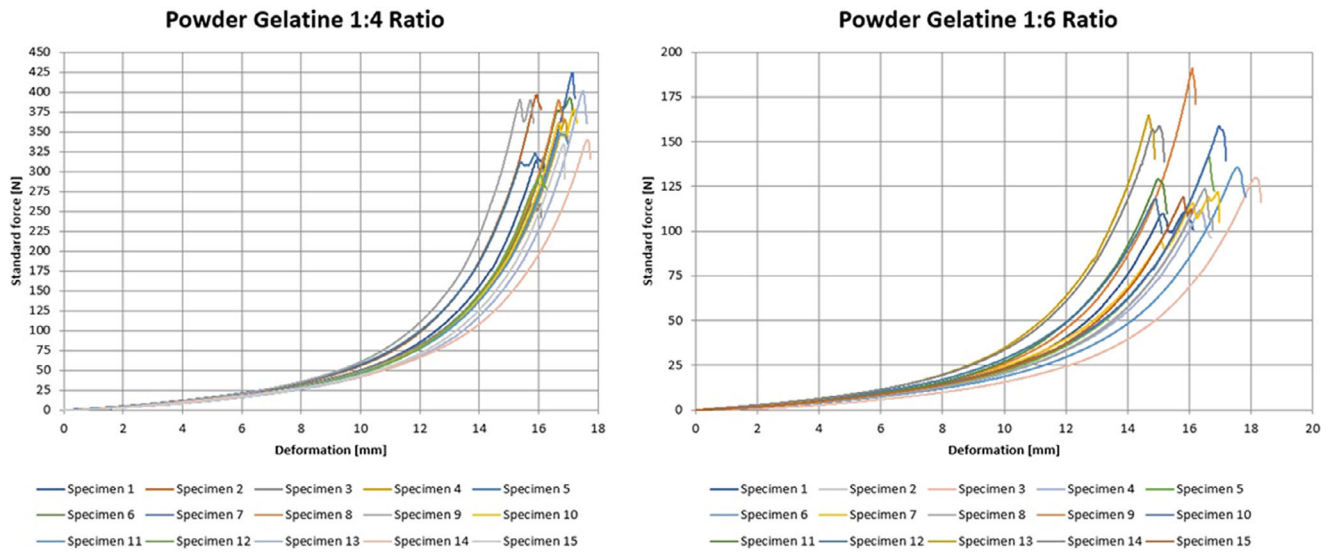


FIGURE 15 | Foodstuffs powder gelatine ratio comparison on performance.

to deform uniformly and subsequently resulted in early failure through shearing. This is not advantageous to ballisticians who rely on materials with higher elastic modulus regardless of applied load to monitor impact trauma and ammunition lethality [1, 2, 4, 120]. Standard deviations for average deformation across all ratios can be seen within Figure 19.

Table 4 and Figure 20 highlight each materials repeatability and ability to reduce variance within datasets which is extremely advantageous within the research community.

Post-test visual inspection of each sample within the whole data series was undertaken which highlighted that samples at higher ratios resulted in minor fracturing and a petaling failure which recovered elastically during platen separation. By contrast, lower ratios resulted in shearing and significant plastic deformation caused by minimal elasticity. No trends were revealed with the shearing failure occurring randomly throughout the material.

It was also noted that some samples had an inconsistent parallel top surface caused during the removal of the sacrificial material during decanting. Although not consistent with any sample type in particular, this inconsistent surface would have contributed to a localized increase in load and, therefore, increase the probability of premature failure. This was observed previously for the powdered porcine samples under test. However, all samples

that produced a failure mode most closely associated to fracturing were able to recover to within ~10% of their original height with some visual signs of plastic deformation still present. No barrelling of the samples was observed during test which is contradictory to the porcine gelatine samples tested previously, as load was applied to the samples deformation of the bottom surface occurred while the sides of the sample remained parallel to each other. Pretest inspection highlighted air bubbles within the material around the bottom surface. These were not distributed uniformly which was predicted would contribute to localized weak points within the material resulting in premature material failure. During test, audible noise of trapped air being ejected from the sample during larger air bubble collapse was heard, and witness by a small decrease in the load being applied to the sample which did not result in material failure, before continuing to increase to ultimate material failure. Air bubbles were present in all samples; however, the volume of air bubbles decreased as the ratio increased, with weaker ratios enabling bubbles to rise to the surface of the liquid before the material set. Sample density is, therefore, the main driver in air bubbles being present which was an identical observation made during porcine sample tests [5]; however, more diluted ratios had an adverse effect on performance by up to 82.96% in vegan gelatine. Air bubble presence could be avoided by placing the samples under vacuum, however, was not undertaken during this study due to a lack of available equipment.

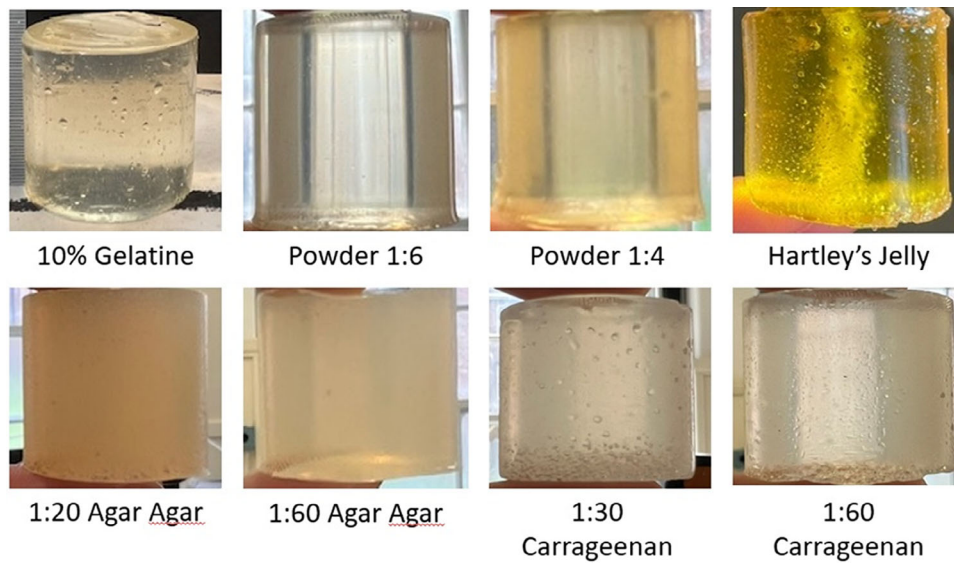


FIGURE 16 | Sample transparency assessment using natural light (all samples 25 mm dia × 25 mm high).

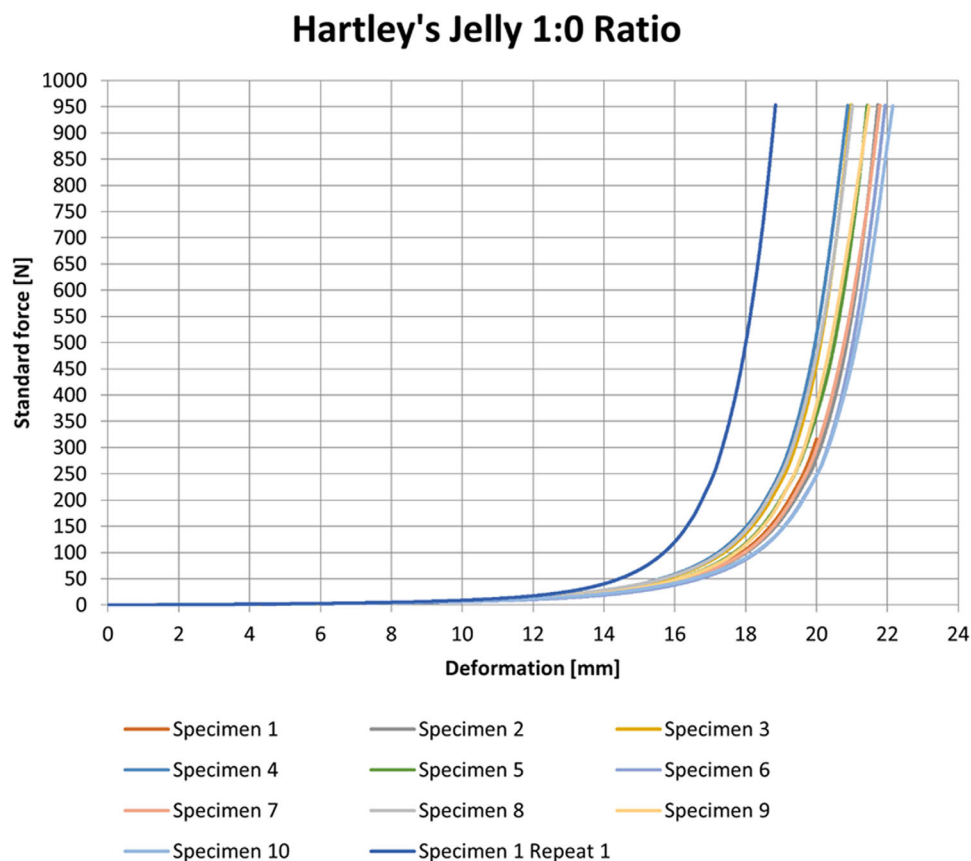


FIGURE 17 | Hartley's Jelly applied force compared against material deformation.

Manufacturing methodology is key to obtaining a material with sufficient homogeneity to perform advantageously. The manufacture of products containing porcine material was significantly easier to make, with less time and effort required to obtain the correct homogeneity. By comparison, samples that were made with vegan products were considerably more time consuming, taking an average of 10 min more per mould (excluding the

bloom period) and required an increased effort to mix correctly. It was observed that the Carrageenan Kappa raw product had to be poured incrementally into water; failure to do so or pouring water over the raw product would result in the raw product bonding together and requiring additional effort to mix. This was the only observed drawback of this material during manufacture. By contrast, Agar Agar required a longer time to

TABLE 4 | Average applied load (N) before material failure and average material deformation (mm).

Product name	Average max force at failure (N) One standard deviation in parentheses	Average deformation (mm) One standard deviation in parentheses
10% Ballistic gelatine	93.05 (13.14)	14.64 (1.18)
Gelatine powder 1:4	357.01 (45.45)	16.18 (0.66)
Gelatine powder 1:6	135.15 (23.45)	16.61 (1.00)
Hartley's Jelly 1:0	952.69 (0.71)	21.49 (0.46)
Agar Agar 1:10	81.52 (19.43)	6.75 (0.72)
Agar Agar 1:15	60.90 (12.04)	6.85 (0.62)
Agar Agar 1:20	51.03 (4.84)	6.59 (0.39)
Agar Agar 1:25	34.48 (4.39)	6.77 (0.72)
Agar Agar 1:30	34.74 (1.38)	6.46 (0.40)
Agar Agar 1:35	31.99 (0.68)	6.47 (0.51)
Agar Agar 1:40	25.63 (0.95)	6.79 (0.22)
Agar Agar 1:45	22.22 (1.17)	6.51 (0.43)
Agar Agar 1:50	19.04 (2.79)	7.31 (0.004)
Agar Agar 1:55	17.15 (0.82)	6.67 (0.30)
Agar Agar 1:60	13.89 (0.68)	6.49 (0.52)
Carrageenan Kappa 1:15	245.69 (59.73)	14.69 (0.65)
Carrageenan Kappa 1:20	166.28 (28.75)	12.64 (0.27)
Carrageenan Kappa 1:25	96.18 (5.33)	11.49 (0.18)
Carrageenan Kappa 1:30	83.04 (5.43)	11.79 (0.42)
Carrageenan Kappa 1:35	76.29 (5.02)	11.21 (0.47)
Carrageenan Kappa 1:40	63.55 (7.69)	11.31 (0.38)
Carrageenan Kappa 1:45	53.89 (3.27)	11.39 (0.36)
Carrageenan Kappa 1:50	42.83 (2.69)	11.07 (0.17)
Carrageenan Kappa 1:55	30.79 (3.44)	10.58 (0.65)
Carrageenan Kappa 1:60	28.23 (1.78)	10.58 (0.65)



FIGURE 18 | Plastic deformation on Hartley's Jelly samples. Rear: Smooth face located on bottom platen. Front: Smooth face located on top platen.

manufacture due to the 10-min rest period required for gelatine blooming and the need to gradually heat the mixture to 100°C before decanting into moulds can begin. The gradual heating alongside the need to continually stir throughout this process is significantly more labor intensive and results in increased time to manufacture per batch. Noting this experiment was on a smaller scale, Agar Agars applicability to a larger ballistic trial would

result in increased economic burden being driven into research programmes through time and resource required to manufacture. When considering materials which contain animal product, it is clear that vegan alternatives to increase time to manufacture. Powder and cubed foodstuffs gelatine was produced in less than 5 min per batch with minimal equipment. Although varying in methodology for manufacture, the time taken, and level of effort required for the materials containing animal based was comparable to the 10% ballistic gelatine to which this study is compared.

Regardless of sample ratio, Carrageenan Kappa showed transparency traits similar to that of Porcine Powder 1:6 samples shown in Figure 16—sample transparency assessment using natural light with the higher ratios showing marginally increased benefits but at the cost of performance. This is also true for the Agar Agar samples; however, transparency within the Carrageenan samples was superior to that of Agar Agar. Transparency is a vital trait to have for applications in wound ballistics, survivability, and lethality assessments and is a staple for ballisticians to examine wound tracks, ammunition performance, and behind armor effects during and post impact [1–4, 16, 58, 59, 110, 120], with

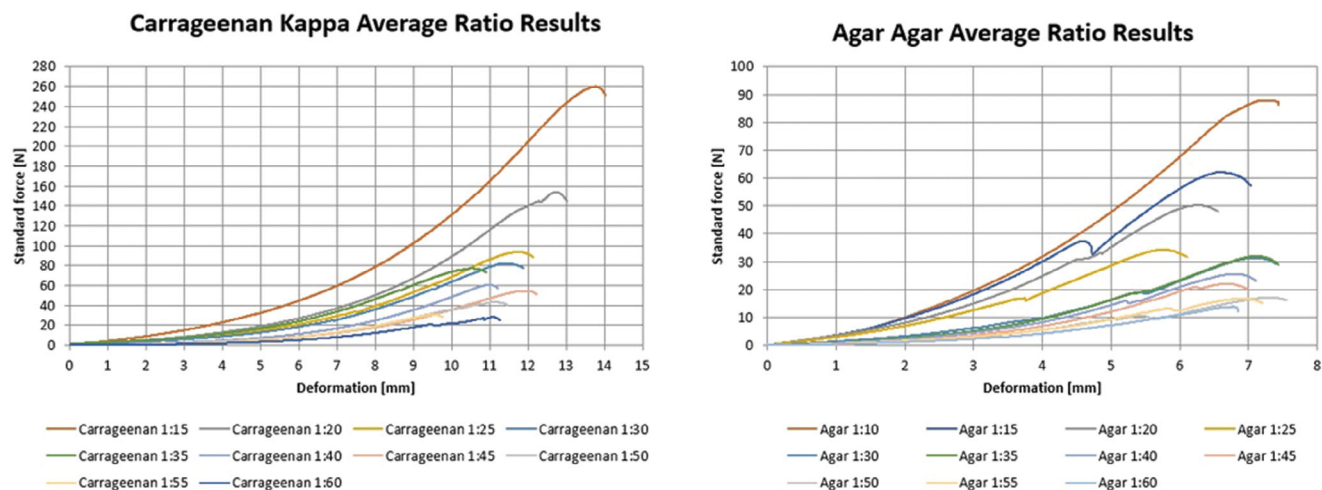


FIGURE 19 | Carrageenan Kappa performance under quasi-static compression compared to Agar Agar.

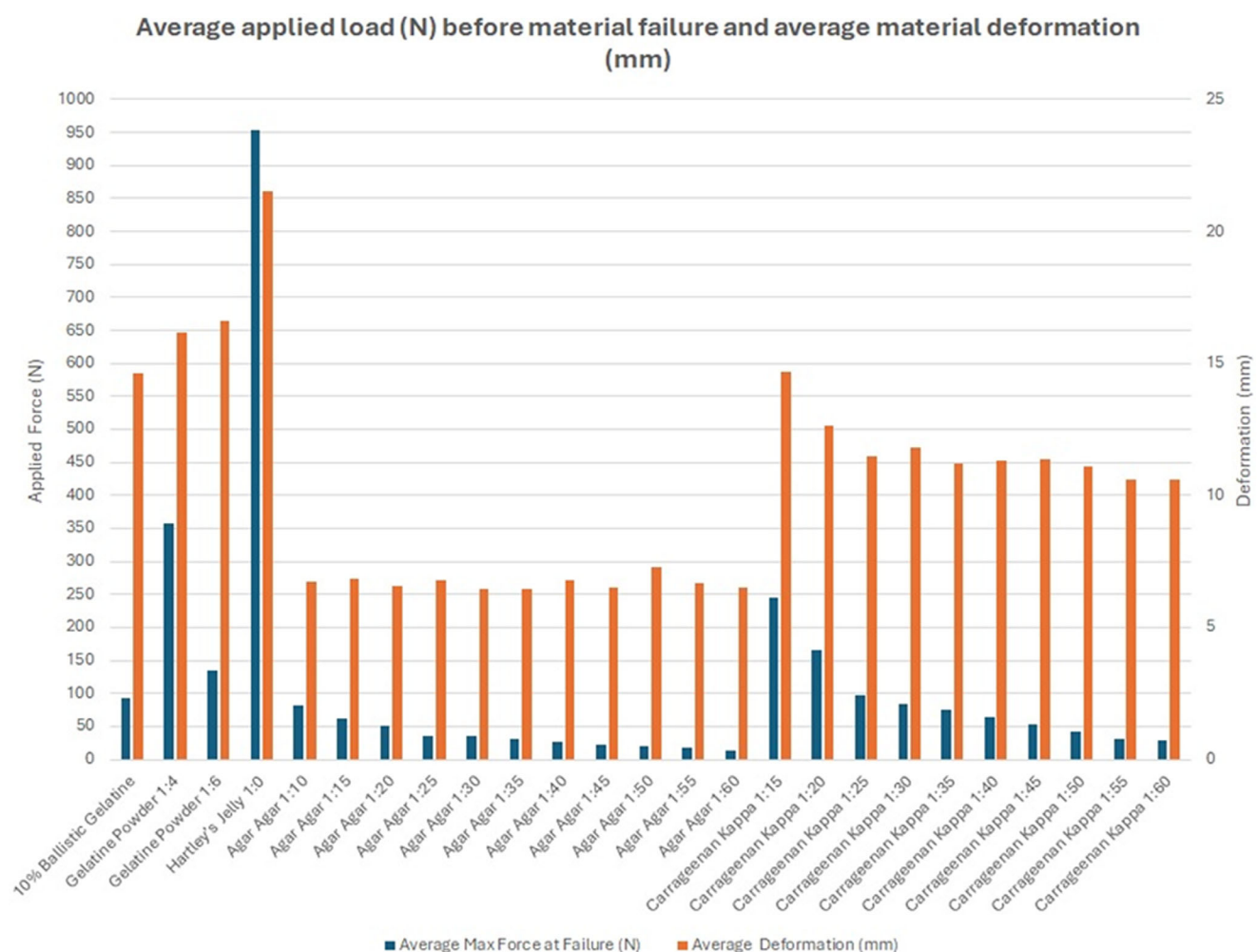


FIGURE 20 | Average applied load (N) before material failure alongside material deformation (mm).

Figure 16—sample transparency assessment using natural light (all samples 25 mm dia × 25 mm high), highlighting Carrageenan Kappa samples provided an increased clarity when compared to 10% ballistic gelatin, regardless of ratio. However, all samples within this study presented transparency traits that would enable

the research community to undertake visual and high-speed video analysis of the material's response to impact and cavitation without issue. This is true for samples of this size, and scaling of sample size is required to validate this result and confirm each material's viability in a ballistic setting.

Highest Performing Ratios Compared to 10% Ballistic Gelatine

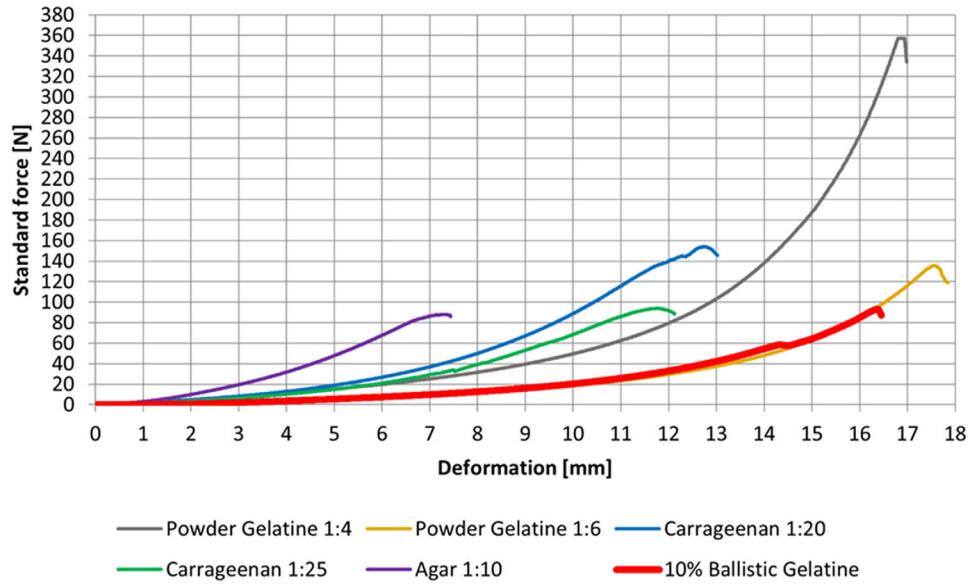


FIGURE 21 | Highest performing ratios compared to 10% ballistic gelatine.

Table 4 highlights the average applied load and average material deformation at material failure. Based on results in Table 4 and Figure 21, both powder porcine gelatine and Carrageenan Kappa are proposed for investigation under Fackler methodology to compare performance at higher strain rate conditions. Figure 21 highlights that certain ratios appear to provide better benefits than the material proposed (Powder Gelatine 1:4 and Carrageenan 1:20); however, the materials that show ability to withstand higher applied load before failure are considerably stiffer resulting in a shearing failure and did not provide elastic recovery which is a key mandate for materials used in survivability assessment. Cubed foodstuffs gelatine has been removed from Figure 21 due to the material averaging 952.7 N applied load without material failure, but is a candidate for further investigation as it did deform without failure and exhibited the ability to elastically recover with minimal plastic deformation. This down-selection of materials (Powder Gelatine 1:6, Carrageenan 1:25, and Cubed Gelatine) for further investigation is not solely based on the material's ability to withstand applied load and elastically recover but also how repeatable the material is, as evidenced by standard deviation, thereby resulting in more accurate datasets.

The results of the quasi-static compression testing have been compared to the wider literature to investigate the feasibility of using alternative materials to ballistic gelatine and inform future work. The review found that the literature was lacking in this area; however, an assessment method for characterizing alternative polymer materials was found to include both mechanical (tensile and shear) and optical [121]. This study did not focus on the depth of penetration using a velocity-driven projectile, but did focus on material deformation to investigate elastic and failure characteristics of materials under tests, thereby confirming the areas of investigation for this study are valid, albeit in compression. The focus on global compression for this study has been driven by the need to focus not exclusively on

the temporary and permanent cavity but rather focus on the use of ballistics gelatine as a Behind Armour Blunt Trauma (BABT) injury assessment material [1, 16, 59, 122]. Additionally, where experimental testing has included backing plates to ensure the test material does not move during projectile impact, the material is subjected to a compression-related impact and subsequent compressive shock wave throughout the material [122].

It should be noted that quasi-static testing alone cannot confirm a material's suitability for use within a ballistic setting, but rather provides evidence that commercial off-the-shelf materials can be sought to provide greater economic benefit and reduced environmental impact caused by supply from countries outside of the United Kingdom. To better understand material suitability within a ballistic environment, a Low Velocity Impact System was used to validate the results seen during quasi-static experimentation.

6.3 | Dynamic Testing

A down selection of materials was conducted using the results produced during quasi-static experiments. The 10% ballistic gelatine was used as the benchmark and tested using the Fackler methodology to confirm calibration and, therefore, suitability for the test [5, 10, 123]. Calibration of mediums associated with wound ballistics and lethality assessment is paramount to ensuring an accurate dataset is generated from experimentation. The Fackler methodology has been used since 1985 as a trusted standard to which many government institutions and research establishments have successfully produced high-ranking datasets using 10% gelatine.

The Fackler method was repeated across the down-selected materials and produced the results seen in Table 5, with 8.5 cm $\pm$ 0.5 cm as the success criteria.

TABLE 5 | Dynamic testing results.

Material	Pass	Fail	Input velocity (ms ⁻¹) when fired at 3.5 bar	DoP result (cm)
10% Gelatine #1	X		178	8.69
10% Gelatine #2	X		175	8.60
10% Gelatine #3		X	161	7.84
10% Gelatine #4	X		181	9.00
Carrageenan 1:20 #1		X	177	14.80
Carrageenan 1:20 #2		X	170	13.70
Carrageenan 1:20 #3		X	178	14.20
Carrageenan 1:25 #1		X	174	17.60
Carrageenan 1:25 #2		X	174	15.60
Carrageenan 1:25 #3		X	181	15.70
Carrageenan 1:30 #1		X	180	18.60
Carrageenan 1:30 #2		X	178	17.0
Carrageenan 1:30 #3		X	178	17.0
Agar 1:20 #1		X	185	Perforation 22 ms ⁻¹ exit velocity
Agar 1:25 #1		X	181	Perforation 36 ms exit velocity
Agar 1:30 #1		X	180	Perforation 34.8 ms exit velocity
Powder 1:4 #1		X	152	4.60
Powder 1:4 #2		X	175	5.87
Powder 1:4 #3		X	152	5.02
Powder 1:6 #1		X	153	7.48
Powder 1:6 #2		X	157	6.30
Powder 1:6 #3	X		165	8.55
Hartley's #1		X	160	5.26
Hartley's #2		X	164	5.26
Hartley's #3		X	164	5.35

It can be seen above that all samples bar one met the success criteria with an average depth of penetration of 8.76 cm. Specimen 3 of that batch was exposed to a lower impact velocity, which resulted in a smaller depth of penetration, this has been categorized as an outlier. This batch of material was manufactured from in-date raw product and manufactured in one mould before being decanted to smaller moulds, thereby ruling out batch-to-batch variability and confirming that input velocity was the key factor in not successfully meeting the pass criteria.

By contrast, both vegan gelatines failed to meet the pass criteria with results exceeding the 8.5 cm (± 0.5 cm) required. The main driver for this result is predicted to be the viscosity of the material; however, this was the minimum viable pour afforded to the authors with the equipment available. Additionally, the transparency of vegan gelatine when scaled resulted in an opaque appearance (Figure 22), meaning no high-speed video footage could be captured, and therefore, the depth of penetration was unmeasurable by video. This is disadvantageous for ballisticians

who are regularly required to assess ammunition lethality and behind armor effects such as shock wave propagation. The opaque nature of the material at scale is hypothesized to be due to the ratios employed within this study, which showed a close match to ballistic gelatine when exposed to quasi-static compression. More diluted ratios may result in a more transparent medium; however, this would come at the cost of performance and would need additional additives to be included within the manufacturing process to strengthen the polymer matrix. By contrast, all samples manufactured from traditional animal products were transparent in all ratios under test (Figure 23).

Gelatines which contained a raw product containing animal produce showed the opposite effect, with all results showing the depth of penetration insufficient enough to meet the success criteria. This was not predicted when reviewing the results from the quasi-static data. Quasi-static data show that 1:6 is the closest match to 10% ballistic gelatine which has been proven within a dynamic environment. However, Table 5 shows variability in

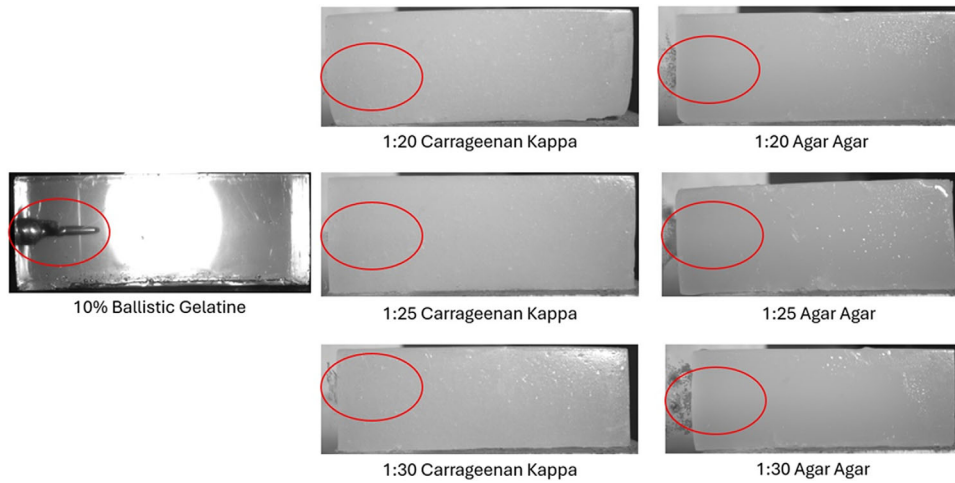


FIGURE 22 | Vegan gelatine transparency under HSV lighting.

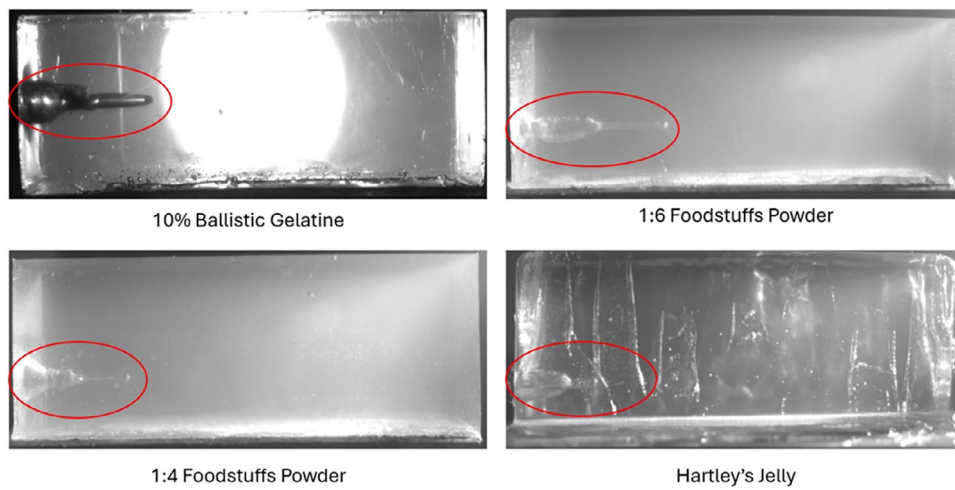


FIGURE 23 | Traditional gelatine transparency under HSV lighting.

input velocity. The samples under test were manufactured in a single batch being poured into smaller moulds, again ruling our variability triggered by batch-to-batch variation. Using a linear scale, it cannot be calculated the even with the required 180 ms^{-1} input velocity, the 1:6 material would have been the closest match to the 10% ballistic gelatine but would have still failed by being $\sim 0.65 \text{ cm}$ in excess of the success criteria.

Additionally, 1:4 and Hartley's was also proven to follow a similar trend to quasi-static testing in that more force was required to enable the material to deform and during dynamic testing, the input velocity of the ball bearing was not sufficient to enable the depth of penetration to meet the success criteria, which is contradictory to the vegan gelatine results. Table 6 highlights the pros and cons of the options presented within this paper with key observations noted.

The results shown within Table 5 highlight that quasi-static testing alone cannot confirm a materials suitability for use within a higher strain rate environment, with results offering no correlation to each other using any metric. Analysis of the video footage has shown that the materials response globally varies

significantly to the local response seen during projectile impact. Research conducted in 2011 explored quasi-static compressions when compared to a flywheel impact machine and a split Hopkinson bar test [32]. The graphs within this research also show that gelatine reacts very differently under higher velocity impacts and no correlation between quasi-static and more dynamic testing can be made.

It is noted that the use of global compression testing alone cannot be used to quantify material performance. Rather, this method of testing can be used to assess material feasibility at a small scale before justification for additional studies. Further work will investigate the use of indentation tests with a spherical impactor with the aim of providing a more detailed investigation as to why the samples within this study are behaving so differently under higher strain rates.

7 | Conclusions

Previous experimental investigation on alternative materials for use within survivability assessment had revealed promise

TABLE 6 | Material pros and cons summary table.

Material	Pros	Cons	Key observations
10% ballistic gelatine	Ease of manufacture Transparency Calibration standard	Price Time-bound Single use Single supplier	Superior transparency. Can only be tested with conditioned material. Material calibrated to Fackler method.
Powder gelatine	Price Easy to mix Transparency Many suppliers	Refrigeration required	Time to mix was equivalent to 10% ballistic gelatine. Transparency acceptable at ratios tested.
Hartleys gelatine	Ease of manufacture Transparency Many suppliers	Price Sugar content Refrigeration required	Time to mix was equivalent to ballistic gelatine. Economies of scale could be had using direct manufacturer to reduce cost. Sugar content increased probability of damage to sides of samples as a result of sticking to sides of moulds. Transparency was acceptable at samples tested.
Carrageenan Kappa	Price Sets at room temp Many suppliers	Time to mix Effort required during mixing Transparency (at scale)	Time to mix is ~10 min greater than traditional gelatines. Samples were opaque at scale using the ratios chosen—differing from quasi-static small scale samples.
Agar Agar	Price Sets at room temp Many suppliers	Time to mix Effort required during mixing Transparency (at scale)	Bloom period required (10 min) Time to mix is ~10 min greater than traditional gelatines Samples were opaque at scale using the ratios chosen—differing from quasi-static small scale samples.

for foodstuffs gelatine. Foodstuffs gelatine can be purchased locally, eliminating the cost and environmental impact associated with delivery of materials from foreign nations, thereby further aligning with local, national, and international ambitions for reductions in environmental impact and delivering increased value for money to the research community.

This work has investigated quasi-static compression testing of 10% ballistic gelatine as the industry standard and compared the results against a powder and cubed porcine foodstuffs gelatine variant and two vegan alternatives to explore any differences in performance. The results of which have shown that when a controlled load is applied at 5 mm/min, foodstuffs porcine gelatine in both powdered and cubed form, and Carrageenan Kappa have produced results greater than that of 10% gelatine when considering both applied load, material deformation, transparency, and repeatability. This work provides a significant single point of source data for researchers to consider alternatives that provide increased levels of performance during small scale testing and at low strain rates.

However, when sample size was scaled up and exposed to dynamic experimentation results have shown that there can be no correlation to quasi-static compression results. Quasi-static compression testing alone does not provide a robust enough dataset to examine new materials suitability within higher strain rate environments. Further, the differences between global and local material response differ significantly and global responses alone should not be relied upon to provide an accurate investigation.

Further work should be conducted to investigate “blended mixes” to examine whether increased mechanical properties are produced when multiple gelatines or additional materials used to strengthen materials (i.e., corn starch) are included within a single mixture to further enhance the materials applicability within survivability assessment and wound ballistic experimentation. Additionally, the optimal rate for bubble diffusion within material samples has yet to be determined, the work conducted within this study was determined by author discretion; however, a study into rate variance would be beneficial to sample consistency.

Endnotes

¹ It is noted that Perma-Gel and Ballistic Soap are also available for use as a “bulk simulant” in a ballistic testing. However, as both materials are not part of this study they have not been further described during the introduction.

² Deeper understanding of the manufacturing process was requested by several gelatine manufacturing organizations. Nil responses were given, which was assumed by the authors to protect intellectual property right and techniques.

³ Deeper understanding of the manufacturing process was requested by several gelatine manufacturing organizations. Nil responses were given, which was assumed by the authors to protect intellectual property right and techniques.

⁴ Pectin was considered as part of this experimental campaign but was discounted due to its primary use being a thickening agent for jams and jellies as opposed to a product made specifically for generation of gelatine.

⁵ 1:05 ratio was attempted to be manufactured. Post bloom inspection revealed a non-homogenous mix due to lack of water content. This ratio was, therefore, discounted.

⁶ 1:05 and 1:10 ratios were manufactured but found to be not homogenous enough due to lack of water content. These ratios were too thick to pour and, therefore, discounted.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data supporting this study are openly available from the corresponding author on request.

Institutional Rights Retention Policy

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