THE EFFECT OF GELATIN COMPOSITION ON ITS STIFFNESS, PUNCTURE FORCE AND COHESIVENESS

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ABSTRACT

The many applications of gelatin rely on its unique mechanical properties, so understanding how various gelatin ratios affect puncture strength, cohesiveness, and elastic stiffness forms a basis for further research and innovation using gelatin. Puncture tests were performed on nine different gelatin percentages between 3-25% by mass weight to find the force and displacement over time with the Texture Analyzer. The puncture strength and cohesiveness for each concentration revealed an exponential relationship, and the pre-puncture behavior was modeled as a coupled spring system, with the elastic stiffness parameters k_s and L_0. Using the fits, the gelatin percentage needed can be found for a specified threshold puncture strength, cohesiveness, or elastic stiffness for applications in food industries, bioengineering, packaging research, and more.

INTRODUCTION

Gelatin, a functional biopolymer derived from animal collagen, has diverse and growing applications in science due to its low cost, high biocompatibility and biodegradability, and properties such as elastic stiffness, puncture strength, and cohesiveness [1][2]. We may recognize it most for its texture for culinary uses such as Jell-O, but it is also used to create skin care products, biodegradable packaging films and coatings, a majority of pharmaceutical capsules, scaffolds for tissue engineering, and more [3]. Since the many applications of gelatin rely on its unique mechanical and structural properties, understanding more about the stiffness, puncture strength, and cohesiveness of this material is important to study as a basis for further research and innovation.

Existing literature discusses the many uses of gelatin, the effect of different types of gelatin on material properties, optimal mixed solutions for structural purposes, and more. However, in the abundance of gelatin research, the direct relationship between gelatin percentages and material properties has been understudied because most research focuses on a specially designed gelatin composite material for a specific application. To investigate the effect of different gelatin percentages on associated mechanical properties, I measured the stiffness, puncture strength, and cohesiveness of a variety of gelatin samples to serve as a broader foundation for different applications.

In my study, I prepared a range of bovine gelatin percentages in ice cube trays and used a Texture Analyzer with a 3mm puncture probe to gather force and displacement data. The gelatin samples were created by using a standard kitchen scale to mix a percentage of gelatin powder and water measured by weight. Solutions were poured into half of the ice cube trays, leaving a gap in the tray between two batches for solution overflow that was not used in testing. Filled ice cube trays were then labeled and placed in the fridge to set. After at least eight hours, samples were taken out of the fridge and brought to room temperature for at least one hour. Using the Texture Analyzer's TA-52-3MM puncture probe, I collected the sample's force, displacement, and time data for further analysis.

The data presented by the Texture Analyzer included force vs. time and displacement vs. time. Using this, I created a force vs. displacement graph to extrapolate the elastic stiffness, puncture strength, and cohesiveness for each gelatin percentage sample, providing a basis for understanding of our experiment results. I then organized the elastic stiffness, puncture strength, and cohesiveness data by their gelatin percentages and analyzed, compared, and presented the relationship between gelatin percentages and resulting mechanical properties. As a result, given an elastic stiffness, puncture strength, or cohesiveness requirement, I can return a threshold for the gelatin percentage that meets the mechanical requirement. In this way, we can verify the statistical significance between gelatin percentages, and the results can be used to make more informed decisions for the many innovations using gelatin.

BACKGROUND THEORY

MATERIAL PROPERTIES OF GELATIN

Gelatin is derived from collagen, a structural protein. These proteins, or polypeptides, are chains of peptides held together by bonds. When gelatin is made, some of these bonds in the collagen, along with cross-linkages between polypeptide chains, are broken down. The unique properties of gelatin are demonstrated when it is dissolved in liquid. Once dissolved, the mixture of peptides starts reorganizing as a homogenous solution into structures through protein-molecule interactions. However, the liquid remains "trapped" in the protein network, thus creating the gel-like properties we associate with gelatin [3].

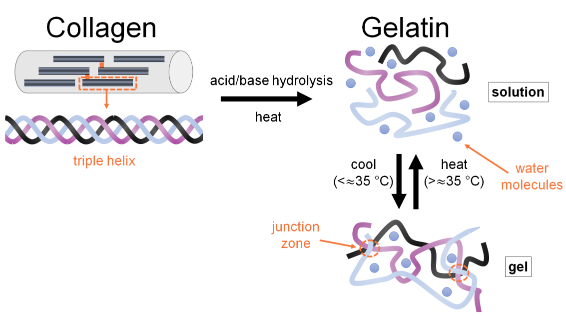

Figure 1: The breakdown of collagen to form gelatin. As gelatin is dissolved using heat and reforms its structural network while cooling, water molecules stay trapped in spaces in the gel because of the junction zones in the gelatin network [4].

Prior research in material science and polymers has provided insight into the impact of polymer composition on mechanical properties. For instance, research on a polymer-based gel revealed how increasing polymer concentrations resulted in more solid and less viscous material [5]. Another study found that the stress and strain of a ballistic gel increased with three increasing gelatin percentages, but focused on presenting a method for obtaining strain of ballistic gelatin [6]. Additionally, there has been much exploration of how different types of gelatin and gelatin composites affect stiffness [1]. While these studies offer relevant methodologies and insights regarding polymer's mechanical properties and uses, our research aims to specifically address gelatin and delve into its mechanical properties concerning stiffness and puncture force.

MECHANICAL PROPERTIES OF GELATIN

Once gelatin sets and becomes a solid structure, there are many mechanical properties applicable to solids and polymer gels that can be measured. It is important to note that gelatin has an existing standardized measurement, bloom strength, which refers to gelatin's rigidity before puncture. This tests the strength of the gel, and the "optimal" strength depends on its application. However, when testing bloom strength, the sample shape, size, maturation temperature, time, instrumental parameters, and gelatin concentrations are fixed [1]. As a result, although bloom strength is a very standard measurement for gelatin composites, it is not applicable when testing various concentrations of gelatin.

A study on an array of different gelatin types and derivatives measured mechanical properties using a Texture Analyzer. Using puncture and compression tests, data was gathered and extracted relating to cohesiveness, gumminess, puncture strength, melting properties, stiffness, and more [1]. These mechanical properties are relevant to gelatin because they define how the gelatin can be used. For example, gelatin with high puncture strength would be suitable for applications that need to resist puncture, whereas it may not be suitable in the food industry as it would make the gelatin harder to chew. These properties be measured when manipulating gelatin percentages. Although the study applied its results to gelatinous desserts, our study focuses on elastic stiffness, puncture strength, and cohesiveness for broader gelatin usages.

ELASTIC STIFFNESS, PUNCTURE STRENGTH, AND COHESIVENESS

Elastic stiffness, puncture strength, and cohesiveness play a substantial role in the performance of gelatin materials. Elastic stiffness defines a gelatin's ability to support loads, which is especially useful in its structural applications. Puncture strength influences the durability of the gelatin when encountering external piercing forces, such as packaging materials, fingernails, sharp objects, or even chewing. Cohesiveness determines how gelatin adheres to itself under compressive stress which is important for material durability. Understanding the factors that influence stiffness, puncture force, and cohesiveness is crucial for designing products that meet specific performance criteria.

Elastic stiffness quantifies a material's resistance to deformation when subjected to an applied force. Because gelatin materials are not solids, their stiffness is not constant. Instead, gelatin samples can be modeled as coupled springs shown in Figure 2:

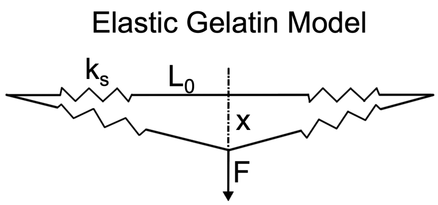

Figure 2: The coupled spring model for gelatin to find the effective spring constant k_s and unstretched spring length L_0 [7]. As F increases, the springs stretch and displace.

Gelatin's elastic stiffness can be modeled as a coupled spring model and uses the measurements of the applied force as well as the displacement to find the effective spring constant (k_s) and unstretched spring length (L_0) [7]. The equation relating L_0, k_s, and F is as follows:

$$F = x\left(k_s - \frac{1}{\sqrt{1+(\frac{x}{L_0})^2}}\right) \qquad (1)$$

Puncture strength pertains to the magnitude of force required to puncture the material. In our force vs. time data, this can be defined as the maximum force in Newtons that is applied to a sample. At this peak force, the sample ruptures. As the probe retracts up through the sample after puncture, the negative integral of negative forces is the cohesiveness. In other words, cohesiveness is the amount of force it takes to remove an item from the material mass.

These properties are important in determining the suitability of gelatin compositions for specific applications. The study focuses on measuring stiffness, puncture strength, and cohesiveness to understand how gelatin percentages can play a role in manipulating these mechanical properties.

EXPERIMENTAL DESIGN

The experimental design guided the investigation of mechanical properties for gelatin samples with varying gelatin percentages. The primary focus was on obtaining data that pertained to puncture strength, cohesiveness, and elastic stiffness to see how these properties related to gelatin percentage.

CREATING AND TESTING GELATIN SAMPLES

Gelatin samples were created with gelatin percentages ranging from 3% to 25% by mass. NuNatural's bovine gelatin powder was weighed using an AccuWeight digital pocket scale with a 0.01 gram accuracy. At the same time, water was boiled in a standard kettle and weighed to the specified gelatin-to-water ratio. Using a Vernier temperature probe, the temperature of the water was also taken to ensure that it remained within the range of 80 ± 3ºC throughout the process, minimizing the effect of temperature as a variable. Then, the gelatin and water were thoroughly mixed until there was a homogeneous solution with no visible clumps. The resulting solution for a specific percentage was then poured into an ice cube mold and left to set in a refrigerator for a minimum of 10 hours.

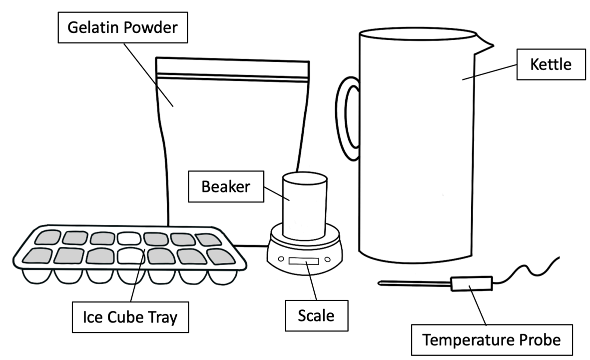

Figure 3: Setup for sample preparation. I used gelatin powder, water, a kettle for water heating a beaker, an AccuWeight digital pocket scale, a TMP20 Vernier temperature probe connected to a Vernier Go!Link, and an ice cube tray to hold samples.

The prepared gelatin samples were removed from the refrigerator and rose to the temperature of the testing room, measured by a Fluke IR Thermometer to maintain a consistent test environment range of 20º-25ºC. The TA.XT Plus Texture Analyzer by Stable Micro Systems was used along with the TA-53 3MM Puncture Probe for puncture tests. Along with the Exponent Software, data was collected by puncturing each sample to a depth of 15mm at a uniform rate of 1mm/s. The Texture Analyzer recorded the data, with time measurements having a 0.005 second resolution, force measurements with a precision of 10^{-9}

gram force, and distance measurements with 0.005 mm resolution.

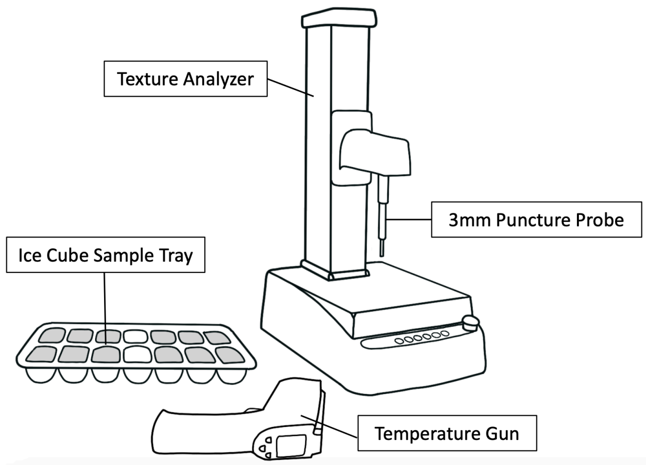

Figure 4: Setup for sample testing with the Texture Analyzer. I used the temperature gun to ensure the temperature was within room temperature range and set the ice cube sample tray on the Texture Analyzer to test samples.

ANALYZING AND EXTRAPOLATING DATA

The Texture Analyzer collected data on force, displacement, and time. The results were compiled for each of the 54 samples, each corresponding to a gelatin percentage. MATLAB was used for data analysis, and mechanical properties were extrapolated for each of the 54 samples. As seen in Figure 5, puncture strength was the maximum force achieved during puncture testing. Cohesiveness was evaluated by calculating the integral of negative force over time, in other words, the negative force on the probe while it retracted. Finally, elastic stiffness constants k_s and L_0 were determined by the constants in the data's best-fit curve using the elastic gelatin or coupled springs model.

The elastic stiffness, puncture strength, and cohesiveness parameters were later compared against their corresponding gelatin percentages, allowing for further exploration of the relationship between mechanical properties and gelatin concentration. Overall, the experimental methods, data collection, and data extrapolation grounded the following discussion.

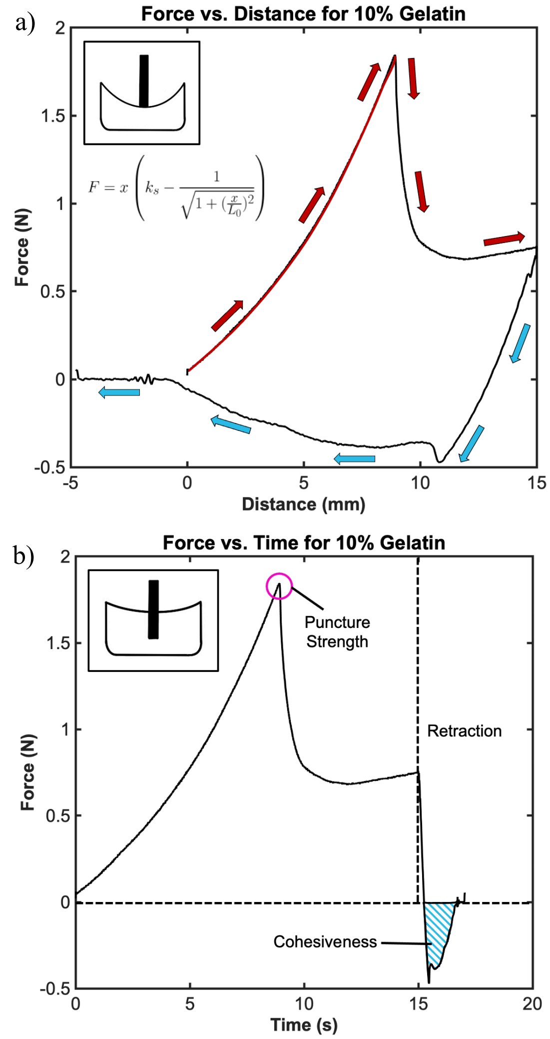

Figure 5: a) A force vs. distance graph for a 10% gelatin sample with the fitted elastic stiffness function. The fit relates the measured force to the constants k_s and L_0, which we later analyze to understand how these elastic stiffness constants evolve with gelatin concentration. b) A force vs. time graph for one sample of the 10% gelatin with puncture strength and cohesiveness extracted from the graphical data. The puncture strength and cohesiveness can later be graphed with their gelatin concentrations for further trend analysis.

RESULTS AND DISCUSSION

The primary objective of this study was to investigate the influence of gelatin percentage on gelatin samples' mechanical properties, particularly the elastic stiffness based on constants k_s and L_0, puncture strength, and cohesiveness. With these relationships, given a mechanical requirement, I can return a minimum or maximum gelatin percentage for the desired mechanical effects.

As displayed in Figure 6, when the probe begins to puncture the gelatin sample, the pre-puncture property of elastic stiffness varies with gelatin percentage. The elastic stiffness was modeled with the coupled spring model equation as defined in Figure 2 and how constants k_s and L_0 varied with gelatin percentage were found.

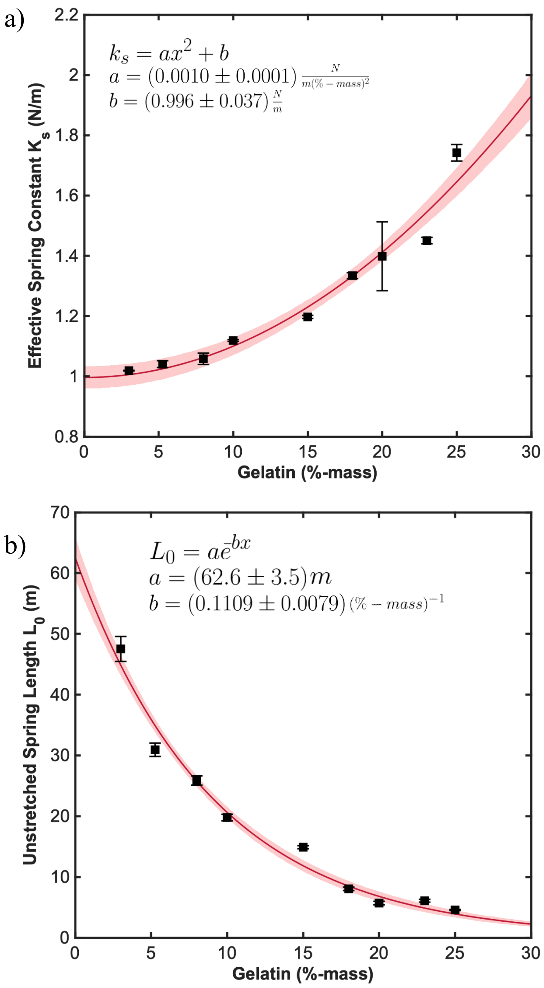

Figure 6: a) Average effective spring constant k_s plotted against gelatin percentage with a polynomial fit. As the gelatin percentage increases, the effective spring constant also increases. The effective spring constant dictates how stiff our gelatin sample behaves, so a high effective spring constant leads to a stiffer gelatin. b) Average unstretched spring length L_0 plotted against gelatin percentage with a decreasing exponential fit. As gelatin percentage increases, the unstretched spring length decreases and approaches 0. A decreasing unstretched spring length means a more rigid gelatin sample, so increasing gelatin percentage results in a more rigid gelatin.

It is important to note that the effective spring constant measurements had an outlier in the 20% concentration batch while taking puncture measurements, which is likely the main contribution to the larger error bounds. One of the six 20% concentration samples had a false measurement start due to noise or external vibrations, where the force, displacement, and time data started recording before the puncture probe had contact with the sample. This resulted in the first part of the data having a force measurement closer to 0 since the sample was not yet being impacted. When fitting the coupled spring model equation to the false start sample, the effective spring constant was the most affected factor and varied from the other 20% concentration samples.

Overall, with a higher gelatin percentage, there was a parabolic increase in the effective spring constant k_s and an exponential decrease in unstretched spring length L_0. A large effective spring constant and shorter unstretched spring length are indicators of a stiffer material since higher spring constants generally lead to stiffer springs and an unstretched spring length approaching zero means that the material behaves more similarly to a rigid body. These results emphasize that as gelatin concentration rises, the material becomes stiffer. This aligns with the behavior in studies with polymers [1, 5, 6], where increasing polymer concentrations resulted in more solid-like material.

The post-puncture properties of puncture strength and distance of gelatin samples were also investigated in relation to gelatin percentage. Puncture strength was the maximum force on the sample before puncture, and puncture distance was the depth a sample was punctured before breaking through the surface.

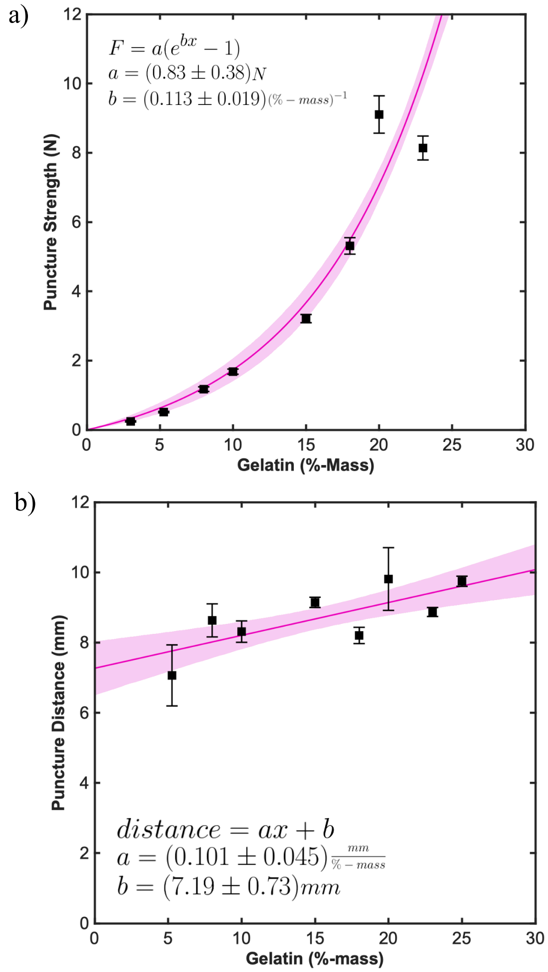

Figure 7: a) The average puncture strength is plotted against the gelatin percentage. As gelatin percentage increases, the puncture strength increases exponentially. b) Average puncture point distance linearly increases with gelatin percentage. Together, the puncture strength and puncture distance relationships indicate that gelatin is more resistant to puncture as the concentration increases.

The puncture strength and distance results underscore the importance of gelatin concentration in determining gelatin's resistance to external piercing forces. As gelatin content increases, the material is more resistant to puncture and is punctured with greater depth before breaking.

Figure 8 illustrates cohesiveness, a post-puncture property, in relation to gelatin percentage. Cohesiveness is determined by calculating the integral of negative force over time during the retraction phase of the Texture Analyzer.

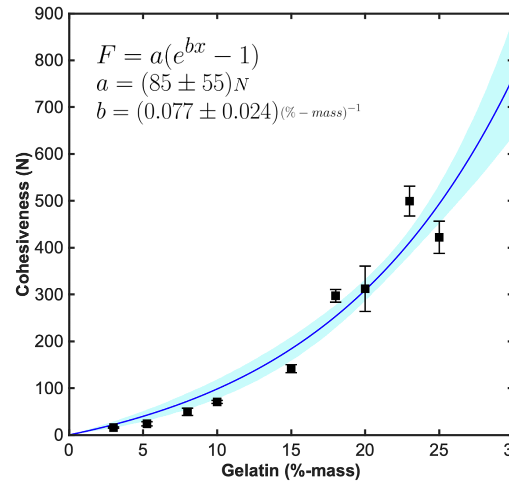

Figure 8: Cohesiveness as a function of gelatin percentage. As the gelatin percentage increases, the cohesiveness exponentially increases. This means that with a gelatin percentage increase, a greater force is needed to remove the puncture probe from the sample.

The cohesiveness of the material increased exponentially with gelatin percentage, and this trend indicates that the intermolecular bonds are stronger at higher concentrations and the material can better adhere under compressive stress.

These results are significant for the many applications where gelatin plays a role. For instance, in the domain of bioengineering, gelatin is used to create scaffolds for tissue engineering. By understanding what mechanical properties and strength thresholds are needed, the best range of gelatin percentage can be selected. Scaffolds are used as structure, so stiffer gelatin material and therefore a higher gelatin percentage is desired. As another example, gelatin-based packaging films are ideally durable and resistant to puncture, so higher gelatin percentages would also be suitable for this application. On the contrary, gelatinous desserts should not be hard to chew, difficult to puncture, or super stiff so lower gelatin concentrations may be a better fit.

In addition, the analysis of the data indicates that the puncture strength increases at a more rapid rate than the effective spring constant as gelatin concentration rises. This suggests that if a desired gelatin needs a high puncture strength but a relatively lower stiffness, higher concentrations of gelatin may be best suited. However, further research at higher gelatin concentrations is necessary to validate this observation.

Several challenges and limitations were encountered throughout the study. In one instance, a 1% gelatin solution was prepared, but the resulting gelatin was still liquid and could not be transported and handled with the same method as the other samples. This limitation should be considered when exploring very low gelatin concentrations. For future studies at low gelatin concentrations, a more sensitive probe may be needed to detect the smaller changes in forces or different mechanical properties such as viscosity could be measured. A potential source of error is the use of samples created within the same batch. This means that if an error occurred in one sample within a batch, it applied to all other samples from the same batch. To minimize such potential errors, future studies may consider creating samples for each percentage in different batches to ensure greater independence and reduce the margin of error. Additionally, this study focused solely on bovine gelatin, and different sources of gelatin may produce variations in puncture strength, cohesiveness, and elastic stiffness. Therefore, it is important to acknowledge that although the general trends may be consistent across other gelatin types, the study's percentage and number correlations are specific to bovine gelatin and may not be directly applicable to other gelatin varieties or compositions. Overall, results reveal that higher percentages of gelatin concentration lead to increased elastic stiffness, puncture strength, and cohesiveness properties, which can be used across the fat-reaching disciplines that use gelatin.

CONCLUSIONS

In this study, I have explored the relationship between gelatin percentage and its mechanical properties, focusing on elastic stiffness, puncture strength, and cohesiveness. The objective was to investigate how variations in gelatin concentration impact these key properties, providing insights into the potential applications of gelatin. Results reveal statistically significant trends that have implications across materials science, bioengineering, and the food industry. With increasing gelatin concentration, elastic stiffness, puncture strength, and cohesiveness all increase. By understanding how changes in gelatin percentage influence gelatin's mechanical behavior, more informed decisions on concentration can be made when selecting for specific applications. This can help achieve desired mechanical properties that are tailored to the requirements of various industries.

For applications that need structural support such as scaffolds for bioengineering cells, higher gelatin concentrations, which lead to stiffer materials, are more suitable. On the other hand, in the food industry, where gelatin-based products should be chewable and less stiff, lower gelatin concentrations may be a better fit. Notably, the study finds that puncture strength increases at a more rapid rate than the effective spring constant as gelatin concentration rises. This suggests that for applications requiring high puncture strength without excessive stiffness, higher gelatin concentrations may be the ideal choice. Nevertheless, further research at the higher gelatin concentrations is necessary to validate this observation. With a longer study, it would be interesting to test higher gelatin concentrations, as well as different gelatin sources to examine further impacts on puncture strength, cohesiveness, and elastic stiffness.

In conclusion, this study has contributed to an understanding of gelatin's mechanical properties in correlation to its gelatin concentrations. It provides a foundation for informed decision-making and innovation across gelatin's scientific, engineering, and industrial applications, and encourages future investigation on the potential of this unique biopolymer.

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REFERENCES

[1] Zhou, P., and Regenstein, J. M., 2007, "Comparison of Water Gel Desserts from Fish Skin and Pork Gelatins Using Instrumental Measurements," Journal of Food Science, 72(4), pp. C196–C201.

[2] Su, K., and Wang, C., 2015, "Recent Advances in the Use of Gelatin in Biomedical Research," Biotechnol Lett, 37(11), pp. 2139–2145.

[3] Liu, D., Nikoo, M., Boran, G., Zhou, P., and Regenstein, J. M., 2015, "Collagen and Gelatin," Annual Review of Food Science and Technology, 6(1), pp. 527–557.

[4] Fegan, K., 2020, "Gelatin," ChemBAM.

[5] Borries, M., Barooji, Y. F., Yennek, S., Grapin-Botton, A., Berg-Sørensen, K., and Oddershede, L. B., 2020, "Quantification of Visco-Elastic Properties of a Matrigel for Organoid Development as a Function of Polymer Concentration," Frontiers in Physics, 8.

[6] Richler, D., and Rittel, D., 2014, "On the Testing of the Dynamic Mechanical Properties of Soft Gelatins," Exp Mech, 54(5), pp. 805–815.

[7] Eager, D., Zhou, S., Ishac, K., Hossain, I., Richards, A., and Sharwood, L. N., 2022, "Investigation into the Trampoline

Dynamic Characteristics and Analysis of Double Bounce Vibrations," Sensors, **22**(8), p. 2916.