Predicting the Mechanical Behaviour of Starch Gels through Inverse Analysis of Indentation Data

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Abstract:
Two types of starch gels made with various starch/water concentrations were studied in terms of their mechanical behaviour. Indentation tests were performed which revealed a rate independent load-deflection response. An inverse analysis based on the Marquardt-Levenberg optimisation algorithm and Finite Element Analysis was used to derive the stress-strain behaviour from the indentation data. The inverse predictions for the stress-strain curves are in good agreement with the direct measurements from uniaxial compression and shear tests up to high values of strain. The validity of the method was proven for both self-supporting and non self-supporting gels, with initial moduli ranging from a very small 60 Pa to 55 kPa. Thus the indentation characterisation method is proven as a powerful, fast and efficient way of evaluating and/or monitoring the behaviour of gels.

Zusammenfassung:
Zwei aus unterschiedlichen Stärke/Wasser-Konzentrationen bestehende Stärke-Gel-Arten wurden in Bezug auf ihr mechanisches Verhalten hin untersucht. Eindrucktests wurden durchgeführt, die eine ratenunabhängige Kraftablenkung aufzeigten. Mittels einer auf dem Marquardt-Levenberg-Optimierungsalgorithmus und der Finite-Elemente-Analyse basierenden inversen Analyse wurde das Spannungs-Dehnungs-Verhalten von den Eindruckdaten abgeleitet. Die inversen Voraussagen für die Spannungs-Dehnungs-Kurven stehen bis zu hohen Dehnungswerten in gutem Einklang mit den aus direkten Messungen ermittelten uniaxialen Kompressions- und Scherversuchsdaten. Die Gültigkeit der Methode wurde sowohl für die selbsttragenden als auch für die nicht selbsttragenden Gele bewiesen, wobei initiale Moduli Druckwerten ausgesetzt wurden, die von sehr niedrigen 60 Pa bis zu 55 kPa reichten. Somit ist erwiesen, dass die Eindruckcharakterisierung eine leistungsfähige, schnelle und effiziente Methode der Beurteilung und/oder Überwachung des Verhaltens von Gelen ist.

Résumé:
Deux types de gels d'amidon, obtenus avec des concentrations variées en amidon et eau, ont été étudiés du point de vue de leur comportement mécanique. Des tests d'indentation ont été réalisés révélant une réponse déflection-charge indépendante de la vitesse. Une analyse inverse basée sur un algorithme d'optimisation de Marquardt-Levenberg et une analyse d'élément fini, a été utilisée afin de dériver le comportement contrainte-déformation à partir des données d'indentation. Les prédictions inverses pour les courbes de contrainte-déformation sont en bon accord avec les mesures directes obtenues avec des tests de cisaillement et de compression uni-axiale, jusqu'à des valeurs élevées de déformation. La validité de la méthode est démontrée pour des gels qui se supportent ou non, avec des modules initiaux allant d'un très petit 60 Pa jusqu'à 55 kPa. Ainsi donc, la méthode de caractérisation par indentation se présente comme un moyen puissant, rapide et efficace d'évaluer ou contrôler le comportement des gels.

Key words: starch gels, constitutive behaviour, indentation, inverse analysis, finite element analysis, food rheology

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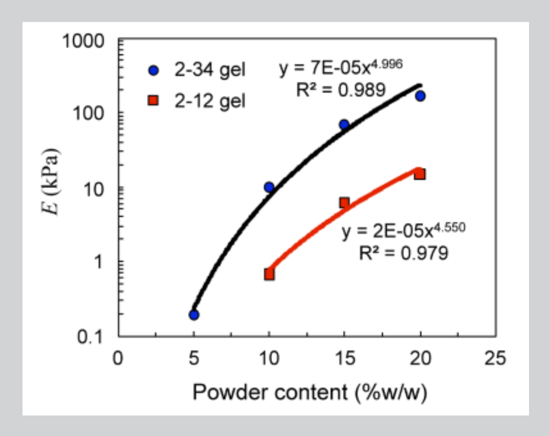

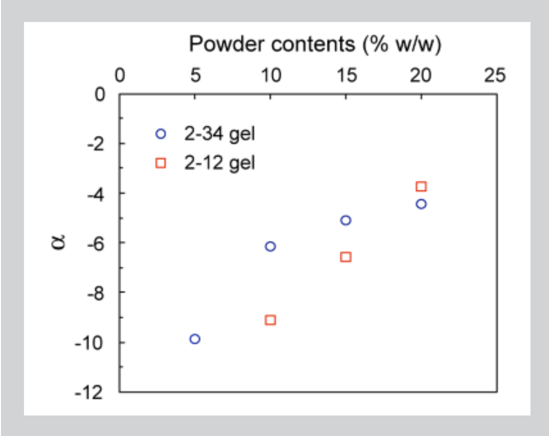

Figure 12 (left): Dependence of E on the powder content (%w/w) for both self supporting and non-self supporting gels. Lines are fitted power laws.

Figure 13: Dependence of α on the powder content (%w/w) for both self supporting and non-self supporting gels.

both gels are in good agreement with the storage moduli obtained from the rheological tests.

Figure 12 shows the dependence of E (calculated from 3μ) on the % powder content for both self-supporting and non-self supporting gels. A semi-logarithmic scale was chosen as the rise in E with increasing % powder content is so dramatic. Power laws were fitted to the data as shown in Figure 12 and for both types of gels, the power exponent was close to 5. This is very close to the values quoted by Genovese and Rao [25]. In addition, Figure 13 shows the dependence of α on % powder content for all seven gels that were investigated. There is a clear trend with α becoming 'less negative' as the powder concentration increases. The parameter α is an indication for the strain hardening part of the stress-strain curve, with less negative values indicating more linear stress-strain curves without significant strain hardening. At small strains, the modulus expression derived from Equation 1 can be expressed as:

$$E = 3\mu\left(1+\frac{\alpha\epsilon}{2}\right) \qquad (5)$$

Clearly, this is linear for $\alpha = 0$. In addition, for $\alpha < 0$, the compression modulus increases with strain whilst the tensile one decreases. For $\alpha > 0$, the reverse is true and the modulus increases for all cases at large strains.

8 CONCLUSIONS

The mechanical behaviour of two starch gels made from various starch/water ratios has been obtained using an inverse analysis on data obtained from indentation tests. The inverse predictions were validated with independent compression and shear data for self-supporting and non-self supporting gels, respectively. Excellent agreement was obtained for all of the gels studied up to high values of strain. The method was tested on a large number of gels with initial shear moduli varying in the large range of 60 Pa to 55 kPa. This is a clear demonstration that the method is a powerful tool for obtaining the stress-strain characteristics of such materials.

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