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Comparative Studies on Fracture Characteristics of Food Gels Subjected to Uniaxial Compression and Torsion

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Stress developments in cylindrically shaped food gels were comparatively investigated by applying uniaxial compression and torsional deformation up to fracture. While torsion tended to result in earlier fracture with lower fracture stress and strain values, the true shear stress vs. true shear strain curves determined based on uniaxial compression and torsion tests were in good agreement up to the point of fracture in torsion in most cases examined. A typical fracture plane was observed at an angle approximately $\pi/4$ radians with respect to the cylinder axis in both uniaxial compression and torsion, suggesting that those compressed and twisted gels fractured in shear and tension, respectively. Both fracture stress and strain values increased with increasing deformation rate, regardless of the mode of deformation. The present results confirm that torsion can be used for fundamentally assessing fracture characteristics of a material that deforms and/or fractures in an unpredictable manner under uniaxial compression.

Keywords: texture, fracture stress, fracture strain, compression, tension, torsion, gel

The mechanical characterization of food is essential for understanding the mechanisms determining its sensory texture (Steffe, 1996; Bourne, 2002; Nishinari, 2003). Fundamental fracture tests have been found to provide not only physically interpretable results but also good correlation with human sensory evaluation (Montejano *et al*., 1985). Uniaxial compression is the most widely utilized deformation mode for fundamental fracture testing, perhaps due to the commercial availability of testing instruments and ease of sample preparation and experimental performance. Uniaxial tension is often difficult with food materials since a strong attachment of the specimen to the testing device is required. Bulk deformation can be caused by applying perpendicular force uniformly at any points on the surface of the specimen, rather than uniaxially in a single direction; however, this mode of deformation has generated only limited attention among researchers investigating food materials. Another deformation mode of interest is shear, which is produced by a tangential force. In practice, shear deformation is often created using a rotational fixture. A number of rotational viscometers are commercially available, while the use of rotational or torsional deformation for fundamental fracture tests of solid food materials has been a rather unique approach (Hamann, 1983).

The major disadvantage of uniaxial compression testing is that it causes significant changes in the shape of the specimen. For example, uniaxial compression of a cylindrical specimen may result in variations in diameter along the axis and a decrease in volume, especially if the material is undergoing syneresis (Steffe, 1996). Exact changes in the shape of the specimen must be taken into account in order to evaluate the true stress and strain arising within it. Even if the specimen maintains its cylindrical shape throughout compression, changes in the rate of deformation are unavoidable: the strain rate increases as the specimen is compressed at a constant speed (Bot, 1996a, 1996b). Friction between the test fixture and specimen can also be a matter of concern (Steffe, 1996). Additionally, uniaxial compression tends to cause shear fracture (fracture by shear force) regardless of material characteristics: even a material weaker in a tensile stress can fracture in shear in uniaxial compression (Hamann, 1983). In contrast, torsional deformation does not cause changes to the shape of a specimen. Thus, the rate of deformation does not change at a constant twisting speed. Furthermore, the magnitude of the maximum shear stress generated in the specimen is equal to that of the maximum normal stresses (Hamann, 1983). A specimen is therefore anticipated to fracture without restriction due to a tension, compression, or shear stress or a combination of some of these stresses for whichever the material has the least strength. In other words, observation of the plane along which the specimen fractures in torsion would provide additional information on fracture mechanisms (Hamann, 1983).

Texture characteristics of food materials greatly vary, while current instrumental analytical techniques rely predominantly on uniaxial compression tests. In order to standardize instrumental texture characterization protocols and establish relationships between instrumental and sensory assessments of food texture, it is desirable to develop methods for overcoming problems associated with uniaxial compression. The objective of this study was to demonstrate the validity of the torsion fracture testing on food gels as an alternative to uniaxial compression by comparatively investigating stress developments in various types of these gels subjected to uniaxial compression and torsional deformation.

Theoretical

In previous studies on torsion fracture tests in the literature (Diehl *et al*., 1979; Hamann, 1983; Montejano *et al*., 1985; Lelievre *et al*., 1992; Mirza & Lelievre, 1992; Tang *et al*., 1994, 1997; Ikeda & Foegeding, 1999; Ikeda *et al*., 1999; Truong &

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Daubert, 2000, 2001; Ikeda, 2001, 2003), a specimen was frequently carved or molded into a capstan shape. In this study, cylindrical gels were examined with the intention of facilitating mathematical treatments and minimizing uncertainties accompanying sample preparation. Gels were assumed to be purely elastic and stress vs. strain relationships were assumed to be linear for the sake of simplicity.

Uniaxial compression Given that the volume of the specimen is constant, true compressive stress (σ_C) and strain (ε_C) can be calculated as follows (Hamann, 1983):

$$\sigma_C = F(L-\Delta L)/(\pi R^2 L), \tag{1}$$

$$\varepsilon_C = -\ln[1-(\Delta L/L)], \tag{2}$$

where F is the compressive force, L is the initial height of the specimen, ΔL is the deformation length, and R is the initial radius of the specimen.

Uniaxial compression of food gels often results in fracture at a plane inclining at an angle of $\pi/4$ radians from the cylinder axis. This is the principal shear stress plane, along which the maximum shear stress in the specimen is produced (Timoshenko & Goodier, 1987). True shear stress (τ_C) and strain (γ_C) acting on the principal shear stress plane are given as (Hamann, 1983):

$$\tau_C = \sigma_C/2, \tag{3}$$

$$\gamma_C = \varepsilon_C(1+\mu), \tag{4}$$

where μ is Poisson's ratio; this ratio was assumed to be 0.5 throughout this study. Equation (3) implies that the magnitude of the maximum shear stress produced by uniaxial compression is only half that of the maximum normal stress. Nevertheless, even a material weaker in a normal stress than a shear stress can fracture in shear under uniaxial compression. Occurrence of a vertical crack in a cylindrical specimen is assigned to a tensile fracture.

Torsion In torsional deformation, the maximum true shear stress (τ_T) and strain (γ_T) occur at the circumference of the ends of the cylinder (Hamann, 1983; Ikeda, 2003):

$$\tau_T = 2M/(\pi R^3) \tag{5}$$

$$\gamma_T = \phi R/L \tag{6}$$

where M is the twisting moment and ϕ is the angular deformation.

Similar to the case of uniaxial compression, twisted food gels often fracture at a plane inclining at an angle of $\pi/4$ radians from the cylinder axis. This is, however, a plane of maximum tensile stress in the case of torsion (Timoshenko & Goodier, 1987). A unique feature of torsional deformation is that the magnitude of the maximum shear stress is equal to that of the maximum compressive and tensile stresses generated in the specimen (Hamann, 1983; Timoshenko & Goodier, 1987). Such a condition of stress is called pure shear (Hamann, 1983; Timoshenko & Goodier, 1987). A material weaker in shear fractures along a horizontal plane of maximum shear stress.

Materials and Methods

Gel preparation Weighed powders of cornstarch (Sanwa Cornstarch Co., Ltd., Nara) were dispersed in distilled water in a 500 ml separating flask and stirred at 200 rpm for 60 min at room temperature using a motorized stirrer (HEIDON BL600, Shintoh Science, Ltd., Tokyo) equipped with a Teflon mixing blade. In order to avoid microbial growth, 0.05% w/w sorbic acid (potassium salt) was added. The dispersions were then heated in an oil bath with stirring at 200 rpm until the temperature reached 60°C and then at 400 rpm until the temperature reached 95°C in about 30 min from the beginning of heating. Stirring was continued for another 30 min at 400 rpm while the temperature was maintained at 95–98°C. The gelatinized hot starch dispersions were poured into cylindrical Teflon molds (20 mm in diameter and 30 mm in height), left at room temperature for 60 min, and then stored at 5°C for pre-specified periods.

Agar (Wako Pure Chemical Industries, Ltd., Osaka) and gelatin powders (Daiei, Inc., Kobe) were dispersed in distilled water in Erlenmeyer flasks and heated at 40°C for 15 min with stirring using a magnetic stirrer. The agar dispersions were further heated to 95°C with stirring and stirred at 95°C for 30 min. The gelatin dispersions were heated to 70°C with stirring and stirred at 70°C for 30 min. The hot dispersions were poured into cylindrical Teflon molds (20 mm in diameter and 30 mm in height), left at room temperature for 60 min, and then stored at 5°C overnight.

Commercial fish meat sausage (20 mm diameter and 120 mm long) manufactured by Nippon Suisan (Tokyo) was purchased from a local grocery and cut to 30 mm lengths.

Fracture tests Gel samples were immersed in silicone oil and equilibrated to be 25°C in a water bath for 60 min before measurements. Gel preparation and measurements were conducted at least in triplicate.

Uniaxial compression tests were performed using a Rheoner RE-3305 (Yamaden Co., Ltd., Tokyo) equipped with a 2- or 20-kgf load cell. A cylindrical gel was vertically mounted on the testing stage and compressed with a plunger (40 mm diameter) at a constant crosshead speed of 0.5–5 mm/s.

Torsion tests were made using prototype apparatus constructed by Toyo Seiki Seisakusho, Ltd. (Tokyo). Each end of the cylindrical gel was glued to an aluminum disk (36 mm×36 mm ×2 mm) using cyanoacrylate glue. The upper end of a vertically mounted gel was fastened to make it stationary and the disk glued to the bottom of the gel cylinder was twisted at a constant rotational speed of 0.48–7.2 rpm while the twisting moment was recorded.

Data evaluation Compressive stress (σ_C) vs. strain (ε_C) curves were obtained based on measured compressive force vs. deformation data in uniaxial compression tests using Eqs. (1) and (2). The value of Young's modulus E was evaluated as the slope of the initial part of the curve that contained at least 10 data points. The true shear stress (τ_C) and strain (γ_C) values were then calculated using Eqs. (3) and (4). Torque response to angular deformation in torsion tests was converted into a true shear stress (τ_T) vs. strain (γ_T) curve using Eqs. (5) and (6). The shear modulus G was evaluated as the initial slope of the curve, similar to the determination of E. Direct comparisons between uniaxial compression and torsion were made at an equivalent initial strain rate.

Results and Discussion

Figure 1 shows results of uniaxial compression and torsion fracture tests on 20% cornstarch gels stored at 5°C for varied periods. Comparisons were first made between compressive stress (σ_C) vs. strain (ε_C) curves obtained from uniaxial compression testing and shear stress (τ_T) vs. strain (γ_T) curves obtained from torsion testing (Fig. 1a). Based on the initial slopes of these curves, Young's modulus E and shear modulus G values are evaluated and summarized in Table 1. In all cases, stress values developed approximately proportionally to strain values up to a maximum that should be regarded as the point of fracture. Stress values at fracture (fracture stress) as well as E and G values increased with increasing storage periods of gels before testing, while strain values at fracture (fracture strain) decreased. Similar trends have been observed in previous uniaxial compression fracture studies on cornstarch gels (Ikeda *et al.*, 2001). Such evolution of firmness and brittleness of starch gels is generally considered to be a consequence of retrogradation of starch occurring during refrigeration. Fracture stress and strain values determined based on uniaxial compression tests were generally larger than those based on torsion tests (Table 2). This can be explained by the difference in the fracture mode: both compressed and twisted gels fractured in a direction angled $\pi/4$ radians with respect to the cylinder axis (data not shown), which is the direction of maximum shear stress in uniaxial compression but that of maximum tensile stress in torsion. It is worth noting that the evaluated ratio of E/G was reasonably close to 3 (Table 1), an ideal value anticipated for an incompressible and isotropic elastic material, underpinning the validity of the examined testing methods even in the small strain regions.

Equations (2) and (6) imply that the strain rate (change in strain per second) increases as the specimen is compressed at a constant speed but remains constant in torsion at a constant angular velocity. It is therefore technically difficult to make a comparison between these two types of tests at an identical strain rate. Alternatively, comparisons were made using an identical initial strain rate in this study. Uniaxial compression data converted into true shear stress vs. strain curves exhibited good agreement with curves determined based on torsion tests up to the fracture points in torsion (Fig. 1b). In most previous studies, true shear stress vs. strain curves have been shown to be almost identical up to fracture points in uniaxial compression and torsion, resulting in comparable fracture stress and strain values between these two deformation modes (Montejano *et al.*, 1985; Lelievre *et al.*, 1992; Mirza & Lelievre, 1992; Tang *et al.*, 1997; Truong & Daubert, 2000, 2001). A possible cause of such discrepancy is the difference in the shape of gel specimens between these studies (cylindrical vs. capstan-shaped).

Agar can form a firm gel at a much lower solid content compared to starch (Morris, 1998). Fracture stress, E, and G values of agar gels increased with increasing polymer concentration but fracture strain values decreased (Fig. 2a and Table 1). The E/G ratio for 1% w/w agar gels seems to be overestimated (Table 1), indicating an error in evaluating the initial slope of stress vs. strain curves due to low stress response of these specimens. All twisted gels and compressed 1% w/w gels presented a fracture plane at an angle of $\pi/4$ from the cylinder axis, while compressed 2% w/w and 4% w/w gels fractured in vertical cracks or

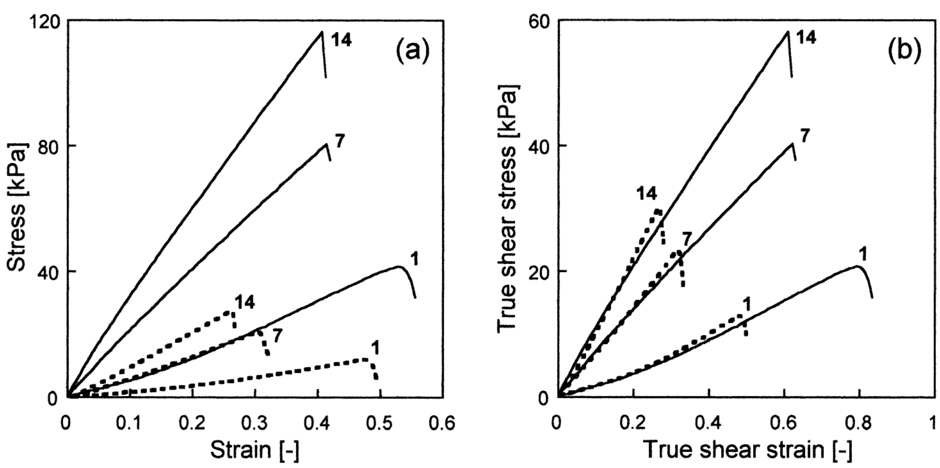

Fig. 1. (a) Comparisons between true compressive stress vs. strain curves in uniaxial compression (solid) and true shear stress vs. strain curves in torsion (dotted) of 20% w/w cornstarch gels. Numbers in the figure represent the storage period (days) of the gels before measurements. The initial compressive and shear strain rates were 0.017 s^{-1}. (b) True shear stress vs. strain curves of 20% w/w cornstarch gels subjected to uniaxial compression (solid) and torsion (dotted). Numbers in the figure are those in (a). The initial true shear strain rate was 0.025 s^{-1}.

Table 1. Comparison between uniaxial compression and torsion tests of food gels.[a)]

Gel	Uniaxial compression			Torsion			E/G
	σ_f (kPa)	ε_f (−)	E (kPa)	τ_f (kPa)	γ_f (−)	G (kPa)	
20% w/w cornstarch stored at 5°C for 1 day	42.1 (2.8)	0.52 (0.05)	49.0 (2.7)	12.1 (2.4)	0.47 (0.04)	15.9 (3.3)	3.08
20% w/w cornstarch stored at 5°C for 7 days	77.4 (10.7)	0.42 (0.03)	215.7 (14.6)	20.9 (2.4)	0.31 (0.03)	64.4 (1.2)	3.35
20% w/w cornstarch stored at 5°C for 14 days	116.7 (8.9)	0.41 (0.03)	345.0 (36.8)	27.5 (2.2)	0.26 (0.01)	105.6 (8.9)	3.27
1% w/w agar	6.5 (0.6)	0.21 (0.01)	16.5 (1.9)	1.2 (0.1)	0.23 (0.01)	3.3 (0.4)	4.98
2% w/w agar	24.0 (0.7)	0.20 (0.01)	97.4 (1.2)	5.7 (0.3)	0.18 (0.01)	29.4 (2.9)	3.31
4% w/w agar	48.0 (0.4)	0.13 (0.01)	379.3 (14.1)	11.9 (2.8)	0.10 (0.02)	134.8 (2.4)	2.81
fish meat sausage	65.5 (4.9)	0.67 (0.05)	102.5 (1.8)	32.7 (2.9)	0.91 (0.07)	37.3 (2.5)	2.75
10% w/w gelatin	26.4 (3.9)	1.06 (0.11)	10.0 (1.4)	2.1 (0.4)	0.97 (0.08)	1.6 (0.3)	6.26
15% w/w gelatin	52.2 (3.5)	1.36 (0.06)	12.9 (0.9)	3.9 (0.6)	0.99 (0.07)	3.3 (0.6)	3.94

[a)] σ_f, true compressive stress at fracture; ε_f, true compressive strain at fracture; E, Young's modulus; τ_f, true shear stress at fracture; γ_f, true shear strain at fracture; G, shear modulus. The initial strain rate was 0.017 s^{-1}. The numbers in the parentheses are standard deviation.

shattered (data not shown). Additionally, substantial liquid excretion was visually observed for all compressed gels. Due to such ambiguity in identifying the fracture plane and release of liquids during compression, torsion appears to be more suitable for assessing fundamental fracture properties of agar gels. True shear stress vs. strain curves were in good agreement between uniaxial compression and torsion tests up to the fracture points in torsion (Fig. 2b).

Both compressive stress vs. strain curves and shear stress vs. strain curves of fish meat sausage appeared to be approximately

Table 2. Fracture characteristics of food gels subjected to uniaxial compression and torsion.[a]

Gel	Uniaxial compression		Torsion	
	τ_f (kPa)	γ_f (−)	τ_f (kPa)	γ_f (−)
20% w/w cornstarch stored at 5°C for 1 day	21.1 (1.4)	0.78 (0.07)	12.9 (1.2)	0.48 (0.05)
20% w/w cornstarch stored at 5°C for 7 days	38.7 (5.3)	0.64 (0.05)	23.4 (3.1)	0.31 (0.03)
20% w/w cornstarch stored at 5°C for 14 days	58.4 (4.5)	0.61 (0.05)	30.2 (4.0)	0.27 (0.04)
1% w/w agar	3.3 (0.3)	0.32 (0.02)	1.4 (0.0)	0.23 (0.01)
2% w/w agar	12.0 (0.4)	0.30 (0.01)	5.7 (0.3)	0.18 (0.01)
4% w/w agar	24.0 (0.2)	0.20 (0.01)	14.5 (1.7)	0.12 (0.02)
fish meat sausage	32.8 (2.5)	1.00 (0.07)	33.0 (2.8)	0.92 (0.07)
10% w/w gelatin	13.2 (2.0)	1.60 (0.17)	2.2 (0.3)	0.98 (0.02)
15% w/w gelatin	26.1 (1.7)	2.04 (0.09)	3.9 (0.7)	0.99 (0.04)

[a] τ_f, true shear stress at fracture; γ_f, true shear strain at fracture. The initial strain rate was 0.025 s^{-1}. The numbers in parentheses are standard deviation.

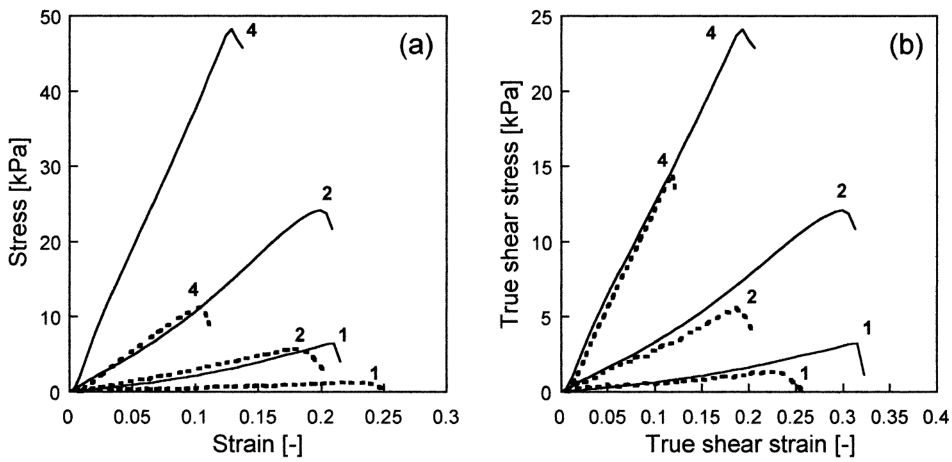

Fig. 2. (a) Comparisons between true compressive stress vs. strain curves in uniaxial compression (solid) and true shear stress vs. strain curves in torsion (dotted) of agar gels. Numbers in the figure represent the agar concentration (% w/w). The initial compressive and shear strain rates were 0.017 s^{-1}. (b) True shear stress vs. strain curves of agar gels subjected to uniaxial compression (solid) and torsion (dotted). Numbers in the figure are those in (a). The initial true shear strain rate was 0.025 s^{-1}.

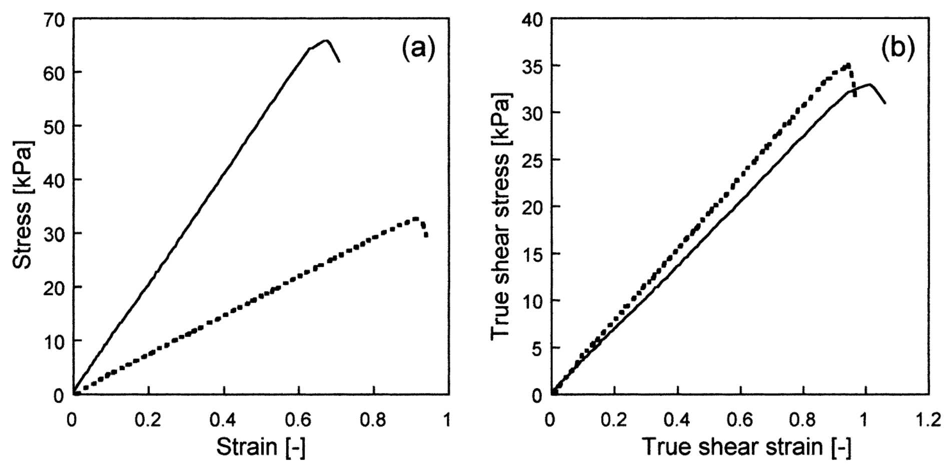

Fig. 3. (a) Comparisons between true compressive stress vs. strain curves in uniaxial compression (solid) and true shear stress vs. strain curves in torsion (dotted) of fish meat sausage. The initial compressive and shear strain rates were 0.017 s^{-1}. (b) True shear stress vs. strain curves of fish meat sausage subjected to uniaxial compression (solid) and torsion (dotted). The initial true shear strain rate was 0.025 s^{-1}.

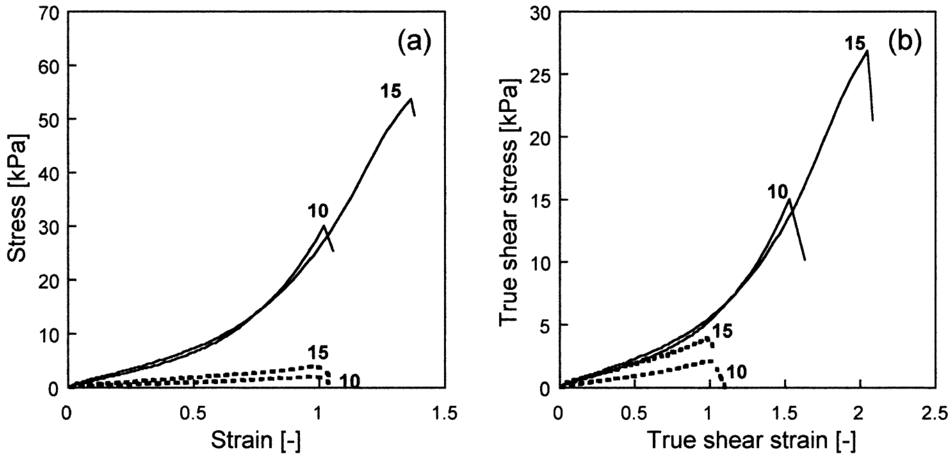

Fig. 4. (a) Comparisons between true compressive stress vs. strain curves in uniaxial compression (solid) and true shear stress vs. strain curves in torsion (dotted) of gelatin gels. Numbers in the figure represent the gelatin concentration (% w/w). The initial compressive and shear strain rates were 0.017 s^{-1}. (b) True shear stress vs. strain curves of gelatin gels subjected to uniaxial compression (solid) and torsion (dotted). Numbers in the figure are those in (a). The initial true shear strain rate was 0.025 s^{-1}.

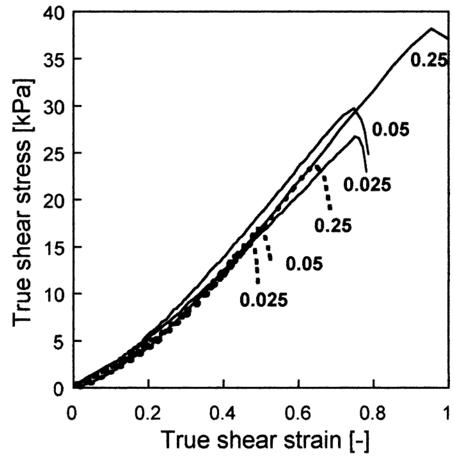

Fig. 5. Effects of deformation rates on true shear stress vs. strain curves of 22% w/w cornstarch gels subjected to uniaxial compression (solid) and torsion (dotted). Numbers in the figure represent the initial true shear strain rates (s^{-1}). Gels were stored at 5°C overnight before testing.

linear up to fracture points (Fig. 3a). The evaluated *E*/*G* ratio was close to 3 (Table 1). True shear stress vs. strain curves were approximately superposed (Fig. 3b). In uniaxial compression, it was difficult to identify the mode of fracture since compressed specimens eventually fractured in a number of cracks in various directions (data not shown). The visually observed fracture plane in torsion inclined ca. 60° from the cylinder axis, suggesting that the specimens fractured in a combination of shear and tensile modes.

Figure 4a shows significant strain-hardening (increasing stress/strain ratio with increasing strain) behavior of gelatin gels in uniaxial compression, consistent with previous studies (Bot *et al.*, 1996a, 1996b; Nishinari, 2003), and almost linear stress developments in torsion up to fracture. Fracture stress, *E*, and *G* values increased with an increase in the polymer concentration, while fracture strain values increased in uniaxial compression but remained almost unchanged in torsion. The evaluated *E*/*G* ratio of 10% w/w gels was more than twice the expected value (Table 1), indicating a possible error due to low stress response in the linear strain region. True shear stress vs. strain curves of 15% w/w gels were superposed up to the fracture point in torsion, while true shear stress values of 10% w/w gels in uniaxial compression were larger than those in torsion at a certain value of the shear stress. Even though we cannot judge if these results are due to an overestimation of stress in uniaxial compression, underestimation in torsion, or both at this point, it is still clear that interpretation of data in uniaxial compression would not be straightforward due to the presence of strain-hardening. Additionally, all compressed gels eventually shattered or fractured in vertical cracks, while all twisted gels fractured in a plane of maximum tensile stress (data not shown). Torsion tests therefore seem to be more suitable for fundamentally examining fracture behavior of gelatin gels.

Both fracture stress and strain values determined based on torsion tests were smaller than those determined based on uniaxial compression tests except for the case of fish meat sausage (Table 2). This is probably because twisted specimens normally fractured in tension. It is known that uniaxial tension often results in a smaller fracture strain value than uniaxial compression and torsion, presumably due to rapid decrease in the cross-sectional radius of the specimen (Hamann, 1983; Tang *et al.*, 1994). Since true shear stress development patterns in uniaxial compression and torsion were comparable in most cases in this study, a smaller fracture stress in torsion appears to be a consequence

Table 3. Effects of the deformation rate on fracture characteristics of 22% w/w cornstarch gels stored at 5°C for 1 day.[a]

Initial shear strain rate (s^{-1})	Uniaxial compression		Torsion	
	τ_f (kPa)	γ_f (−)	τ_f (kPa)	γ_f (−)
0.025	27.4 (2.9)	0.75 (0.06)	15.5 (1.0)	0.48 (0.02)
0.05	30.6 (1.6)	0.74 (0.07)	16.9 (2.3)	0.50 (0.04)
0.25	37.4 (1.7)	0.98 (0.06)	23.5 (1.2)	0.64 (0.02)

[a] τ_f, true shear stress at fracture; γ_f, true shear strain at fracture. The numbers in parentheses are standard deviation.

of a smaller fracture strain.

It is well established that the rate of deformation is a critical factor that affects fracture behavior of food gels (Lelievre *et al*., 1992; Bot *et al*., 1996a, 1996b; Truong & Daubert, 2000, 2001; Nakamura *et al*., 2001). Thus, effects of strain rates were examined using 22% w/w cornstarch gels that were free from technical difficulties such as a complicated fracture mode, strain-hardening, or syneresis. All true shear stress vs. strain curves up to fracture points were approximately superposed, regardless of the initial strain rates (Fig. 5). Both fracture stress and strain values increased with increasing strain rates in most cases, and those determined based on uniaxial compression tests tended to be larger than those based on torsion tests (Table 3). It is therefore believed that not only differences in the mode of fracture but also an increase in the strain rate during uniaxial compression contributed to larger fracture stress and strain values in the uniaxial compression. Torsion tests would be more suitable when the strain rate is a matter of interest since it is difficult to manipulate the strain rate at fracture *a priori* in uniaxial compression.

Conclusion

Torsion fracture testing was confirmed to be useful to complement conventional uniaxial compression testing. These two types of tests produced interchangeable true shear stress vs. true shear strain curves up to fracture points in torsion except for a case in which significant strain-hardening was observed in uniaxial compression. Compressed gels fractured either in shear or a combination of shear and tension, while most twisted gels fractured in tension. Thus, fracture stress and strain values determined based on uniaxial compression were systematically larger than those determined based on torsional deformation. Effects of the solid contents in cornstarch, agar, and gelatin gels on fracture stress and strain values, as well as effects of the storage period of cornstarch gels, showed similar trends in both types of tests. Agar gels exhibited a significant loss of internal liquids when compressed. The substantial strain-hardening behavior was observed in uniaxial compression of gelatin gels at strains over ca. unity, while stress developments in torsion were approximately linear up to fracture. Based on these results, torsion fracture tests are believed to be more suitable for fundamental analyses of various types of food gels and are expected to widen the range of testable specimens, especially towards the ends of large fracture stress and strain values.

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