

Dielectric anisotropy of nonwoven fabrics by using the microwave method

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ABSTRACT A new method uses polarized microwaves to determine the fiber orientation of nonwoven fabrics without contact and destruction. The angular dependence of transmitted microwave intensity at 4.0 GHz allows the fiber orientation to be determined in only 30 s. The molecular orientation ratio and the orientation angle changed with changing position in the cross direction of nonwoven fabric sheets. The anisotropy in the dielectric constant and dielectric loss at 4.0 GHz was shown to reflect directly the anisotropy of fibers in the nonwoven fabric. An orientation function was estimated from the angular dependence of ϵ'' as a measure of the distribution of fibers in the nonwoven fabric. The resonance frequency can be used to estimate the variation in basis weight in the cross direction.

KEYWORDS

Analysis
Anisotropy
Cross direction
Microwaves
Orientation
Synthetic fibers

Nonwoven fabrics consisting of polymer fibers have been used for various purposes, and the range of their industrial use is expanding rapidly. Thus, the mechanical properties of nonwoven fabric sheets are important from a practical point of view.

The mechanical nonuniformity of a sheet in the cross direction (CD) gives such troubles as low tear strength in some directions. Low tear strength is related to the orientational distribution of fibers in the sheets, and the experimental determination of the fiber distribution in the plane of the fabric sheet is therefore of basic importance.

Generally, it is time consuming to measure the anisotropy of a nonwoven fabric sheet by the mechanical breaking strength method, which also destroys the sheet. Since any sheet contains a number of voids, the reproducibility of data for the mechanical breaking strength is not good, but

there has been no alternative method.

In recent work (1-6), we showed that a microwave method is useful for determining the fiber and molecular orientation quickly and nondestructively. We have applied this method to polymer films and blood vessels, but the method also allows us to measure the density dependence of a complex dielectric anisotropy constant for paper sheets (7).

This work led us to study the dielectric anisotropy of nonwoven fabrics and fiber distribution at microwave frequencies by our microwave method. Here, we describe such an experimental study, comparing the results with those from the mechanical breaking strength method.

Experimental

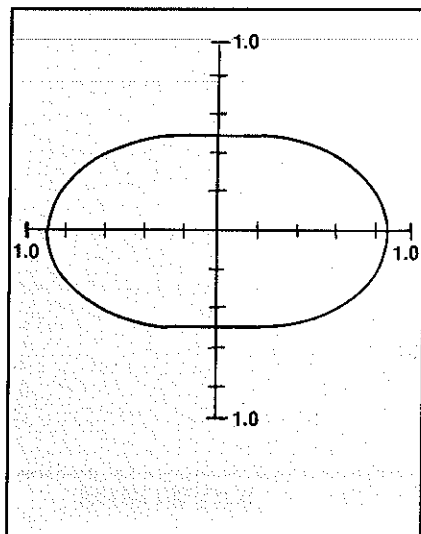
The samples were nonwoven fabrics consisting of rayon fibers with a basis weight of 43 g/m² and those consisting

of polyester fibers with a basis weight of 100 g/m², all prepared by the dry process method. Binders were used for bonding these fabrics.

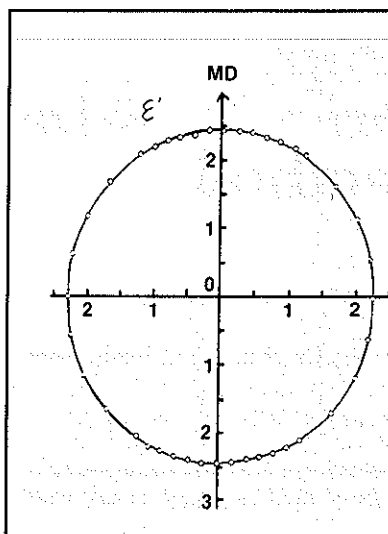
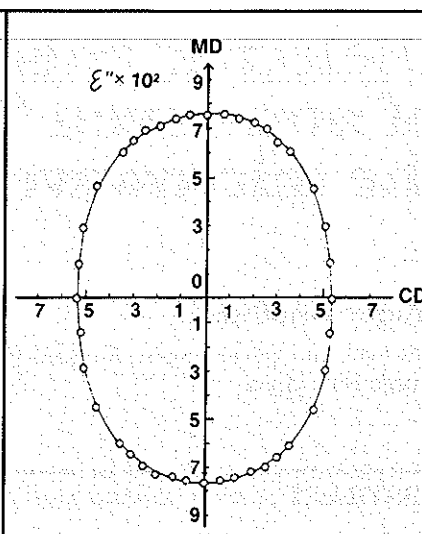
Dielectric measurements at microwave frequencies were made on a microwave molecular orientation analyzer, MOA-2001A (1-7). Polarized microwaves were irradiated perpendicularly to the plane of a test sample, which was inserted in a cavity resonator system. The sample, 10 cm × 10 cm, was rotated around its central axis normal to the sheet plane. The measuring frequencies ranged from 3.8 GHz to 4.2 GHz.

The orientation pattern, the orientation angle, and the molecular orientation ratio were obtained within 30 s. Here, the orientation pattern corresponds to the angular dependence of transmitted microwave intensity at a fixed frequency (3). The molecular orientation ratio, which is related to the ratio of maximum to minimum

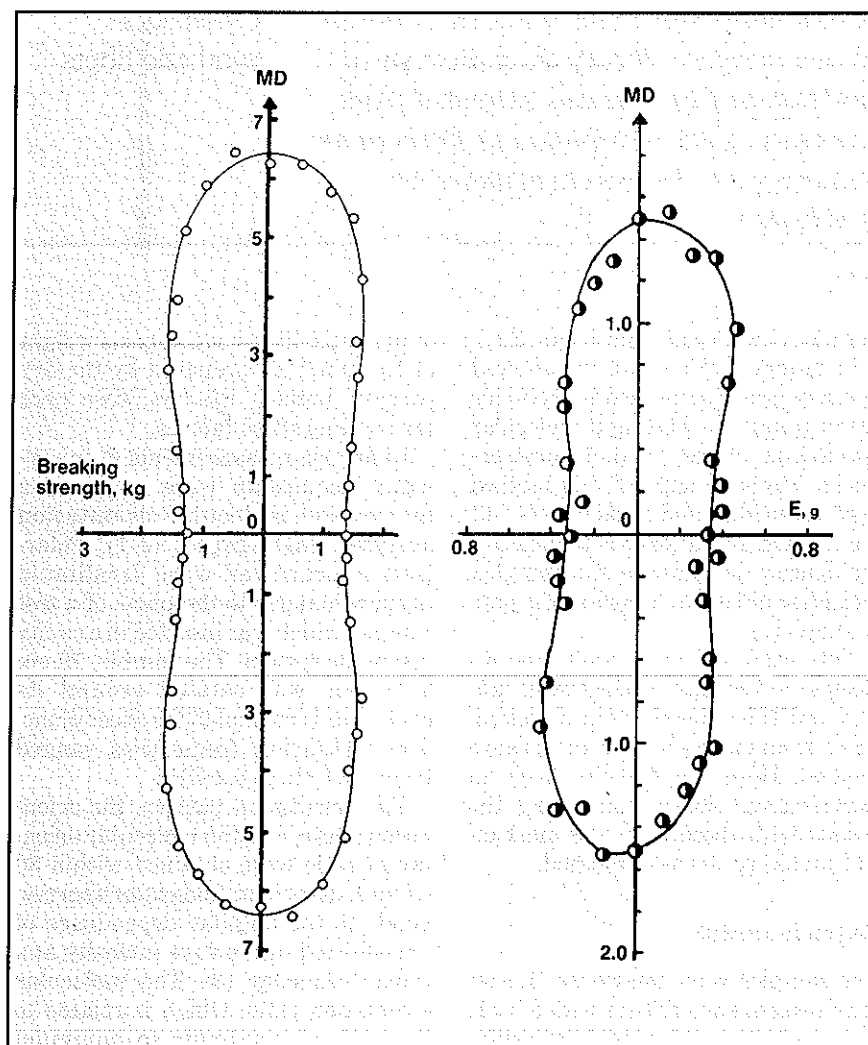
1. Angular dependence of transmitted microwave intensity at a fixed frequency (frequency = 3.98160 GHz, orientation angle = 0°, MOR = 1.764, CD/MD = 1.763, 43 g/m²)



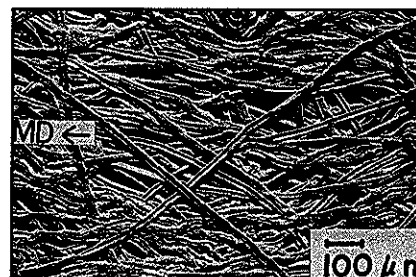
2. Angular dependence of ϵ' and ϵ'' at 4.0 GHz



3. Angular dependence of mechanical breaking strength and elastic modulus (43 g/m²)



4. Electron microphotograph for the surface of the fabric (43 g/m²)



transmitted microwaves, can be used as a measure of anisotropy (β). The ratio of transmitted microwave intensities in the cross-machine direction (CD) to the machine direction (MD) is designated as "CD/MD."

At each rotating angle, the complex dielectric constant (dielectric constant ϵ' and dielectric loss ϵ'') was also determined within 30 s by measuring a resonance frequency and a Q value in the resonator system. Here, the resonance frequency is defined as one at a maximum of the transmitted microwave intensity in the resonance curve. The Q value is defined as the ratio of the resonance frequency to half the width of the resonance curve.

Mechanical breaking strength was measured for a nonwoven fabric consisting of rayon fibers with a basis weight of 43 g/m² and a size of 15 mm wide by 50 mm long at an extension rate of 50 mm/min using a testing machine manufactured by INTESCO

Co., Ltd., Japan. Young's modulus was obtained from the slope of a stress-strain curve at low strains. The temperature and the humidity were 20°C and 65% RH, respectively. The sample thickness was measured with a micrometer.

Evaluation of basis weight

A perturbation theory is applicable for the complex dielectric constant when the dielectric loss is small and the frequency shift is much smaller than the resonance frequency. For a sample inserted into a cavity resonator, the resonance frequency f_2 is given by Eq. 1 (4, 5):

$$f_2 = f_1 \{1 - (\epsilon' - 1)/cA_s\} \quad (1)$$

where

- c = parameter related to the depth of the cavity
- t = thickness of the sample
- A = constant associated with the MOA-2001A instrument
- ϵ' = dielectric constant of the sample
- $(\epsilon' - 1)$ = dielectric increment at the resonance frequency.

When the dielectric relaxation belongs to the Debye type the dielectric increment $(\epsilon'(\omega) - \epsilon'_\infty)$ at an angular frequency of ω is expressed by Eq. 2 (7, 8):

$$\epsilon'(\omega) - \epsilon'_\infty = (4N\mu^2/3\gamma) \{1/[1 + (\omega\tau)^2]\} (E_r/E) \quad (2)$$

where

- N = number of dipoles per unit volume
- μ = dipole moment
- γ = restoring force
- τ = relaxation time
- E_r = local electric field
- E = applied electric field
- $\epsilon'(\omega)$ = dielectric constant at the angular frequency of ω
- ϵ' = dielectric constant at high frequencies.

Since the density of the sample sheet is defined by the weight per unit volume, it is proportional to N . Putting the dielectric increment in Eq. 1 equal to that in Eq. 2, at the angular frequency considered, we have

$$f_2 = f_1 (1 - B_p t) \quad (3)$$

where

- B = constant
- ρ = density.

Equation 3 is rewritten as

$$f_2 = f_1 (1 - BW) \quad (4)$$

where

- W = basis weight, or weight per unit area.

Thus, we find that f_2 is proportional to W after the sample is inserted.

Results

Anisotropy

Figure 1 shows the angular dependence of transmitted microwave intensity at a fixed frequency of 4.0 GHz for nonwoven fabric consisting of rayon fibers with a basis weight of 43 g/m². The transmitted microwave intensity is the smallest in the machine direction. This means that the interaction between the electric field and the fibers in the fabric is the strongest in the machine direction.

The orientation pattern is similar to that observed previously (2, 4) for uniaxially oriented paper sheets consisting of pulp fibers. The value of 1.764 for the molecular orientation ratio (MOR) indicates an anisotropic orientation of fibers in the nonwoven fabric. The CD/MD value is 1.763. Since the orientation angle is set equal to zero in this case, the orientation pattern suggests that the fibers in the nonwoven fabric are oriented mainly in the machine direction. When the fibers are oriented randomly, the transmitted microwave intensities must be almost equal in all directions. Figure 2 shows the angular dependence of ϵ' and ϵ'' at 4.0 GHz for the same nonwoven fabric as that in Fig. 1. Both ϵ' and ϵ'' are larger in the machine direction than in the cross direction. The angular dependence of ϵ' and ϵ'' is similar to that observed for uniaxially oriented paper consisting of pulp fibers (2, 4). The unsymmetrical pattern for ϵ'' implies a remarkable anisotropy of the fibers, suggesting that the fibers are oriented mainly in the machine direction. We found that the angular dependence of ϵ' and ϵ'' gave almost circular patterns for a sample with randomly oriented fibers.

The angular dependence of mechanical breaking strength and that of elastic modulus (E) for the nonwoven fabric are shown in Fig. 3. (The sample size was of 15 mm wide $\times$ 50 mm long, and the extension speed was 50 mm/min.) Both mechanical breaking strength and the elastic modulus are largest in the machine direction and smallest in the cross direction, being consistent with the angular dependence of transmitted microwave intensity and that of ϵ'' .

The electron microphotograph for the surface of the nonwoven fabric, Fig. 4, confirms the suggestion that the rayon fibers in the nonwoven fabric are oriented predominantly in the machine direction. As in Fig. 3, the direction for the maximum for ϵ'' —the machine direction—coincides with that for the maximum in mechanical breaking strength and with that in which the main axes of the rayon fibers are oriented. Such coincidence was also found for uniaxially oriented paper sheets consisting of pulp fibers and voids (2, 4). Therefore, we conclude that the fibers of the nonwoven fabric are oriented mainly in the direction of the maximum in ϵ'' .

Basis weight

Figure 5 shows the dependence of resonance frequency measurements on basis weight for the same nonwoven fabric. Here, the sheets with different basis weights were prepared by piling the fabrics cut successively in the MD direction. The resonance frequency measured in the machine direction decreases with increasing basis weight. This decrease can be expressed as

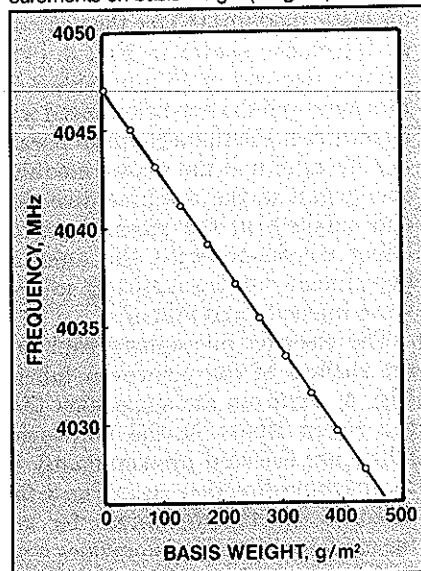
$$f = 4046.882 - 0.0391 W \quad (5)$$

The correlation coefficient between f and W was -0.998. Here, the numerical constant and coefficient in Eq. 5 depend on the cavity resonator system and the species of sample, respectively. Since the accuracy in frequency is at most 0.005 MHz, a change of 0.1 g/m² in W should be detected. Thus, f may be used for estimating W . In other words, a variation in basis weight in the cross direction of fabric sheets may be examined by measuring the resonance frequency.

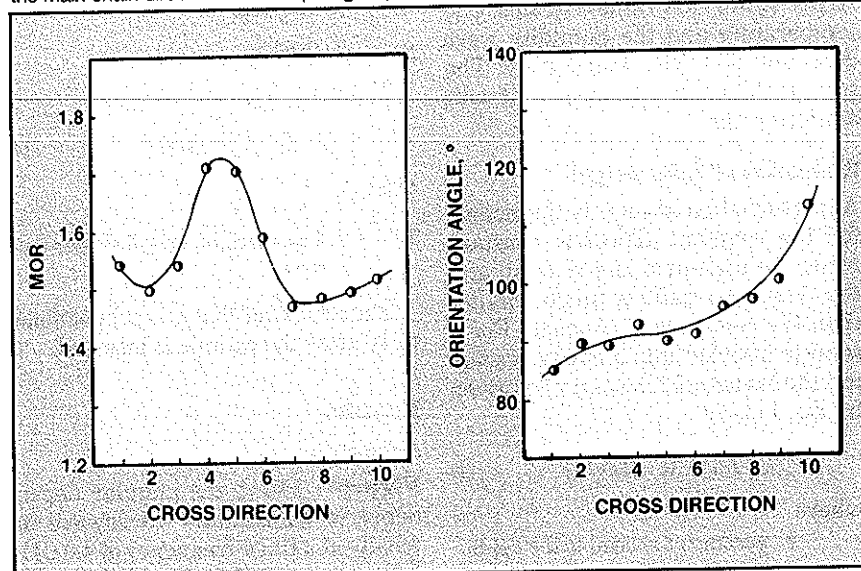
Applications

Figure 6 shows molecular orientation

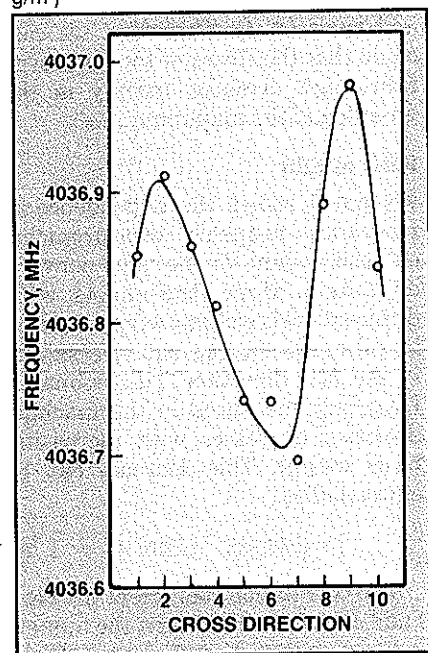
5. Dependence of resonance frequency measurements on basis weight (43 g/m²)



6. The molecular orientation ratio is a measure of anisotropy, and the orientation angle reflects the main chain direction of fibers (100 g/m²)



7. The resonance frequency reflects a variation in the basis weight of the nonwoven fabric (100 g/m²)



ratio and orientation angles observed at different positions in the cross direction for a nonwoven fabric consisting of polyester fibers with a basis weight of 100 g/m² and a width of 1000 mm. The positions are numbered from one end to the other along the cross direction of the fabric. Both molecular orientation ratio and the orientation angles θ change with various positions. The molecular orientation ratio has a maximum near

the center in the cross direction, while θ has a maximum at one end. Figure 7 shows the values of f obtained for the same nonwoven fabric in the cross direction. The variation in f reflects the variation in basis weight, which implies that W of the nonwoven fabric changes with changing position in the cross direction. The results reveal that the distribution of fibers in the polyester fabric is now uniform in the cross direction.

Discussion

The orientation pattern and the angular dependence of ϵ' and ϵ'' give information on physical properties of nonwoven fabrics in the cross direction. For our nonwoven fabrics consisting of rayon fibers, we may write the angle ϕ between the main axis of fibers and the machine direction as

$$\langle \cos^2 \phi \rangle = \frac{\int_0^\pi \epsilon''(\phi) \cos^2 \phi \, d\phi}{\int_0^\pi \epsilon''(\phi) \, d\phi} \quad (6)$$

which becomes equal to 1 for a perfectly oriented film in the machine direction and becomes equal to 1/2 for a randomly oriented sample. Here, $\cos^2 \phi$ was used instead of $\sin^2 \phi$ because ϵ'' was the largest in the direction of the main chains for fibers (5). The values of $\epsilon''(\phi)$ may also be determined from the angular dependence of ϵ'' at a fixed frequency. In the case of two-dimensional distribution of fibers on the plane of fabrics, the

orientation function may conveniently be used:

$$F = (2 \langle \cos^2 \phi \rangle - 1) / 2 \quad (7)$$

where

F = fiber orientation function in the nonwoven fabric.

This function should be 1/2 for a perfectly oriented fabric in the machine direction, while it is zero for a randomly oriented fabric.

We determined this fiber orientation value F to be 0.043 from the angular dependence of ϵ'' in Fig. 2. This F value is relatively small, indicating that the fibers are oriented in a fixed direction, on the average. The quality control for the mechanical uniformity of fabric can be determined by examining dielectric values and then changing machine conditions for the preparation of sheets. Thus, the use of the microwave method will improve the nonuniformity in quality along the cross direction.

It is not feasible to measure the thickness of nonwoven fabrics accurately by contact methods, because the fabrics consisting of fibers and voids are flexible and easily compressed. The quality of nonwoven fabrics may be checked by measuring W of such fabrics instead of measuring thickness with a micrometer. However, since it takes a long time using the conventional method to measure the weight and volume of fabrics and to

determine W , it is not so convenient.

Dielectric measurements at audio frequencies (9-12) are not always effective for studying the physical properties of nonwoven fabrics, owing to the difficulty in making electrodes by evaporating metal. The evaporated metal penetrates into the fiber sheets with many voids. Using the microwave method, the fiber orientation can be determined quickly without contact, avoiding the problem inherent in dielectric measurements at audio frequencies.

In conclusion, the microwave method is quite promising for evaluating the physical properties of nonwoven fabrics consisting of polymer fibers and voids. □

Literature cited

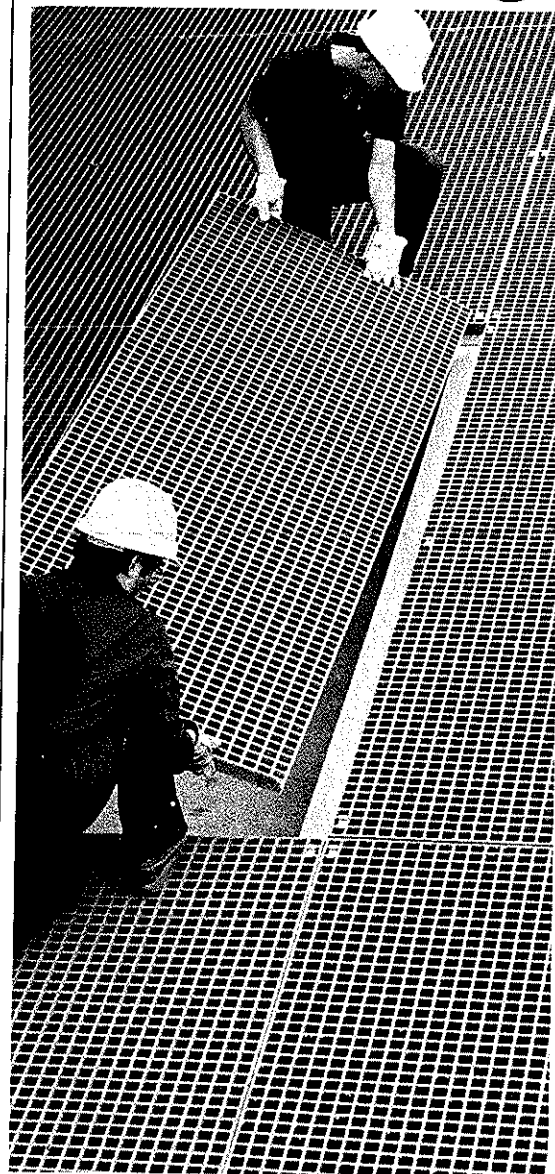
1. Osaki, S., Bul. Jpn. Soc. Print. Sci. Technol., 23(1): 19(1985).
2. Osaki, S., Tappi J. 70(2): 105(1987).
3. Osaki, S., Polym. J. 19(7): 821(1987).
4. Osaki, S., J. Appl. Polym. Sci., 37: 528(1989).
5. Osaki, S., J. Appl. Phys., 64(8): 4181(1988).
6. Yamamoto, K., Osaki, S., Yamashita, S., and Yamada, M., Cell. and Mol. Biol., 37: 527(1988).
7. Osaki, S., to be submitted to J. Appl. Polym. Sci.
8. Debye, P., Polar Molecules, Dover Publications, Inc., New York, 1928.
9. McCrum, N. G., Read, R. E., and Williams, G., Anelastic and Dielectric Effects in Polymeric Solids, Wiley, New York, 1976.
10. Osaki, S., Uemura, S., and Ishida, Y., J. Polym. Sci., A-2, 9: 585(1971).
11. Osaki, S., Ishida, Y., and Yamafuji, K., Polym. J., 12: 171(1980).
12. Osaki, S. and Kotaka, T., Ferroelectrics 32: 1(1981).

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