TORSION TESTING OF POLYVINYL CHLORIDE SHEET

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The behavior of polyvinyl chloride sheet in torsion has been studied. Normal round test pieces were tested at strain rates of 0.3 and 1 rpm. The specimens were cut in the longitudinal and transverse directions of the sheet. The principal strength and plasticity characteristics of the material in torsion were obtained. During the tests torsion diagrams \( M_t \text{ vs. } \varphi \) were recorded. The specimens failed in shear. The shear modulus was determined on a special table device. The experiments showed that the shear modulus, limit of proportionality, and tensile strength have the same values in both longitudinal and transverse directions. The values of the angle of twist at failure are large and vary over a wide range.

There is little information in the literature on the behavior of polyvinyl chloride (PVC) sheet in torsion, although its mechanical properties have been investigated comparatively thoroughly. The purpose of this record was to study the type of failure and to determine the shear modulus and mechanical characteristics of PVC sheet in torsion. The tests were carried out on a KM-50 machine adjusted to give a maximal torque of 1000 kgf·cm. The test specimens were cylindrical with square ends (Fig. 1). Thirty-two specimens were made from 20 mm thick grade B PVC sheet. To study possible anisotropy of the PVC sheet in torsion the specimens were cut along and across the direction of the sheet. The specimens were loaded at strain rates of 0.3 and 1 rpm at a temperature of 20 ± 2°C up to total failure.

During the tests torsion diagrams were recorded in coordinates \( M_t \) (torque) and \( \varphi \) (angle of twist). A typical torsion diagram (Fig. 2) consists of three characteristic sections. The initial section of the diagram up to point A, corresponding to the limit of proportionality is an inclined straight line. Beyond point A deformation of the specimen increases more rapidly than the torque, and a curve develops in the diagram (section AC). At this stage of testing, deformation is reversible and is composed of elastic (section OA) and viscoelastic (section AC) deformations. Along with the reversible deformation there is some irreversible deformation, which can be disregarded for practical purposes.

The load increases up to point C, corresponding to the limit of forced elasticity, at which the torque reaches a maximum. Further increase in deformation occurs at a virtually constant value of the torque. On the torsion diagram this section is a straight line parallel to the x axis. Beyond point C forced elastic deformations appear. These are irreversible at normal temperatures but disappear when the specimen is heated. They are initially concentrated in one or two small zones in the working length, then gradually propagate throughout the entire specimen. The surface of the specimen in these zones becomes light-brown and dull.

The reversible and irreversible deformations are distributed uniformly over the test length of the specimen. Failure occurs at point D at a large value of the angle of twist. The torsion diagrams of specimens cut along and across the direction of the sheet are similar, but differ in the magnitude of the angle of twist at failure. Testing at strain rates of 0.3 and 1 rpm, as the torsion diagrams show, has little effect on the nature of the curves.

The principal strength and plasticity characteristics of PVC sheet in torsion were established from the \( M_t \text{ vs. } \varphi \) diagrams.

The limit of proportionality was calculated from the formula

\[
\tau_{pr} = \frac{M_{pr}}{W_p} \text{ kgf/cm}^2,
\]

where \( M_{pr} \) is the torque corresponding to the boundary of the linear section of the diagram, kgf · cm; \( W_p = \pi d^3/16 \) is the section modulus of torsion for a section with diameter \( d \), cm³, before testing. The nominal strength in torsion was calculated from the formula

\[
\tau_{\nu} = \frac{M_{\nu}}{W_p} \text{ kgf/cm}^2,
\]

where \( M_{\nu} \) is the maximal torque preceding failure of the specimen, kgf · cm.

The value calculated from formula (2) appreciably exceeds the true strength of PVC sheet in torsion.
with account for plastic deformation, which is given by

$$t_{\text{max}} = \frac{M_n}{W_{\text{pl}}} \text{ kgf/cm}^2,$$  \hspace{1cm} (3)

where $p_{\text{pl}} = \pi d^3/12$ is the plastic section modulus of torsion for a specimen with diameter $d$, cm$^3$, before testing. The relation between the torsional strength and tensile strength of PVC sheet, based on Mohr's theory, is

$$\tau_v = (0.5 - 0.6) \sigma_{vt}.$$  \hspace{1cm} (4)

The relation between $\tau_v$ and $\sigma_{vt}$ calculated from the experimental data for purposes of evaluating the experiment has the enhanced value: $\tau_v = (0.684 - 0.800) \times \sigma_{vt}$. For the proportional limits the ratio is equal to $\tau_{pr} = (0.625 - 0.738) \sigma_{pr}$. The ratio of the true torsional and tensile strengths based on the experimental results is: $t_{\text{max}} = (0.510 - 0.596) \sigma_{vt}$. Consequently, the true torsional strength of PVC sheet calculated from formula (3) coincides with its theoretical value.

The method of determining the shear modulus $G$ was as follows. We found the angle of twist during gradual loading beyond the limit of proportionality and calculated from the average value of this angle. The tests were carried out on a special table device which enabled us to apply the load in steps and at the same time measure the angle of twist.

The average increment of the angle of twist within the limits of elastic deformation is related to the increment of torque by the linear law

$$\Delta \varphi_{av} = \frac{\Delta M_t l}{G l_p},$$  \hspace{1cm} (8)

whence

$$G = \frac{\Delta M_t l}{\Delta \varphi_{av} l_p} \text{ kgf/cm}^2,$$ \hspace{1cm} (9)

where $\Delta M_t$ is the torque, kgf·cm (value of loading step); $l$ is the nominal length of the specimen, cm; $\Delta \varphi_{av}$ is the arithmetic mean increment of the angle of twist, radian; $l_p = \pi d^4/32$ is the moment of inertia of torsion, cm$^4$.

The average value of the shear modulus $G$ ($G = 10\,000$ kgf/cm$^2$) was established experimentally. The shear modulus $G$ is related to the modulus of elasticity $E$ and Poisson's ratio $\mu$ as follows:

$$G = \frac{E}{2(1+\mu)} \text{ kgf/cm}^2.$$  \hspace{1cm} (10)

The theoretical value of the shear modulus calculated from (10) with $E = 30\,000$ kgf/cm$^2$ and $\mu = 0.370$ has the value $G = 10\,950$ kgf/cm$^2$, which is comparatively close to the experimental results. The results of the torsion tests on PVC sheet are given in the table.

The twisted specimen failed at large strains produced by shear stresses by shearing in a plane perpendicular to its axis (Fig. 3). The fracture is uneven,

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### Mechanical Characteristics and Shear Modulus of PVC Sheet in Torsion

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Proportional limit $\tau_{pr}$, kgf/cm$^2$</th>
<th>Nominal torsional strength $\tau_{vt}$, kgf/cm$^2$</th>
<th>True torsional strength $t_{\text{max}}$, kgf/cm$^2$</th>
<th>Angle of twist at failure Degrees</th>
<th>Angle of shear in torsion $\gamma$, deg</th>
<th>Specific angle of twist $\varphi$ per 1 mm length, radian</th>
<th>Shear modulus $G$, kgf/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut along direction of sheet</td>
<td>170—210</td>
<td>420—470</td>
<td>320—350</td>
<td>900—2100</td>
<td>15.70—36.63</td>
<td>38—61</td>
<td>0.1570—0.3663</td>
</tr>
<tr>
<td>Cut across direction of sheet</td>
<td>180—210</td>
<td>410—480</td>
<td>310—360</td>
<td>400—1900</td>
<td>6.98—33.14</td>
<td>19—59</td>
<td>0.0698—0.3314</td>
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</tbody>
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