Evaluation of Impact Absorbing Properties of Thermoplastic Elastomers

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Abstract. The thermoplastic elastomers (TPEs) are physical mixtures of polymers. Impact absorbing materials in sports equipment are one of the expected applications of TPEs due to good process ability and less-smell. For examples, face guards, head-gears and protectors are expected to be applied. In this paper, static and dynamic mechanical properties of TPEs were investigated to expand the applicability of TPEs to the impact absorbing material for the sports equipment. In this study, TPEs developed by the Kuraray Plastics Co., Ltd. were applied for static and dynamic tests. To investigate the static mechanical properties of TPEs, the uniaxial tensile loading tests were conducted. The nonlinear viscoelasticity considering damage were applied to representation of the experimental results. The FEM analysis showed good applicability to static mechanical properties including damage which was excited by the maximum deformation. TPE. To investigate the dynamic mechanical properties of TPEs, a drop weight impact testing machine was developed. Impact absorbing properties of TPEs were evaluated by the impact force and impact time with baseball weight.

1. Introduction

The thermoplastic elastomers (TPEs) are physical mixtures of polymers. The TPEs are manufactured by pressing or injection process without vulcanization agents. The mechanical properties of the thermoplastic elastomers are getting similar to rubber by technology developments. The TPEs show good process ability and flexibilities at low temperature, even if TPEs were made by extrusion or injection molding[1]. Now, the TPEs are widely used for numerous products such as automobile parts, lifestyle products and electric appliances. The strong points of TPEs are light weight, rubber-like mechanical behavior and less-smell, so they are expected to apply to various sports equipment, for the purpose of absorbing impact[1][2][3]. The purpose of this study is to expand the applicability of thermoplastic elastomers to impact absorbing material for sports equipment. Tensile loading test and cyclic tensile loading test were conducted to obtain the static mechanical properties of TPEs. An original drop weight impact testing machine for TPEs with real baseball weight was developed and impact tests were conducted to obtain the dynamic mechanical properties of TPEs for shock absorbing material.

2. Tensile loading test

Tensile loading tests and cyclic tensile loading tests were conducted to evaluate the static mechanical properties of TPEs. Materials of the specimens were styrene elastomers, polyolefin and process oil. They were processed by injection molding after heat melting. First, tensile loading tests on specimens were conducted using a uniaxial tensile loading machine. The deformation of the specimens was measured by using a displacement camera system. The strain rates were set to 0.1%/s, 1.0%/s and 10%/s. Fig.1 shows the relationship between stress and strain given by the
tensile loading test. From the tensile loading test results, the TPEs was possible to deform over 400% of strain.

Also, the cyclic tensile loading tests were conducted of which stretch for cyclic deformations were 150%, 200% and 250%. Four cycle of deformation were applied to the tensile specimen continuously and maximum stretch decrease from 150% to 250%. Fig. 2 (a), (b) and (c) show the cyclic loading test results for the first cycle and the third cycle.

![Fig. 1. Tensile loading test results of TPEs](image1)

(a) Strain rate = 0.1%/sec  
(b) Strain rate = 1.0%/sec
3. Nonlinear viscoelastic model

Stiffness softening were obtained by the results. In this study, generalized relaxation model and softening model were applied, in order to reproduce the mechanical properties of TPEs. The following elastic energy function capable of considering compressibility by complement strain energy has been applied to TPEs in this study[4].

\[
W(C, p, Q_l) = \tilde{W}^0(C, \tilde{Z}^m) - \sum_{i=1}^{N_d} \frac{1}{2} C : Q_i + p(f - 1) - U^0_c
\]  

(1)

where \(W\) is the elastic energy function, \(\tilde{C}\) is the volume-preserved right Cauchy-Green tensor, the symbol \(\tilde{\cdot}\) mean the elastic component, \(\tilde{W}^0\) is the elastic energy function of deviation component of hyperelastic constitutive equation, \(\tilde{Z}^m\) is the internal variable for damage like the Mullins effect, \(p\) is the Lagrange multiplier which is equivalent to hydrostatic pressure, \(U^0_c\) is the complement strain energy representing relationship between volumetric strain and pressure, \(Q_l\) is viscous stress and \(N_d\) is number of dashpots. Viscoelastic model consists of springs and dashpots4, as shown in Fig. 3. The 2nd Piola-Kirchhoff stress is given by

\[
S = 2 \frac{\partial W}{\partial \epsilon}
\]  

(2)

The evolutionary equation of viscous stress \(Q_l\) under constant deformation is given as follows:

\[
\dot{Q}_l(t) + \frac{1}{\tau_i} Q_l(t) = \frac{\gamma_i}{\tau_i} DEV \left( 2 \frac{\partial \tilde{W}^0}{\partial \epsilon} \right)
\]  

(3)

where the notation \(DEV\) is correspond to \(DEV(\bullet) = (\bullet) - \frac{1}{3} [(\bullet) : C] C^{-1}\), \(\tau_i\) is the relaxation time, \(\gamma_i\) is the stiffness ratio. From cyclic loading test results, the material parameters of viscosity were determined as \(N_d = 2\), \(\gamma_1 = 0.34\), \(\tau_1 = 12s\), \(\gamma_2 = 0.12\), \(\tau_2 = 350s\), respectively. From the cyclic tensile loading test results, the stress-strain relationships of the TPEs were confirmed to depend on the maximum stretch[5]. To represent this behavior, following internal variable \(\tilde{Z}_e\) was applied to introduce the damage function.

\[
\tilde{Z}_e = \sqrt{2\tilde{W}(\tilde{C}(s))}
\]  

(4)
Now, let $\tilde{\varepsilon}_m^T$ be the maximum value of $\varepsilon_s$ over the past history up to current time $t$. The damage function $\tilde{g}(\tilde{\varepsilon}_m^T)$ was adopted exponential form as follows:

$$
\tilde{g}(\tilde{\varepsilon}_m^T) = \beta + (1 - \beta) \frac{1 - \exp(-\tilde{\varepsilon}_m^T/\alpha)}{\tilde{\varepsilon}_m^T/\alpha}
$$

(5)

Here, $\alpha$ and $\beta$ are material parameters of the damage model. The elastic potential function $\tilde{W}^0(\tilde{\varepsilon}_m^T)$ was replaced by the following function.

$$
\tilde{W}^0(\tilde{\varepsilon}_m^T) = \tilde{g}(\tilde{\varepsilon}_m^T)(C_{11}(\tilde{I}_1 - 3) + C_{12}(\tilde{I}_2 - 3) + C_{21}(\tilde{I}_2 - 3))
$$

(6)

From the cyclic tensile loading test results, material parameters $C_{11}$, $C_{12}$ and $C_{21}$ were determined as 0.555MPa, -0.003MPa, 0.22MPa, respectively. Also, the parameters of damage model $\alpha$ and $\beta$ were determined as 0.735 and 0.0243. In Fig. 2, calculated stress-strain relationships are shown.

4. Drop weight impact test

The drop weight impact testing method is one of the major methods to investigate the dynamic properties of any materials. Drop weight impact testing of materials is a method to measure the ability of a specimen to absorb energy before breaking[6]. Also, the drop weight impact test is applicable to characterize the mechanical properties of thermoplastic material at relatively high strain rates[7]. In order to evaluate impact absorbing properties of materials such as polymers, concrete and carbon fiber reinforced plastics, many drop weight impact tests with a steel impactor have been conducted[6],[8],[9]. It is hard to measure the accurate energy absorbing performance of the TPEs with the normal weight impact testing method because TPEs show fracture at the contact surface with steel impactor.

In this study, original drop weight impact test machine for TPEs was developed to evaluate the applicability to sports equipment. For investigating of applicability to sports fields, some balls in baseball were introduced as the impact weight. The drop weight impact test machine is shown in Fig. 5. The test machine consists of a base plate, an impact plate, four supports and a top plate. Three load-cells were applied between the impact plate and the base plate. The size of TPE specimen which was placed on the impact plate were 50 mm ×50 mm ×10 mm in width, length and depth, respectively. The baseball which was used as the drop weight is shown in Fig. 4. The weight of the baseball (manufactured by the Rawlings Co., Ltd.) was 147g (0.147kg) and the
diameter was 74mm. The ball was dropped from a height of 0.5m, 1.0m and 1.5m on to the impact plate 8-times (n=8) under the same conditions. The impact velocity $v_{in}$ was estimated by $v_{in} = \sqrt{2gH}$. Here, notation $g$ is the gravitational acceleration and $H$ is the height releasing the ball. A high-speed camera was applied to record the digital image during impact tests. The motion tracking software (TEMA 3D) was used to measure the impact velocity $v_{in}$. The impact velocity $v_{in}$ was confirmed that was appropriate by comparing with predicted velocity. The coefficient of restitution (COR) between the impact plate and the ball was calculated as the ratio of initial speed $v_{in}$ and rebound speed $v_{re}$ as follows:

$$\text{COR} = \frac{v_{re}}{v_{in}}$$

where $v_{re}$ was speed of rebounded ball. The COR was calculated on the assumption that the impact plate did not move during the tests. The impulse of impact test was calculated as $I = \int F(t) dt$. $F(t)$ is the total load measured by three load-cells at time $t$. The relationships between impact load and time given by the drop weight impact tests are shown in Fig. 6 (a), (b) and (c). These results show the effects of TPEs which are extension of contact time and reduction of peak load. The COR was decreased as the ball speed increased. Input momentum was calculated as $M_{in} = mv_{in}$. The experimental results are summarized in Table 1.
5. Results and discussion

From the tensile loading test results, TPEs show viscoelastic properties and deformation over 400% of strain. The nonlinear viscoelastic model which is applied to rubber like material show high applicability to the TPE’s mechanical behavior considering the effect of the strain rate and damage phenomena. TPEs are considered to have the same processability as rubber.

From the drop weight impact test results, the shock absorbing properties of TPEs were conducted with the ball weight to evaluate the TPE’s applicability to sports equipment. Developed dropped weight impact test machine worked correctly. Impact load in 0.003s were able to be measured. From the drop weight impact tests results, the peak load was from 1500N to 1800N when the ball was dropped from a height of 1.5m \((v_{in} = 20km/h)\). Reduction of the peak load by 6% to 10% were confirmed regardless of ball speed \(v_{in}\). The contact time of impact tests were slightly extended when the TPEs were applied to the shock absorbing material.
6. Conclusion

In this study, static tensile loading tests and drop weight impact tests were carried out to expand the applicability of TPEs to impact absorbing materials for sports. Tensile loading test and cyclic loading test were conducted under three different strain rates. These results showed that TPEs was possible to deform over 400% and TPEs showed the viscosity and the stiffness softening like rubber material. An original drop weight impact test machine for TPEs with real baseball weight was developed and drop weight impact tests were conducted. The results show that the TPEs reduce the peak load by 6% to 10% and extend the contact time slightly.

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