Article

High Performance Polyurethane Elastomers
Using New Cyclaliphatic DiisocyanateSatoshi YAMASAKI^{*,†}, Goro KUWAMURA^{*}, Hirokazu MORITA^{*}, Daisuke HASEGAWA^{*}, Ken KOJIO^{**,***}, Atsushi TAKAHARA^{**,***}^{*}Specialty Polyurethane materials Development Group, Synthetic Chemicals Laboratory,
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Trans-1,4-bis (isocyanatomethyl) cyclohexane (1,4- H_6 XDI) has been newly developed as a novel cycloaliphatic diisocyanate with a high symmetric chemical structure. The PUEs were prepared with 1,4- H_6 XDI, polyesterpolyol as a long chain polyol and 1,4-butanediol (BD) as a chain extender. As the representative aromatic and aliphatic diisocyanates, 4,4'-diphenylmethane diisocyanate (MDI) and dicyclohexyl methane-4,4'-diisocyanate (H_{12} MDI) were also used as the control. As a result, it was revealed that 1,4- H_6 XDI-based PUEs achieved high elasticity such as higher impact resilience, lower compression set, improved heat resistant, and good light stability which was not able to be realized with the existing diisocyanates. The reason is explained that the hard segment chains of the 1,4- H_6 XDI-based PUEs crystallized well with formation of hydrogen bonds in the PUEs due to the symmetric structure of 1,4- H_6 XDI. Thus, the 1,4- H_6 XDI-based PUEs can provide superior properties such as mechanical and thermal properties and excellent light stability compared to existing diisocyanate-based PUEs by rheological evaluation.

Key Words: 1,4-Bis (isocyanatomethyl) cyclohexane / Micro-phase separated structure / Polyurethane elastomer / Rheological property

1. INTRODUCTION

Most of polyurethane elastomers (PUEs) have been generally produced from three raw materials such as long chain polyol, diisocyanate and short chain polyols (chain extender). Many combinations of these raw materials can control various properties of the PUEs which are composed of alternating hard and soft segments. These segments are micro-phase-separated into two phases depending on their thermodynamical immiscibility. Thus, the chemical structure of diisocyanate is one of the most important factors to control microphase-separated structure. Diisocyanate can be classified into aromatic, aliphatic, cycloaliphatic and aralkyl ones.

The major diisocyanates in the polyurethane industry are aromatic diisocyanates such as 4,4'-diphenyl methane diisocyanate (MDI) and toluene diisocyanate (TDI). MDI is applied to various polyurethane products, in particular, elastomer which requires high resilience, tensile strength and high softening temperature as an indication of heat resistance^{1,2)}.

On the other hand, for applications which requires light and weather stabilities, the aromatic diisocyanates mentioned above will not be desirable because polyurethanes prepared by these aromatic diisocyanates become yellowing due to the formation of a quinoid structure of aromatic ring³⁾ if exposed to light for a long time.

For the light stable applications, aliphatic diisocyanates, such as dicyclohexyl methane -4, 4'- diisocyanate (H_{12} MDI)⁴⁾, isophorone diisocyanate (IPDI)⁵⁾, hexamethylene diisocyanate (HDI)⁶⁾, 2,5(2,6)-bis(isocyanatomethyl)bicyclo[2.2.1] heptane (NBDITM)⁶⁾ and 1,3-bis (isocyanatemethyle) cyclohexane (1,3- H_6 XDI)⁷⁾, have been applied as the raw materials. However, polyurethanes based on these aliphatic diisocyanates exhibits inferior elasticity such as resilience, compression set, strength and dynamic performance and heat resistance¹⁾ due to poor cohesive force of resulting hard segment chain.

So the new aliphatic diisocyanate which produces good elastic property, heat resistance and light stability has been demanded from not only industrial but academic points of view. We have developed and commercialized a new cycloaliphatic diisocyanate, *trans*-1,4-bis (isocyanatomethyl) cyclohexane (1,4- H_6 XDI) which is referred to as 1,4- H_6 XDI⁸⁾. It is

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expected that 1,4- H_6 XDI is applicable to various polyurethane products such as thermoplastic polyurethane elastomer (TPU)^{8,9,10,11,18)}, thermosetting polyurethane elastomer (TSU)^{8,9,12-14)}, polyurethane solution^{8,15)}, polyisocyanate hardener¹⁶⁾, polyurethane dispersion (PUD)^{15,17)} and flexible polyurethane foam^{8,18)}.

This paper will report superior properties of polyurethane elastomers based on 1,4- H_6 XDI, in particular, mechanical and thermal properties using rheological technique. MDI and H_{12} MDI-based polyurethane elastomers were employed for comparison. We synthesized two polyurethanes, which are “basic PUE” and “practical PUE”. Basic PUE is prepared with a condition of making a TSU. On the contrary, practical PUE is prepared with a condition of making a TPU.

2. EXPERIMENTAL

2.1 Materials

Long chain polyol

Polyesterpolyol which is made from the mixture of ethylene glycol and 1,4-butanediol and adipic acid (trade name, U-224, referred to PEBA-2000, Mitsui Chemicals Inc.) were employed. The number-average molecular weight (M_n) and hydroxyl number were ca. 2,000 and 56.2 mgKOH/g, respectively.

Diisocyanate

1,4- H_6 XDI is produced by phosgenation reaction of *trans*-1,4-bis (diaminomethyl) cyclohexane (1,4- H_6 XDA)¹⁹⁾, which are obtained via nuclear hydrogenation and isomerization reaction of *p*-xylylene diamine by using some catalysts and additives. Figure 1 shows the process for 1,4- H_6 XDI. It has a very linear and symmetrical structure with respect to the isocyanate groups, since it is enriched in the *trans* isomer. The product is a clear liquid at room temperature with 43.2 of concentration of isocyanate groups (NCO%). The melting point and flash point are ca. 8 and 167 °C, respectively. It can be stored at room temperature.

MDI (4,4'-MDI, MDI-PH, Mitsui Chemicals Inc.) and H_{12} MDI (Evonik) were used as the aromatic and aliphatic diisocyanates.

Chain Extender

1,4-butanediol (1,4-BDO, Aldrich) was used as a chain extender. 1,4-BDO was distilled and dried by bubbling dry nitrogen under a reduced pressure at 100 °C for 4 h.

2.2 Preparation for basic and practical PUE

Basic PUEs were made by a prepolymer method. Basic PUE in this article is also called thermoset polyurethane elastomer. The isocyanate-terminated urethane prepolymers were prepared from a wide variety of combination of long chain polyol and diisocyanate with various equivalent of [NCO]/[OH] (NCO index) at ca. 80 °C until achievement of target NCO% under a nitrogen atmosphere. The reaction was pursued by an amine equivalent method. The prepolymer and 1,4-BDO were set to be 80 °C and then mixed well for ca. 10 min at 80 °C at stoichiometry of 1.02 at $[NCO]_{\text{prepolymer}}/[OH]_{1,4-BDO}$ after addition of catalyst (Dibutyltin dilaurate, DBTDL, Aldrich) and anti-oxidant bis[3-(3-*tert*-butyl-4-hydroxy-5-methylphenyl) propionic acid], BASF). The reaction mixture was poured into a stainless steel mold with 2 mm of thickness. The curing condition was at 100 °C for 22 hours and then annealed at 23 °C and 55 % relative humidity for 7 days. PUEs with various different hardness were prepared by changing the concentration of the hard segment composed of the diisocyanate and 1,4-BDO.

On the contrary, practical PUEs were also prepared by prepolymer method at a batch procedure for the purpose of investigating the potential of 1,4- H_6 XDI in TPU application. Procedure of practical PUE was as follows. The isocyanate-terminated urethane prepolymers were also synthesized the same procedure at preparation of PUEs. After the temperatures of prepolymer and 1,4-BDO were set to be 80 °C, the prepolymer and 1,4-BDO were mixed well with the ratios of $[NCO]_{\text{prepolymer}}/[OH]_{1,4-BDO} = 1.01$ at 80 °C for 10 min after

Fig. 1. The production process for 1,4- H_6 XDI.

addition of catalyst (DBTDL), anti-oxidant bis[3-(3-tert-butyl-4-hydroxy-5-methylphenyl) propionic acid], BASF) and hindered amine light stabilizer (bis(1,2,2,6,6-pentamethyl-4-piperidyl) sebacate, ADEKA) under a nitrogen atmosphere. Then the reaction mixture was poured into the Teflon® coating container and then cured for 2 hours at 130 °C and 20 hours at 110 °C to obtain a polyurethane sheet. Next, the polyurethane sheet was cut and granulated. After drying the TPU (practical PUE) granule, TPU pellets were prepared by a uniaxial extrusion at the range from 200 °C to 235 °C of cylinder temperature.

The TPU pellets obtained were dried in an oven at 80 °C for 12 h at a reduced pressure. The TPU sheets were made by injection molding operated by NEX-140 (Injection machine, D = 40 mm, L/D = 24, NISSEI PLASTIC INDUSTRIAL) with the cylinder temperature range from 200 °C to 220 °C at injection speed of 60 mm s⁻¹ and back pressure range from 10 MPa to 20 MPa. TPU sheets were stored at 23 °C and 55 % relative humidity for at least one week.

2.3 Characterization

Mechanical and physical properties

Hardness, tensile test, tear strength and impact resilience, were measured by JIS K-7311 and JIS K-7312, respectively.

In particular, tensile test of the basic PUE and injection molding sheet prepared by TPU pellet was performed with an Instron type tensile tester (model U4410/U4400, Toyo Seiki Co., LTD.) equipped a device monitoring sample length at 23 °C and 55 % relative humidity. The samples were prepared with a steel stamping die (dumbbell type JIS No. 3). An initial length and elongation velocity were set to 20 mm and 300 mm min⁻¹ according to JIS K-7311 and 500 mm min⁻¹ according to JIS K-7312, respectively.

Thermal Mechanical Analysis (TMA)

The softening temperature of PUE and injection molding sheet prepared by TPU pellet was measured by using TMA (model TMA/SS6100, Seiko Instruments) according to JIS K-7196. The softening temperature was determined at temperatures ranging from -60 to 260 °C with a heating rate of 5 °C min⁻¹ and load of 500 mN under a nitrogen atmosphere.

Differential scanning calorimetry (DSC)

The thermal behavior was determined using DSC (model DSC6200, Seiko Instruments). DSC thermograms were obtained at temperatures ranging from -100 to 250 °C with a

heating rate of 10 °C min⁻¹ under a nitrogen atmosphere. Each sample was cooled at -100 °C and after being held at -100 °C for 10 min, measurements were carried out up to 270 °C. The sample weighed 8–10 mg and indium was used to calibrate the DSC cell.

Dynamic viscoelastic analysis (DMA)

The temperature dependence of the dynamic viscoelastic properties of injection molding sheet prepared by TPU pellet was measured using a Rheometrics mechanical spectrometer (model RSA III, TA instruments) at temperatures ranging from -80 to 200 °C, at a heating rate of 3 °C min⁻¹ and a frequency of 1 Hz under a nitrogen atmosphere.

Wide angle X-ray scattering (WAXD) and Small angle X-ray scattering (SAXS)

The WAXD profile of PUE was measured by a Rigaku RINT2550. The WAXD intensity distribution was measured with a rotating-anode X-ray generator (model Rigaku Ultrax-18, operated at 40 kV and 370 mA). The intensity was measured by a scintillation counter. Ni-filtered Cu K α radiation was used as an incident X-ray source. The Gonio radius and scan speed were set to be 185 mm and 2° min⁻¹, respectively.

The SAXS profile of PUE was measured by a Rigaku RINT2500 with a three-slit system. The SAXS intensity distribution was measured with a rotating-anode X-ray generator (model Rigaku Ultrax-18, operated at 50 kV and 300 mA). The intensity was measured by a position sensitive proportional counter. The X-ray source was monochromatized to Cu K α radiation. The camera length and exposure time were set to be 990 mm and 3600 sec, respectively.

Light stability

The light stability of TPU films with ca. 100 μ m thickness were evaluated as ΔE using a xenon weather meter (Model: Super xenon weather meter SX-75, Suga Test Instruments) with xenon exposure irradiation of 100 W/m² at black panel temperature of 89 °C and 50 % relative humidity. ΔE is the color difference of each film before and after xenon exposure test. It was measured by a spectral color difference meter (Model: SD7000, Nippon Denshoku Industry, Co., Ltd.).

Demold time at injection molding

The demold time of TPU sheets was evaluated using the injection molding machine described at the above section. The demold time was defined as the time that the mold

shrinkage rate of injection molded sheet was set within 2 %. The rate was calculated by monitoring each vertical and horizontal length of the sheet right after injection molding.

3. RESULTS AND DISCUSSION

3.1 Rheological properties of polyurethane based on 1,4-H₆XDI

The rheological properties of basic PUEs prepared with three different diisocyanate, MDI as the aromatic diisocyanate, H₁₂MDI as the aliphatic diisocyanate and 1,4-H₆XDI with a PEBA-2000 and 1,4-BDO were investigated. Figure 2 shows impact resilience versus hardness of three different diisocyanate-based PUEs.

As one can see from this data, impact resilience of 1,4-H₆XDI- based polyurethanes were higher than those of MDI and H₁₂MDI based ones over all range of hardness. 1,4-H₆XDI- based polyurethanes showed excellent impact resilience of ca. 60 % even at 95A of hardness.

Figure 3 shows softening temperature as an index of heat resistance versus 100 % modulus of three different diisocyanate based PUEs. The hard segment concentration (HSC) of all PUEs was 15 %. HSC was calculated the following equation (1).

$$\text{HSC}(\%) = \left[\frac{\text{CE}(g) + \text{NCO}(g) \times \frac{\text{CE}(eq.)}{\text{Polyol}(eq.) + \text{CE}(eq.)}}{\text{NCO}(g) + \text{Polyol}(g) + \text{CE}(g)} \right] \times 100 \quad (1)$$

, where $\text{CE}(g)$ is the weight of chain extender, $\text{NCO}(g)$ is the weight of diisocyanate, $\text{Polyol}(g)$ is the weight of long chain polyol, $\text{CE}(eq.)$ is the equivalent weight of chain extender, $\text{NCO}(eq.)$ is the equivalent weight of diisocyanate, $\text{Polyol}(eq.)$

is the equivalent weight of long chain polyol 1,4-H₆XDI- based polyurethane showed higher softening temperature and 100 % modulus simultaneously compared to those of MDI and H₁₂MDI- based ones at the same HSC of 15 %. With the same HSC, if the 100 % modulus and softening temperature of polyurethane are high, the elasticity and heat resistance are considered to be excellent. From Fig. 3, 1,4-H₆XDI- based polyurethane showed superior elasticity and heat resistance compared to MDI and H₁₂MDI- based ones.

Figure 4 shows light stability of thin polyurethane films based on MDI and 1,4-H₆XDI with 100 μm of thickness by xenon exposure irradiation of 100 W/m² at black panel temperature of 89 °C and 50 % relative humidity. ΔE of H₁₂MDI- based polyurethane film could not be plotted in this figure, since this film was molten during this test because of the low softening temperature of H₁₂MDI- based polyurethane. From xenon exposure test, ΔE of 1,4-H₆XDI- based polyurethane was below 0.3 over 10 days, so it showed excellent light stability.

1,4-H₆XDI- based polyurethane showed excellent elasticity, heat resistance and light stability compared to those of MDI and H₁₂MDI, as expected from the molecular structure of this diisocyanate. In order to classify the difference in the superstructure of various diisocyanate-based polyurethanes, the measurement of DSC for PUEs were carried out. The glass transition temperature ($T_{g,s}$) of soft segment phase of 1,4-H₆XDI- based polyurethane was observed at -55.4 °C and then those of MDI and H₁₂MDI were observed at -53.5 °C and -52.2 °C, respectively. On the contrary, the endothermic temperature observed at relatively high temperature region was defined as the melting point of crystallized hard segment phase. The melting point ($T_{m,h}$) of the hard segment phase of

Fig. 2. Impact resilience versus hardness of three different diisocyanate-based PUEs.

Fig. 3. Softening temperature versus 100 % modulus of three different diisocyanate-based PUEs with hard segment concentration of 15 wt%.

1,4-H₆XDI- based polyurethane was observed at 170.2 °C and then those of MDI and H₁₂MDI were observed at 152.5 °C and 67.6 °C, respectively. The degree of microphase-separated structure of these polyurethanes must be associated with the difference in $T_{g,s}$ and $T_{m,h}$, $|T_{g,s} - T_{m,h}|$. In other words, the degree of microphase-separated structure might be progressed with increasing the value of $|T_{g,s} - T_{m,h}|$.

Figure 5 shows a comparison with the degree of microphase separation of various diisocyanate- based polyurethanes. The $|T_{g,s} - T_{m,h}|$ of 1,4-H₆XDI- based PUE was the highest value of 226 °C and those of MDI and H₁₂MDI were 206 °C and 119.8 °C, respectively.

Figure 6 (a) and (b) show the WAXD and SAXS profiles for three different diisocyanate- based polyurethanes, respectively. 1,4-H₆XDI- based PUE only exhibited crystalline peaks at $2\theta = 17, 19, 20$ and 24 degree which can be assigned to the crystallized hard segment domains in the WAXD profiles (Fig. 6 (a))²¹⁾. The observation at these crystalline peaks from the hard segment domains are quite rare²²⁾. These results imply that hard segment chains form rich phases and packed well each other in the PUE.

On the contrary, obvious peaks was observed for 1,4-H₆XDI- based PUE in SAXS profile. This peak can be assigned to interdomain spacing of hard segment domains in the microphase-separated structure^{21, 23)}. This indicates that well-developed microphase-separated structure was formed for 1,4-H₆XDI- based PUE. SAXS profiles for MDI-based PUE also exhibited strong intensity at low scattering angle region. This result implies that MDI-based PUE also possess developed microphase separated structure. The peak for 1,4-H₆XDI- based PUE was observed slightly higher scattering angle region, interdomain spacing was smaller than for MDI-based polyurethane. For H₁₂MDI-based PUE, since there are no clear scattering peak in the SAXS profile, indicating the phase mixing trend of this PUE.

From DSC measurement and X-ray scattering patterns as shown in Figs. 5 and 6, the micro phase-separated structure between soft segment and hard segment phases of 1,4-H₆XDI- based PUE might be progressed compared to those of MDI and H₁₂MDI, respectively.

Figure 7 shows the schematic model of super structure of 1,4-H₆XDI- based polyurethane. Since 1,4-H₆XDI has a high symmetrical structure, resulting hard segment chains form a well-organized hard segment phase by reaction with a chain extender, such as 1,4-BDO. Therefore, a micro-phase separated structure between soft segment and hard segment phases is progressed, resulting in a superior elasticity and heat resistance such as softening temperature.

Fig. 4. Time dependence of ΔE of MDI- based and 1,4-H₆XDI- based TPU films by xenon exposure.

Fig. 5. Comparison with the degree of micro-phase separation of various diisocyanate-based PUEs.

Fig. 6. (a) WAXD profiles (b) SAXS profiles for three different diisocyanate-based PUEs.

Fig. 7. Schematic model of super structure of 1,4-H₆XDI-based PUE.

3.2 Application for practical PUEs (TPUs)

It is industrially important to compare their properties with the same hardness of TPUs. 1,4-H₆XDI, MDI and H₁₂MDI-based TPUs were prepared with almost the same hardness range of 85A, respectively. The hardness is the most versatile. Table I shows the mechanical and thermal properties of 1,4-H₆XDI-based TPU compared to H₁₂MDI- and MDI-based TPUs with same hardness range of 85A.

1,4-H₆XDI-based TPU showed excellent elasticity, such as high impact resilience, low compression set at 70 °C, low T_g , high softening temperature, high tear strength and elongation at break compared to MDI and H₁₂MDI based TPUs, respectively.

Figure 8 shows stress-strain curves for three different diisocyanate-based TPUs with the same hardness of 85A. 1,4-H₆XDI-based TPU showed the highest elongation at break with almost the same tensile strength to MDI-based TPU. H₁₂MDI-based TPU showed the most poor tensile strength and elongation at break. This result corresponded to the higher cohesive force and ability of crystallization of hard segment phase, because 1,4-H₆XDI is a high symmetrical structure compared to H₁₂MDI consisting of three kinds of isomers²⁰⁾.

Figure 9 shows temperature dependence of dynamic storage modulus (E') and $\tan \delta$ for three different diisocyanate-based TPUs with the same hardness of 85A. 1,4-H₆XDI-based TPU showed an increase in the E' value and a decrease in the $\tan \delta$ which can be assigned to glass transition of soft segment. 1,4-H₆XDI-based TPU was the lowest of the three TPUs.

Moreover the data shows that 1,4-H₆XDI-based TPU had a flat rubbery plateau region. The temperature of the terminal flow was observed by following order: H₁₂MDI < MDI < 1,4-H₆XDI. H₁₂MDI-TPU was the lowest,

Fig. 8. Stress-strain curves for three different diisocyanate-based TPUs.

next was MDI-TPU, finally 1,4-H₆XDI-TPU, respectively. In other words, 1,4-H₆XDI-TPU showed excellent heat resistance compared to other TPUs. These trends may be associated with the strong microphase separation of 1,4-H₆XDI-based TPU.

In the soft segment glass transition region, 1,4-H₆XDI-based TPU had a significant shoulder which is likely recrystallization and melting of crystallized PEBA of soft segment.

Next, the features of 1,4-H₆XDI-based TPU are described from the industrial point of view.

Figure 10 shows the formulation and comparison among the compositions of TPUs using various diisocyanates with same hardness of 85A. Since 1,4-H₆XDI-based TPU showed high elasticity even at small amount of diisocyanate than those of H₁₂MDI and MDI, the consumption of this diisocyanate could be reduced by half (0.5 times) of H₁₂MDI system and 0.6 times of MDI system, when preparing TPUs with the same hardness.

Figure 11 shows the comparison of demold time at injection molding of various TPUs. The processability of TPU article prepared by injection molding is judged to be good when the demold time was shorter. 1,4-H₆XDI-based TPU showed shortest demold time due to the faster solidification from molten state, since the hard segment phase composed from 1,4-H₆XDI aggregated faster than those of H₁₂MDI and MDI even at cooling process evaluated by DSC measurement. The elasticity of 1,4-H₆XDI-based TPU achieved to settle quickly compared with other TPUs because of faster aggregation of the hard segment phase.

After injection molding, the hardness of TPU sheets were measured every other day at 23 °C and 55 % relative humidity. Figure 12 shows the aging time dependence of hardness after injection molding. 1,4-H₆XDI-based TPU

Table I. Mechanical Properties of 1,4-H₆XDI and other isocyanate based TPUs

Properties	unit	1,4-H ₆ XDI-TPU	H ₁₂ MDI-TPU	MDI-TPU
Hardness	A	86	85	87
Impact resilience	%	69	30	51
Compression set 23 °C / 70 °C	% / %	14.7 / 30.0	17.3 / 73.5	16.7 / 38.7
T_g	°C	-46	23	-27
Softening temperature (TMA)	°C	171	105.6	148.4
100 % modulus	MPa	5.8	5.8	6
300 % modulus	MPa	9.1	12.1	10
Tensile strength	MPa	35.1	29.5	35.7
Elongation at break	%	710	500	520
Tear strength	kN/m	118	101	102

Fig. 9. Temperature dependence of dynamic storage modulus (E') and $\tan \delta$ for three different diisocyanate-based TPUs.

Fig. 11. Comparison of demold time at injection molding of various TPUs.

Fig. 10. Formulation and comparison among the compositions of TPUs using various diisocyanates with same hardness of 85A.

Fig. 12. Aging time dependence of hardness for three different diisocyanate-based TPUs.

achieved constant hardness quickly compared to MDI and H₁₂MDI-based TPUs. This result was contributed to the same mechanism as mentioned above.

In summary, 1,4-H₆XDI- based TPU shows non-yellowing, high elasticity, such as low $\tan \delta$, low compression set and high impact resilience. They have high heat resilience such as a high softening temperature and high productivity such as short demold time and fast achievement of designed hardness compared to the conventional diisocyanate- based TPUs.

4. CONCLUSIONS

New cycloaliphatic diisocyanate, 1,4-H₆XDI, gives high-performance to polyurethane elastomers. This new aliphatic diisocyanate with a high symmetrical structure results in a superior aggregation of hard segment reacted with 1,4-BDO, giving a high softening temperature and forms well organized micro-separated structure from the experimental results of WAXD, SAXS, DSC and DMA. So that polyurethane based on 1,4-H₆XDI achieve high elasticity, heat resistant and light stability which was not able to be realized with the conventional diisocyanate. For TPU application, the mechanical and thermal properties of 1,4-H₆XDI- based TPU are superior to those based on MDI and H₁₂MDI, in particular, low $\tan \delta$, low glass transition temperature, low compression set, high softening temperature, high impact resilience and high tear strength. In addition, 1,4-H₆XDI- based TPU gives high productivity such as short demold time and fast achievement of designed hardness.

These results support that elastomer systems based on 1,4-H₆XDI shows superior mechanical and thermal properties and excellent light stability, dynamic fatigue performance as a high performance PUEs.

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