Effects of Nucleating Agent on the Thermal Conductivity and Creep Strain Behavior of Rigid Polyurethane Foams Blown by an Environment-Friendly Foaming Agent

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Abstract: The effects of liquid-type additive, methoxynonafluorobutane, on the morphology, thermal conductivity, creep strain, and mechanical strength of polyurethane (PU) foams with an environment-friendly foaming agent, hyrdofluoroolefin, were investigated. The methoxynonafluorobutane under the trade name of NOVEC likely acted as a nucleating agent during the formation of PU foams. When NOVEC was added in the amount of 3 parts per hundred polyol by weight (php), the cell size of the foam was minimal, and the cell size distribution was relatively uniform. At the NOVEC content of 3.0 php, the thermal conductivity of the PU foams was also minimal. This decrease in thermal conductivity was due to the smaller cell size of the foams lowering their thermal conductivity. At 3.0 php NOVEC content, the creep strain of the PU foams was minimal being 0.29% at 1,000 h. At 3.0 php NOVEC, the estimated creep strain of the PU foam exhibited the lowest creep strain of 3.47% at 50 years.

As a result, at 3.0 php NOVEC content, the cell wall was relatively less fractured, resulting in a small deformation of the PU foam. These results suggest that the main factors in improving the thermal insulation properties and stability of the PU foams are smaller cell size and narrow cell size distribution.

Keywords: polyurethane foam, morphology, thermal conductivity, creep strain behavior, hydrofluoroolefin.
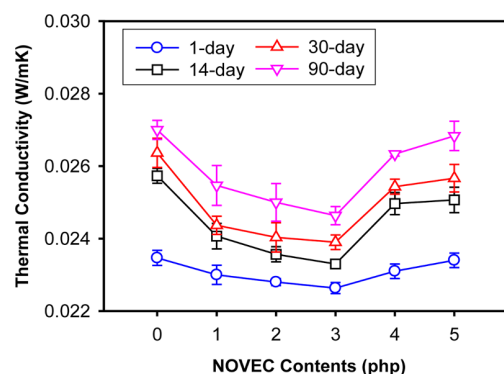
1. Introduction

Polyurethane (PU) has been used as a soft cushioning material for clothes, shoes, sofas, automobiles, etc., due to its excellent physical properties. PU has also been applied as a rigid material for liquified natural gas (LNG) storage thermal insulation, refrigerated containers, and structural material.[1-6] In addition, it is used for commercial use, such as flooring material, adhesive, film, and coating.[7] Among the PUs, rigid PU foam is a kind of cellular plastic, which compared to other synthetic polymers, has superior insulation and processability.[8]

For these reasons, PU foams have been widely used as thermal insulating material. However, due to increasing environmental regulations worldwide, it is necessary to use blowing agents that can replace chlorofluorocarbon (CFC) and hydrofluorocarbon (HFC) blowing agents, which are known to cause ozone destruction and global warming.[9]

Previous studies have used HFC as a blowing agent;[2] however, under the 2016 Montreal Convention, the HFC was selected as a regulated substance, due to its high global warming potential. Therefore, this study was conducted to develop an eco-friendly insulation system by applying hydrofluoroolefin (HFO),[10] which

is known as a fourth-generation eco-friendly foaming agent, and is under test at DuPont and Honeywell Co. The HFO is an unsaturated organic compound that is composed of hydrogen, fluorine, and carbon. Unlike traditional HFC and CFC, which are saturated, HFO is olefin, otherwise known as alkene. HFO can be used as a blowing agent in the preparation of PU foam,[10] particularly for low temperature insulation, and its application is expected in PU insulation for the LNG carrier.

The cell morphology of PU foam is an important property to obtain good thermal insulation of the foams. There have been several studies of reducing cell size using surfactants and nucleating agents such as graphene,[4] carbon nanofiber[11] and cellulose nanoparticles[12,13] with the blowing agents of water,[4,11] hydrofluorocarbon[12] and cyclopentane.[14] Our previous studies conducted experiments to make the cell size small and uniform by adding nucleating agents, such as perfluoroalkane,[2] hexamethyldisilazane (HMDS)[14] and tetramethylsilane.[15] The large number of nucleation sites during the synthesis of polyols and isocyanates generate many bubbles. If the adhesion of bubbles is inhibited by reducing the surface tension of the two mixtures during growth, bubbles with small cells can be produced.[2,14]

However, in the preparation of PU foams, the use of methoxynonafluorobutane under the trade name of NOVEC as a nucleating agent, in combination with HFO as an environment-friendly blowing agent, has not yet been reported by other researchers. The purpose of this study was to increase the

thermal insulating properties of PU foams by adding a new nucleating agent, NOVEC, in combination with HFO as an environment-friendly foaming agent. Perfluoroalkane and HMDS would be good nucleating agents during the preparation of the PU foams, however, perfluoroalkane has a low boiling point which is about 52.5 °C, compared to that of the NOVEC (61.0 °C). For the HMDS, Seguin et al.[16] reported that the HMDS hydrolyzes in the presence of water to trimethylsilanol and ammonia. Therefore, the NOVEC as a nucleating agent was chosen to investigate the thermal insulating properties of the PU foams.

The addition of NOVEC may induce smaller cell size of the PU foams, probably due to the lower surface tension of the polyol and NOVEC mixture, resulting in high nucleation rate.[2] In this study, we also focused on the creep behavior of the PU foams, which can be used to predict the deformation of PU foams after several years' use, by observing the creep strain curve of PU foams with time.[17,18]

2. Experimental

2.1. Materials

In this study, the polyether type and polyester type polyols were used. Diethylene glycol-based polyester polyol (KOH content of the OH value = 330 mg/g) was supplied by Aekyung Co. Sucrose-based polyether polyol (KOH content of the OH value = 480 mg/g) was supplied by KPX Chemical. The weight ratio of diethylene glycol-based polyether polyol and sucrose-based polyester polyol used in this study was 65:35 (wt%). Polymeric 4,4-diphenyl-methane diisocyanate (MDI) was provided by BASF Korea Ltd. In this study, HFO-1233zd, which was supplied by Honeywell Co., was used as a blowing agent. Pentamethyldiethyltriamine (PC 5), which was provided by Air Products and Chemicals, Inc., was used as a blowing catalyst. Silicone-type surfactant (L6900) was supplied by Momentive Co. The methoxynonafluorobutane was supplied by 3M Co., under the trade name NOVEC.

2.2. Preparation of PU foams

First of all, polyols, catalyst, and surfactant were put into an open-cup reactor, and mixed for 90 s at ambient conditions.[2,14] Rotating speed started at 300 rpm, and was gradually increased to 3,000 rpm. Then, the blowing agent (HFO-1233zd) was added into the polyol mixtures in the amount of 5.0 php. Also, NOVEC as a nucleating agent was added into the polyol mixtures in the amounts of (1.0, 2.0, 3.0, 4.0, and 5.0) parts per hundred polyol by weight (php). The mixed reactants were stirred at 3,000 rpm

for 30 s. Then, the MDI was put into the reactants mixture, and all the reactants were stirred for 15 s using brushless-type stirrer at 5,000 rpm. Finally, the reactants were poured into the open mold ($250 \times 250 \times 250$ mm³), to produce free-rise foams. The amount of blowing agent was controlled to set the average density of (120.5 ± 2.0) kg/m³ for all the PU foam samples. The density of the foams with (0.0, 1.0, 2.0, 3.0, 4.0, and 5.0) php NOVEC contents was observed to be (122.5, 121.8, 120.6, 120.1, 119.2, and 118.5) kg/cm³, respectively. To prepare the PU foams, the chemical compositions of the materials shown in Table 1 were used.

2.3. Morphology

The morphology of the PU foam was determined by scanning electron microscopy (SEM).[2] The samples were fractured under liquid nitrogen and the surface was coated with gold. The accelerating voltage was 15 kV. From the obtained SEM pictures, we counted 50 cells from the obtained SEM pictures and then the cell size was measured and averaged from the selected 50 cells. To obtain the cell size of the foams, we used image analysis software (Image J).[4]

2.4. Measurements of surface tension

The surface tension of the polyol solutions with the NOVEC contents was measured using a contact angle analyzer (Model GonioStar150, Surfacetech, Korea). Mixed polyol solutions were dropped on the glass plate. After that, contact angle between mixed polyol droplet and glass plate was measured. The surface tension is obtained using Eq. (1):[2,19]

$$\cos \theta = 2\phi \left(\frac{\gamma_s}{\gamma_L}\right)^{\frac{1}{2}} - 1 \tag{1}$$

where θ is the contact angle, ϕ is approximated to 1.0, γ_s the surface tension of glass plate (24.8 mN/m), and γ_L the surface tension of polyol solution.

2.5. Thermal conductivity

The thermal conductivities of PU foams were measured using a thermal conductivity analyzer, according to the ASTM C518 standard test method.[2] The size of the specimen was ($200 \times 200 \times 25$ mm³) (W × L × T). Three specimens per sample were measured and averaged.

2.6. Measurements of water absorption

The water absorption of the PU foams of ($50 \times 50 \times 25$ mm³)

Table 1. Chemical compositions used in the preparation of polyurethane foams

Materials	Description	Weight (g)
Polyol	Polyester polyol/Polyether polyol	100.0 (65/35)
Catalyst	Dimethylcyclohexylamine (PC-5)	0.15
Surfactant	Silicone type (L6900)	2.5
Blowing agent	HFO-1233zd	5.0
Nucleation agent	Methoxynonafluorobutane	0, 1.0, 2.0, 3.0, 4.0, 5.0
MDI	Polymeric 4,4'-diphenylmethane diisocyanate	100.0
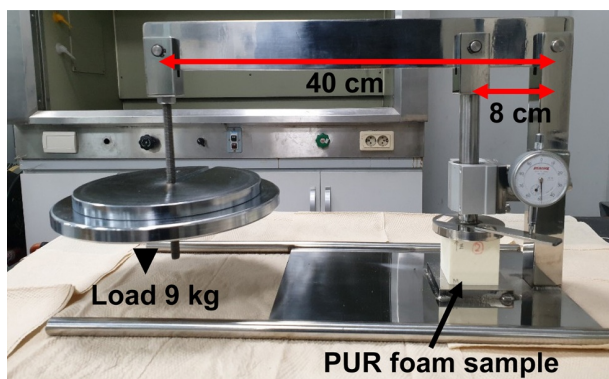
Figure 1. Equipment for the creep strain test with the polyurethane (PU) foam sample.

(W × L × T) dimensions was measured according to ASTM C272 with six replicates. In the test, the initial mass of the PU foam was designated as M_1 (g). After immersion of the PU foam sample in water for 24 h, the mass of the water-immersed foam sample was designated as M_2 (g). Thus, the water absorption of the foam sample was calculated as follows: water absorption (%) per unit mass = $(M_2 - M_1)/M_1 \times 100$.

2.7. Creep test of PU foams

The creep test of the PU foams was conducted to predict the creep strain of PU specimens after several years use, by observing the strain curve of PU specimens with time. Figure 1 shows the equipment of the creep test and PU foam sample. The size of each specimen was ($50 \times 50 \times 50$ mm³) (W × L × T). The specimens were tested at room temperature, and a 9 kg load of compressive strength was applied to each specimen up to 1,000 h. In this study, the load of the creep test was chosen to be 9 kg per specimen, so that the load on the foam specimen would be 45 kg.[17,20] From the measured time (t) and strain variation, the coefficients of a and b can be obtained from the Findley equation of Eq. (2), as follows:[20,21]

$$\varepsilon_t - \varepsilon_0 = at^b \qquad (2)$$

where, ε_t is the total creep strain, and ε_0 is the initial strain of the PU foam samples, which is the instantaneous strain response that is obtained by extending the constant rate portion of the creep curve back to $t = 0$; and where a and b are empirically determined constants. The strain of PU foams after several years' use can then be estimated from the Findley's coefficients a and b obtained by Eq. (2).[17,18]

2.8. Mechanical properties

The mechanical strengths of PU foam samples were measured by universal testing machine (Instron 4467).[2] The specimen sizes for the compressive and shear strength tests were ($50 \times 50 \times 50$ mm³) and ($50 \times 50 \times 5$ mm³) (W × L × T), respectively. The compressive and shear strength tests were performed according to the ASTM D1621 and ASTM D732 test methods, respectively. The strengths of 10 specimens per sample were measured and averaged for each mechanical test.

3. Results and discussion

3.1. Morphology of PU foams

Figure 2(a)-(f) shows the SEM morphology of the cell structure of PU foams with NOVEC contents of (0.0, 1.0, 2.0, 3.0, 4.0, and 5.0) php, respectively. Figure 2 shows that with the increase of NOVEC content up to 3.0 php, the cell size of the PU foams decreased. Then with the addition of (4.0 and 5.0) php NOVEC contents, the cell size of the foams increased. Figure 2(a)-(f) was used to determine the average cell size, which when the NOVEC contents ranged (0.0 to 5.0) php, was found to be (219, 191, 177, 171, 183, and 195) μm with a standard deviation of (72, 64, 45, 34, 52, and 63) μm, respectively. When the NOVEC content was 3.0 php, the cell size of the foam showed minimum (171 μm). These results are likely due to the lower surface tension of the NOVEC (13.6 mN/m), which allows it to be emulsified more uniformly in the polyol solution, allowing a higher nucleation rate.[22] It is thought that the low surface tension of NOVEC prohibits the coalescence of bubbles and promotes the formation of small and dense cells.[2]

However, for the NOVEC content was (4.0 and 5.0) php, the cell size of the PU foams increased to (183 and 195) μm compared that of the foam with 3.0 php NOVEC content, respectively. It is thought that adding too much nucleating agent interferes with the binding reaction between the polyol and the isocyanate, and
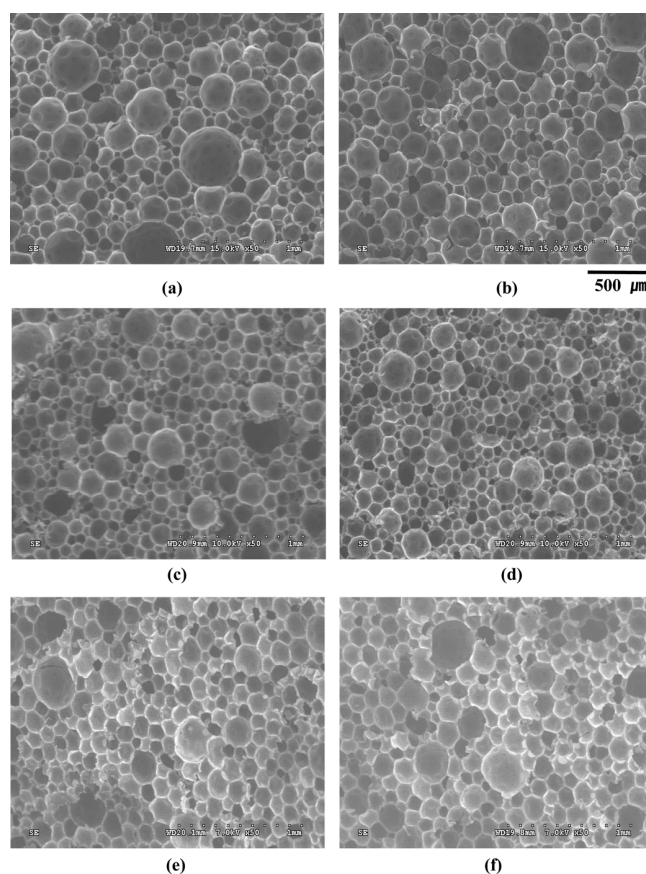
Figure 2. Scanning electron micrographs of the polyurethane foams with differing NOVEC contents of (a) 0.0, (b) 1.0, (c) 2.0, (d) 3.0, (e) 4.0, and (f) 5.0 php.
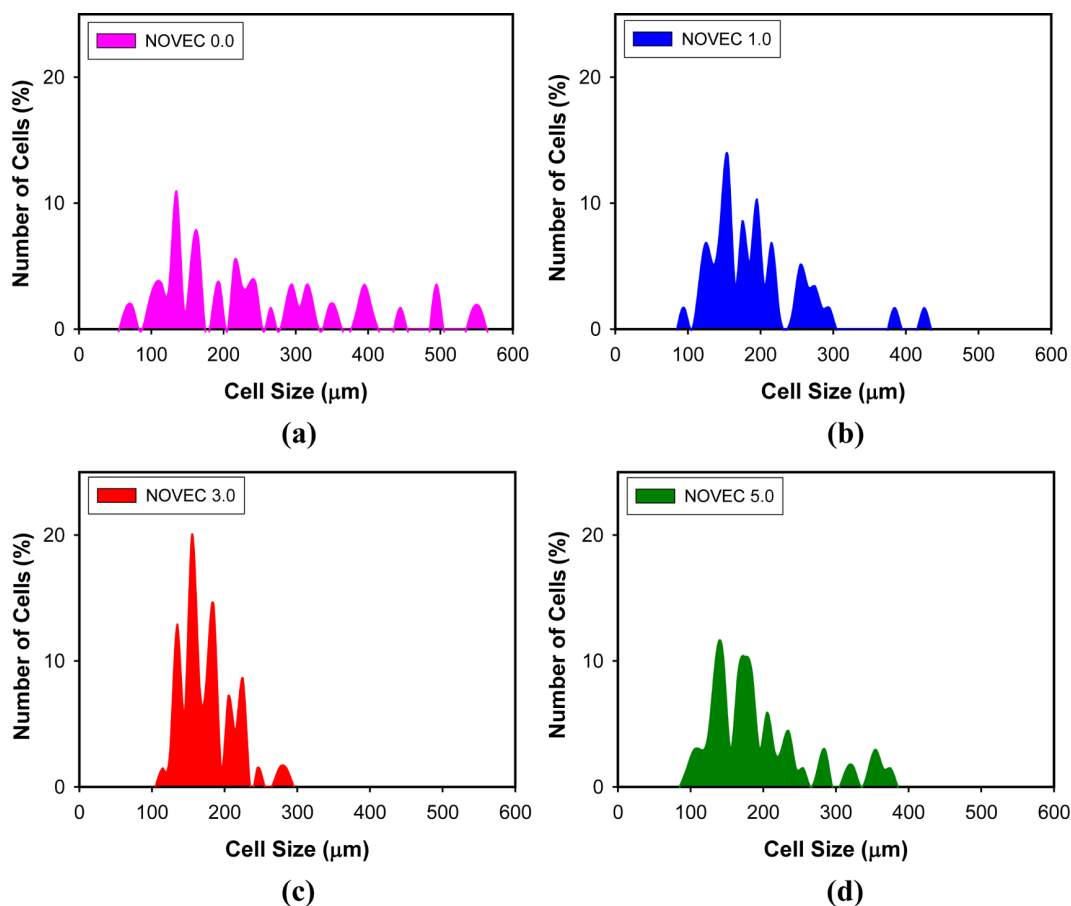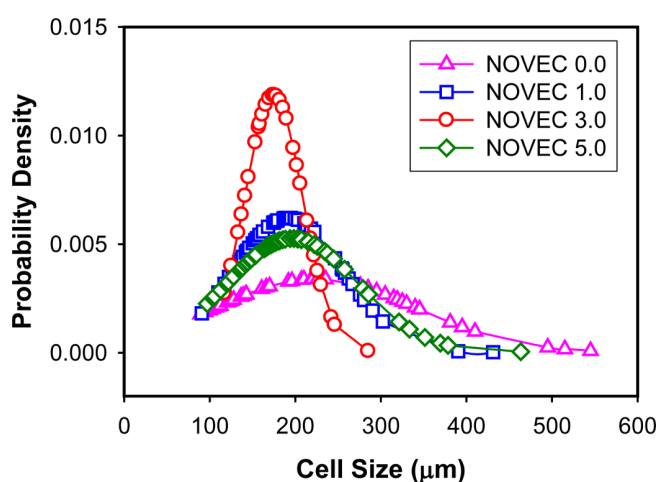
Figure 3. Cell size distribution of the polyurethane foams with the NOVEC contents of (a) 0.0, (b) 1.0, (c) 3.0, and (d) 5.0 php.

does not act as a physical nucleating agent. When the NOVEC content was (4.0 and 5.0) php, it is also observed that the density of the PU foams decreased to (119.2 and 118.5) kg/cm^3 compared that of the foam without adding NOVEC (122.5 kg/cm^3), respectively. This result suggests that the nucleating agent may also act as a blowing agent when it is added too much during the preparation of the PU foams.

In the foaming process, many bubbles are generated if there are many nucleation sites during the process. If coalescence of bubbles is prohibited by reducing surface tension of solution during the growth phase of PU foam, small cellular structure can be produced.[23,24] The thermal properties of PU foams are highly affected by the cell morphology of the foams. The next sections of this study further explain the relationship between the cell size and thermal conductivity.

Figures 3 and 4 show the cell size distribution of the PU foams with the NOVEC contents. The figures show that for the PU foam with the 3.0 php NOVEC content, the cell size distribution is quite uniform, compared with the foams with the (0.0, 1.0, and 5.0) php NOVEC contents. These results suggest that the NOVEC may contribute to reduction of the cell size and cell size distribution of the PU foams.

Figure 5(a)-(f) shows the contact angle measurements of the polyol solutions with NOVEC contents of (0.0, 1.0, 2.0, 3.0, 4.0, and 5.0) php, and found to be 70.7, 65.9, 64.5, 63.0, 62.3, and 59.6 degrees respectively. In the measurements of surface tension, the polyol solutions with NOVEC contents of (0.0, 1.0, 2.0,

Figure 4. Normalized cell size distribution of the polyurethane foams with respective NOVEC contents.

3.0, 4.0, and 5.0) php showed 55.4, 50.1, 48.5, 46.9, 46.2, and 43.7 mN/m, respectively. The polyol solution without NOVEC has a surface tension of 55.4 mN/m. This value is further reduced by the addition of nucleating additive to the lower value of 46.9 mN/m when the 3.0 php NOVEC is added. The decrease of surface tension with NOVEC contents is maybe due to the lower surface tension of NOVEC itself (13.6 mN/m). Lowering surface tension of mixed polymer solution is one of the important factors to control the size of the cells.[2,14] From the above results shown in Figures 2
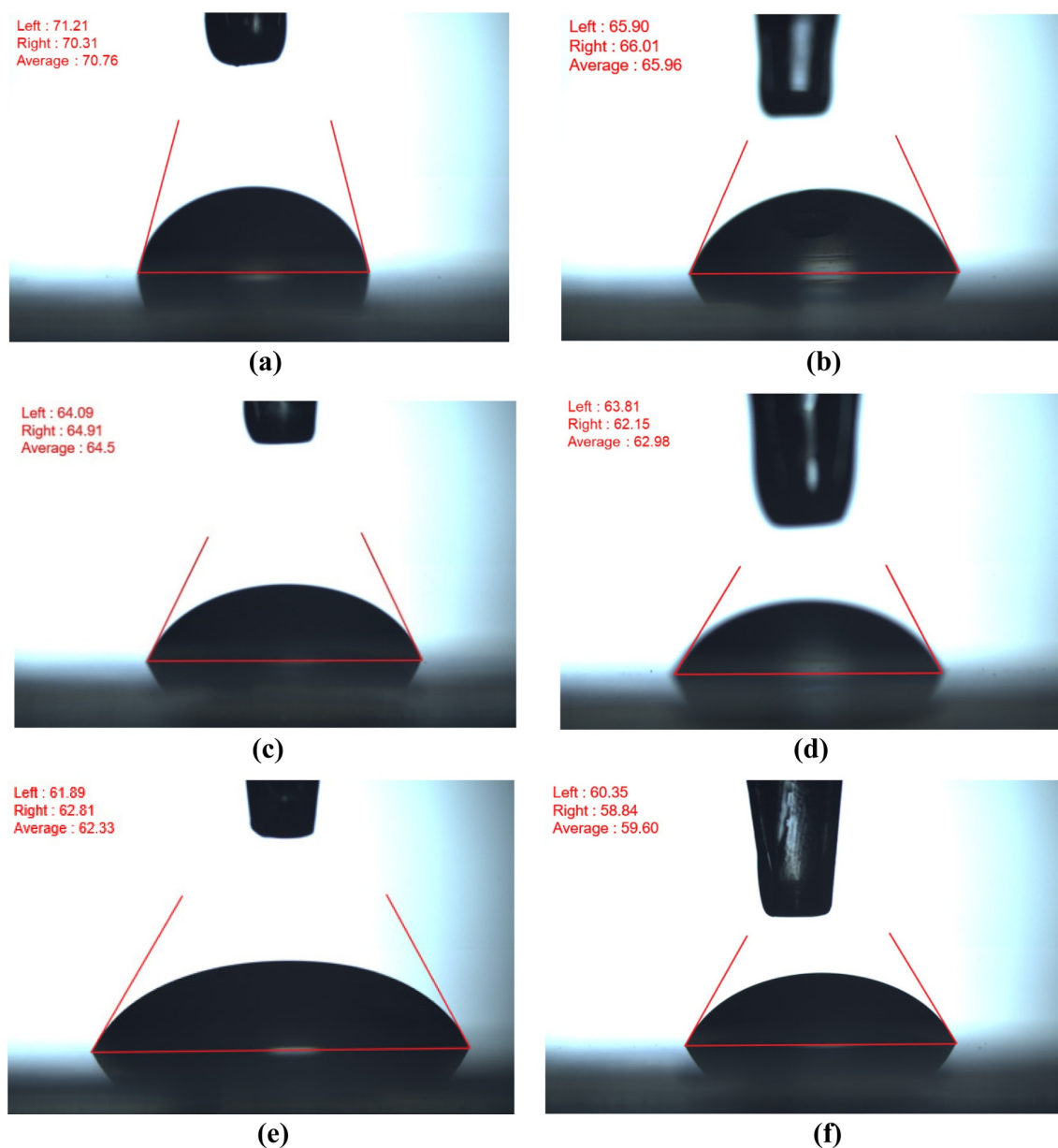
Figure 5. Measurement of the contact angle of polyol solutions with the NOVEC contents of (a) 0.0, (b) 1.0, (c) 2.0, (d) 3.0, (e) 4.0, and (f) 5.0 php.

and 5, it is suggested that NOVEC acts appropriately as a nucleating agent in the preparation of PU foams.

3.2. Water absorption of PU foams

Figure 6 shows the effect of the NOVEC content on the water absorption of the PU foams. Only a part of the foam was observed through the SEM analysis of Figure 2; therefore, the water absorption test was performed to examine the total cell morphology of the inside PU foams. Figure 6 shows that at the NOVEC content of 3.0 php, the water absorption of the PU foams was minimum. For the foams with (0.0 and 3.0) php NOVEC contents, the water absorption was observed to be (3.91 and 3.26) %, respectively. As the cell size becomes smaller, it is harder for the water molecule to pass through the PU foams.[25] The results of water absorption supported the SEM results that among the foams investigated, the PU foam with 3.0 php NOVEC content showed
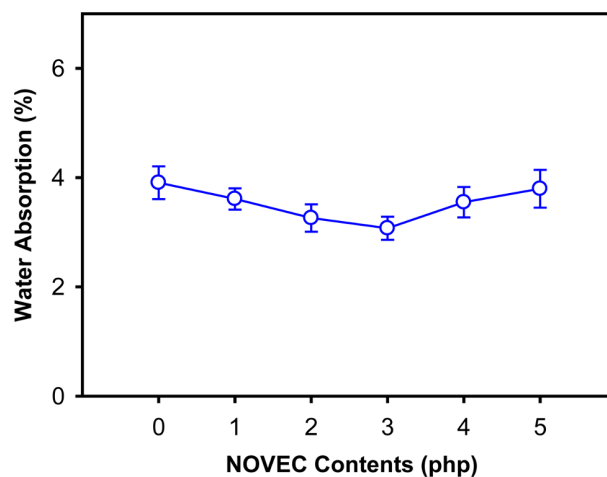
Figure 6. Water absorption of the polyurethane foams with respective NOVEC contents.

the smallest cell size.

3.3. Thermal conductivity of PU foams

Figure 7 shows the thermal conductivity of the PU foams with aging time and the NOVEC content as a nucleating additive. The aging times for the PU foams were (1, 14, 30, and 90) days. When the aging time increased from (1 to 90) days, the thermal conductivity increased for all the NOVEC content of the foams. This is because as the aging time increases, the foaming agent may gradually be replaced by the air. Therefore, the thermal insulation capability of the foams decreases with their aging time.

Figure 7 shows that for all the aging times, at the NOVEC content of 3.0 php, the thermal conductivity was minimum. At the aging time of 90 days, the thermal conductivities of the PU foams with (0.0 and 3.0) php NOVEC contents were observed to be (0.0270 and 0.0246) W/mK, respectively. This decrease of the thermal conductivity from 0.0270 to 0.0246 W/mK is because the cell size of the foams affects the thermal conductivity of PU foams. When 3.0 php NOVEC was added to the foam, the smallest cell size was observed among the foams shown in Figure 2.

Figure 8 shows the thermal conductivity of the foams with the average cell size of the PU foams synthesized in this study.
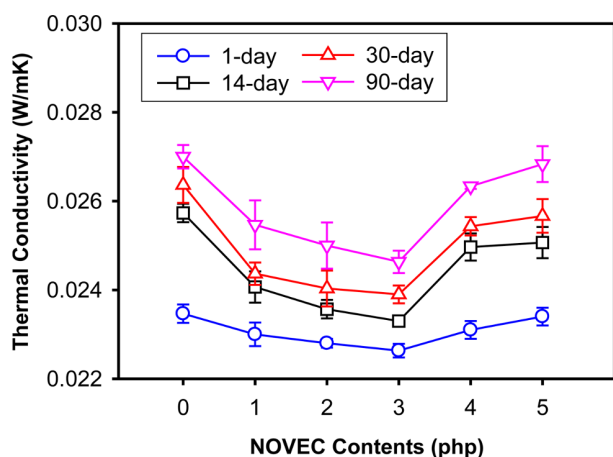

Figure 7. Thermal conductivity of the polyurethane foams with differing NOVEC contents and aging time.
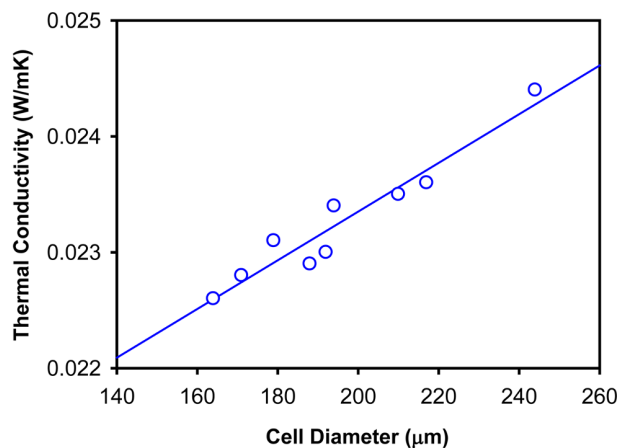

Figure 8. Relationships between the thermal conductivity and the cell size of the polyurethane foam.
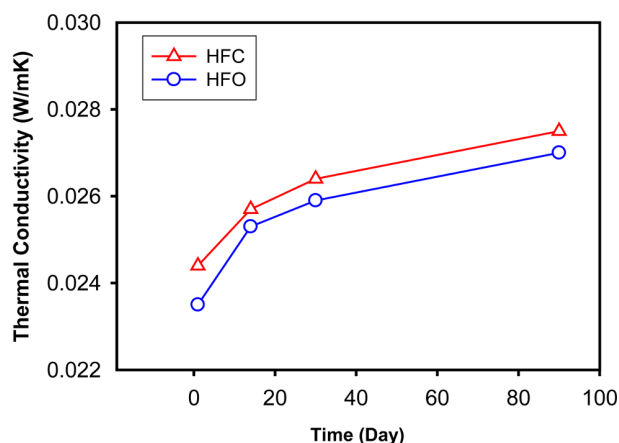

Figure 9. Thermal conductivity of the polyurethane foams blown with HFO and HFC-245fa. The aging times for the foams were 1, 14, 30, and 90 days.

The figure shows that with the increase of the average cell size of PU foams, the thermal conductivity of the foams increases. Figure 8 suggests that the smaller cells show a longer pathway for the thermal particles to pass through, resulting in a lower thermal conductivity of the PU foams.

In a PU foam, the thermal conductivity is controlled through three heat transfer mechanism processes, heat transfer through the gaseous phase, through the solid phase and through the convection within the cells.[9,26] There is no difference in the mechanism of heat transfer through the gaseous and solid phases in that the polyols, isocyanates and blowing agents that make up the PU component remain unchanged. However, as the cell size is reduced by the effects of the nucleating agent, the heat transfer through the convection within the cell is reduced.[2,14] This tends to decrease the overall thermal conductivity of the foam.

In order to compare the thermal conductivity of PU foams blown with HFO and another blowing agent, we have measured the thermal conductivity with aging time for the foams blown with HFO and HFC-245fa without adding NOVEC. The aging times for the PU foams were (1, 14, 30, and 90) days. Figure 9 shows that when the aging time increased from (1 to 90) days, the thermal conductivity increased for both the blowing agents. Also, the thermal conductivity of the foam blown with HFC-245fa showed higher value compared that of the foam blown with HFO for all the aging times. At the aging time of 90 days, the thermal conductivities of the PU foams blown with HFO and HFC-245fa were observed to be (0.0270 and 0.0276) W/mK, respectively. This increase of the thermal conductivity from (0.0270 to 0.0276) W/mK is maybe because that the average cell size increased slightly from (219 to 234) μm for the foams blown with HFO and HFC-245fa, respectively. For both the blowing agents of HFO and HFC-245fa, the ozone depletion potentials are zero, however, the global warming potentials are 9 and 1030, respectively.[27] Therefore, the HFO would be a good blowing agent in the aspect of environmentally as well as thermal conductivity of the PU foams.

3.4. Creep strain of the PU foams

The creep strain can predict the deformation of PU foams after
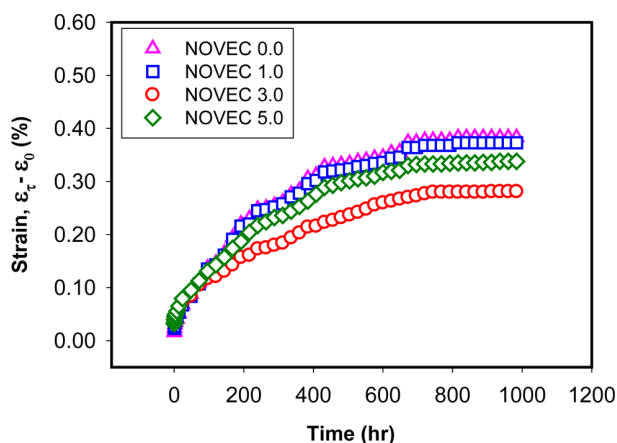
Figure 10. Creep strain curves of the polyurethane foams with differing NOVEC contents over time.

several years' use by observing the strain curve of PU foams with time.[17,18] Figure 10 shows the strain curve of PU foams with the NOVEC contents and time (t), while Figure 10 shows that the strain of the foams increases with time up to 1,000 h. Among the PU foams investigated with the NOVEC contents, the PU foam with 3.0 php NOVEC shows the lowest creep strain value, which is 0.29% at 1,000 h. The PU foams without added NOVEC showed the highest value of creep strain, which was 0.38% at

1,000 h. The results of creep strain shown in Figure 10 suggest that the PU foam with the 3.0 php NOVEC content had the lowest deformation, compared with the foams with (0.0, 1.0, and 5.0) php NOVEC contents.

Factors affecting the strain in the creep test are the density of the foams, and the characteristics of the cell structure in the foams that are uniformly formed, so that the cell wall is not bent.[18,25] The average density was set at (120.5 ± 2.0) kg/m^3 for all the foams investigated in this study. Therefore, it can be assumed that the creep strain of the PU foams was mainly affected by the cell uniformity and cell size. In the case of PU foam with 3.0 php NOVEC content, Figures 3 and 4 show that the cell size is small and the cell distribution is narrow, compared to those of the other foams investigated in this study, so that the cell wall is relatively less fractured and the microstructure changes are small, resulting in low deformation.

Figure 11 shows the log-log plots of creep strain with time (t) and linear square curve fittings of the foams with the NOVEC contents of (0.0, 1.0, 3.0, and 5.0) php. Figure 11 shows that the coefficients of Eq. (2), a and b, can be obtained to estimate the creep strain of the PU foams after several years' use.[17,18] Figure 11 shows that for the foams with 3.0 php NOVEC, the coefficients of a and b were (0.0219 and 0.3795), which showed the lowest values among the foams investigated, respectively. The coefficients a and b represent the intercept of the y-axis and the
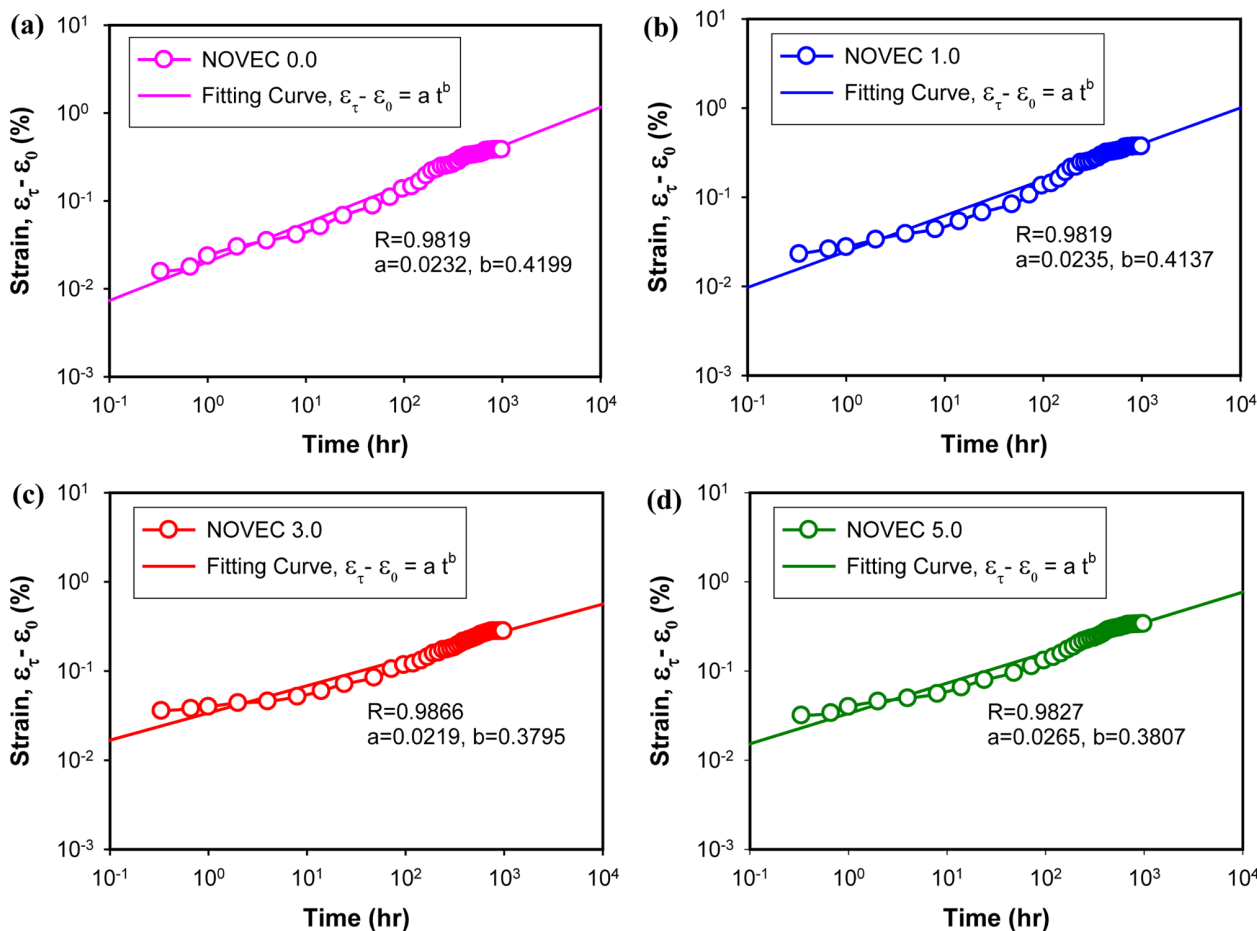
Figure 11. Logarithmic plots of the creep strain of the polyurethane foams over time with respective NOVEC contents of (a) 0.0, (b) 1.0, (c) 3.0, and (d) 5.0 php.
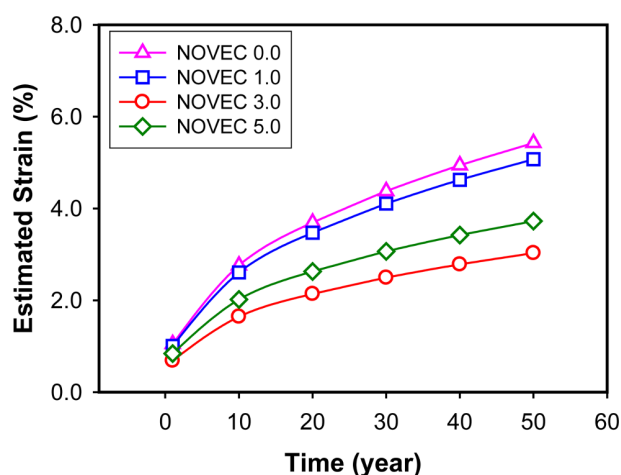
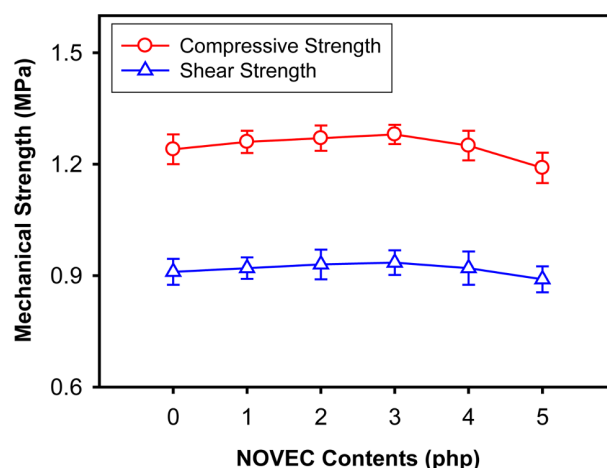**Figure 12.** Estimated creep strain of the polyurethane foams with respective NOVEC contents over time.

Figure 13. Compressive and shear strengths of the polyurethane foams with differing NOVEC contents.

slope of the linear square fitting of the creep strain curve with time (t), which is shown in Figure 11.

By substituting the obtained values of a and b into Eq. (2), it is possible to obtain the creep strain of the PU foams after several years' use. Figure 12 shows the estimated creep strain of the PU foams with time (t) and different amounts of NOVEC contents using Eq. (2). Figure 12 shows that the estimated strain of the PU foams increased with time up to 50 years, which showed similar behavior to that of the foams shown in Figure 10. Among the PU foams investigated with the NOVEC contents, the foam with 3.0 php NOVEC showed the lowest strain value, which was 3.47% at 50 years. The foam without added NOVEC showed the highest strain value, which was 5.88% at 50 years. The results of the strain curves shown in Figure 12 suggest that the PU foam with 3.0 php NOVEC had the lowest deformation, compared with the foams with the (0.0, 1.0, and 5.0) php NOVEC contents; and this result is consistent with that of the PU foams shown in Figure 10.

3.5. Mechanical properties of the PU foams

Figure 13 shows the compressive and shear strengths of the PU foams prepared with different NOVEC contents. The compressive and shear strengths of the PU foams show no improvement after the addition of NOVEC up to 3.0 php NOVEC, as the change is within the range of standard deviation. For the foams with (0.0 and 3.0) php NOVEC contents, the compressive strength was observed to be (1.23 and 1.28) MPa, respectively. For the foams with (0.0 and 3.0) php NOVEC contents, the shear strength was observed to be (0.91 and 0.94) MPa, respectively. For the foam with 5.0 php NOVEC, however, the compressive and shear strengths decreased slightly to (0.92 and 0.89) MPa, respectively.

The mechanical strengths of the PU foams mainly depend on the foam density and cell morphology, such as the cell size and cell size distribution.[2,14] In this study, the density of the foams with (0.0, 1.0, 2.0, 3.0, 4.0, and 5.0) php NOVEC contents was observed to be (122.5, 121.8, 120.6, 120.1, 119.2, and 118.5) kg/cm^3, respectively. From the results of mechanical strength of the PU foams, the decrease of compressive and shear strengths of the foams at the NOVEC content of 5.0 php can therefore be explained by the decreased density of the foam. For the foams with (1.0, 2.0, and 3.0) php NOVEC contents, the compressive and shear strengths did not change appreciably, even though densities of the foams decreased slightly. This behavior may be explained by the decreased cell size of the foams with (1.0, 2.0, and 3.0) php NOVEC contents.

4. Conclusions

In this study, the morphology, thermal conductivity, creep strain behavior, and mechanical properties of the PU foams according to the NOVEC content were investigated. The results of the morphology showed that when the NOVEC content was 3.0 php, the cell size of the foam was minimum, and the cell size distribution was observed to be quite uniform. This result suggests that the NOVEC may contribute to reducing the cell size and cell size distribution of the PU foams.

The results of the thermal conductivity of the PU foams showed that for all the aging times, at the NOVEC content of 3.0 php, the minimum thermal conductivity was observed. At the aging time of 90 days, when the NOVEC content was (0.0 to 3.0) php, the thermal conductivities of the PU foams were observed to be (0.0270 to 0.0246) W/mK, respectively. This decrease of the thermal conductivity is because the smaller cell size of the foams lowered the thermal conductivity of the PU foams.

The results of the creep strain of the PU foams with the NOVEC content showed that at 3.0 NOVEC content, the lowest creep strain was observed, and was found to be 0.29% at 1,000 h. In the case of PU foam with 3.0 php NOVEC content, the cell size was small and the cell distribution was narrow, compared to those of the other foams investigated. The estimated creep strain of the PU foam with 3.0 php NOVEC also showed the lowest strain, which was 3.47% at 50 years. As a result, the cell wall was relatively less fractured and the microstructure changes were small, resulting in low deformation for the PU foam with 3.0 php NOVEC content. The above results of the morphology, thermal conductivity, creep strain behavior, and mechanical properties of the PU foams show that the properties of the PU foams were mainly affected by the cell size and cell uniformity.

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