Effect of Moisture on Mechanical Behaviour of Polymer by Experiments

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Abstract: The effect of moisture content on mechanical behavior of polymer materials is experimentally investigated in this paper. In particular, nylon-6 is selected as testing samples, which were studied by an effective experimental technique called digital marker correction. An equivalent relationship between time intervals and the moisture content for polymer nylon-6 has been obtained based on the experimental observation and results. The generalized curves for the time versus moisture contents of nylon-6 are obtained and then the approximate equation of shift factor is presented in this paper.

1 Introduction

Polymer material is a time-dependent material, which is very sensitive to the environmental factors such as moisture and temperature. Therefore it is important to explore the effect of environmental factors on material properties of polymer in achieving high performance of the materials.

Current research effort on effect of moisture factors on macromolecule polymer has been mainly focused on the following two distinct aspects. The first aspect is to study the residual stress induced by moisture expansion of the material. The second aspect is to investigate influence of moisture on the mechanical behavior. Following this line, Lee[1] investigated the stress singularity between film and the rigid substrate induced by moisture and temperature. Based on linear elasticity theory, Chang[2] analyzed the mechanical behavior of pipe subjected to moisture and temperature change. In addition, some work has been done on the influence of moisture on the mechanical behavior of polymer materials during the past years. For example, temperature-time superposition principle was presented for predicting remaining lifetime of materials and material properties due to temperature change [3-5]. Schapery[6] pointed out that the accelerating factor should be applied not only on the effect of stress and temperature fields but also on the effect of other factors such as moisture and aging [6]. ManBePcTep studied temperature-time superposition principle and indicated that there was also a kind of equivalence between moisture and time [5]. To our knowledge, however, there is very few valid and systemic works available in this field. In particular, there is a lack of the experimental confirmation about the moisture-time equivalence principle for polymer. This is the motivation of this work.

More recently, Kang and her associates [7,8] investigated experimentally the effect of relative moisture environment on material properties of thin film. Speaking of relative moisture, it should be noted that there is a clear distinction between moisture content and relative moisture. The former means the saturation of moisture state in a sample and the latter is the moisture environment surrounding the sample. In this paper, a series of experiments has been performed to explore the effect of moisture content on mechanical properties of polymer in which the samples nylon-6 are subjected to the different moisture content and the corresponding material parameters are measured. The study indicated that the moisture content will be more suitable than relative moisture for the purpose of investigating the effect of moisture-time equivalence relation on material behavior of
materials. Based on the experimental observation and testing results, an equivalent relationship
between time intervals and an increase of the moisture content for material properties has been
established. The generalized curves [5] of the material properties of Nylon-6 versus moisture
contents have also been obtained and the approximate equations of shift factor are presented at the
end of this paper.

2. Samples and experimental procedure

2.1 Sample and testing

To study the effect of moisture content on material properties, a series of moisture experiments
were made on the sample called Nylon-6 films the dimension of which is shown in Fig 1. For the
experiments, various moisture contents are acquired by dipping method and are quantified by
sensitive weighing device. Firstly experiment work for the effect of moisture in the material
property is done by tensile test. The moisture contents of the specimens were 1.6%, 2.0%, 2.5%,
3.0%, 3.8%, 5.1%, 5.7%, 8.3%. During the measurement the ambient temperature has been kept
constant at 24°C. The experiment has been performed on a CSS-44100 electronic universal
testing-machine. The crossbeam speed has been set as 0.1/min. Some tensile curves are showed in
Fig 2. From a series of experiments on nylon-6 under different moisture it can be found that
moisture has an effect on mechanical property of the materials, such as the strength and yielding
stress of the polymer material.

![Fig 1 the sample size of Nylon-6](image)

![Fig 2 Stress-strain curve of Nylon-6 with the different moisture contents](image)

Based on the tensile test, the time relativity with the moisture is made up by a series creep
testing. A constant load 40N is applied on the sample within the elastic stage and the time interval is
24 hours. It is important to keep the moisture content of the sample stable, as the time needed for
the creep experiment is relatively long (24 hours in our study). It should also be mentioned that a
series of basic tests on moisture losing is performed in order to keep constant moisture content
before the creep experiment. It is found from the experimental results that the moisture content of
the samples in creep test can be kept stable by controlling the ambient humidity in environmental
cabinet, which can control the change of moisture content within ±0.1% during the 24 hours.
Experimental curves of creep with different moisture content are shown in Fig 6, which is evident
for influence of moisture.

2.2 Marked points Correlation method

It is necessary in the creep experiments for precisely measuring the deformation of samples
from small till large deformation. To this end, an efficacious optical experimental method called
digital marker correlation is employed. The method is designed for non-contact optical measurement of in-plane displacements based on correlation analysis. It can be used to identify the position of markers on a surface of the samples before and after deformation. Deformations and strains can be calculated using the information obtained from some markers' displacements [9]. The method is sensitive than normal mechanical techniques in experimental processing. It can be efficiently used for thin or soft material to measure large deformations.

2.3 Analysis and discussion for the result of tensile test

As was mentioned in [10] the effects of moisture on material properties can be investigated from two following aspects. One is the change of molecular microstructure due to moisture from the viewpoint of materials science. The other is the effect of moisture factor on mechanical properties of the material, such as elastic modules, strength, percentage elongation and pliability of material. Two aspects above are fundamental in studying the effect of moisture on material properties and affected mutually. The former, i.e. the change of molecular microstructure results in the change of mechanical properties of the material. Based on experiment results, the effect of moisture on material properties is analyzed as below. Fig 2 shows the effect of moisture content on material properties of polymer samples. It can be found from these two figures that the strength of the material decreases along with the increase of moisture. Typically, the elastic modulus, elastic limit, and yield limit decrease with an increase in moisture. It is also evident from the module-strain curve in Fig. 3 that the effect of moisture in more obvious in small strain than in the large strain. As was shown in Fig. 4, the effect of moisture content on material module is obvious, especially at the initial stage. The relation of moisture and module is approximately linear within this stage. After this stage, the effect of moisture on material module becomes weaker. In addition, it can be shown from the experimental observation and results that the yielding of the material is affected by moisture obviously and a relationship between them can be established accordingly.

![Fig 3 Module-strain curve of Nylon-6 with the different moisture contents in experiments](image1)

![Fig 4 Module-moisture curve of Nylon-6 with the different moisture contents](image2)

3 Discussion

3.1 Analysis of the experimental results for moisture-time superposition

The curves for the creep of samples with different moisture contents are shown in Fig 5. In the figure Y-coordinate denotes the strain of sample, and X-coordinate the time interval. The curve in Fig. 6 shows the corresponding compliance which denotes the reciprocal of module [5] versus the...
logarithm $t$. It is found that the creep behavior is sensitive to the moisture contents. It should be noted that the curves of creep versus moisture contents can be shifted by a constant distance $ln a_T$ to form a generalized curve, as was pointed out in [5] that there is some equivalence between moisture and time. Mannmieten [5] indicated that the generalized curve defined a creep curve that was not obtained from experiment directly but from the original curve shifting based on the time-temperature superposition principle. Following this way, Fig. 7 is obtained from the creep curves in Fig. 6, that are shifted by shift factor to the location of the creep curve with the moisture content 1.0%, and then they are joined together. Figure 7 actually represents the generalized curve with moisture content 1.0%. It is shown that there are some equivalence between moisture and time for mechanical material property. Similarly the generalized curves for other moisture contents can be obtained which is listed in Fig. 8 showing the generalized curves with the moisture content 5.6 %, 3.0%, 1.0%, 0% (from left to right in turn). Using the generalized curves the material characteristic about time relativity under other moisture conditions can be pre-estimated.

![Creep experiment curve of Nylon-6 with different moisture contents under the loading N=40N](image1.png)  
**Fig.5** Creep experiment curve of Nylon-6 with the different moisture contents under the loading N=40N (strain-time curve under the loading N=40N)

![Compliance-ln t generalized curves on Fig.6.](image2.png)  
**Fig.7** Compliance-ln t generalized curves on Fig. 6.

![Generalized curves under other moisture contents](image3.png)  
**Fig.8** Generalized curves under other moisture contents

### 3.2 Analysis of experimental results for Shift factor and shift function

The equivalence between moisture and time is established based on the concept of the shift function and the shift factor that can be obtained from the experimental results. Following the way of [5], the shift factor logarithm $a_M$ can be defined as:

$$ln a_M = f(M-M_0)$$  \hspace{1cm} (1)
where M stands for moisture content, \( M_0 \) is the referenced moisture content (\( M_0 = 1.0\% \) in our analysis); \( f \) is a function of variable (\( M - M_0 \)), which can be fitted in a way described below.

The curve of \( \ln \alpha_M \) versus time can be plotted based on the shift factor obtained from experiments. The function used to fit the curve is defined as [5]:

\[
y = y_0 + A_1 \times \left[ 1 - \exp\left( -\frac{Y}{t_1} \right) \right] + A_2 \times \left[ 1 - \exp\left( -\frac{Y}{t_2} \right) \right]
\]

(2)

The fitting results are shown in Fig. 9, which represents a curve of the following shift function:

\[
\ln \alpha_M = 0.17 + 2.49 \times \left[ 1 - \exp\left( -\frac{(M - M_0)}{2.55} \right) \right]
\]

(3)

Similarly, if moisture content 0 was selected as the referenced moisture content, the fit curve as shown in Fig 10, but it represents a different shift function:

\[
\ln \alpha_M = -0.05 + 4.41 \times \left[ 1 - \exp\left( -\frac{(M - M_0)}{2.55} \right) \right]
\]

(4)

Based on the shift function and the generalized curve above, the generalized curve for other moisture contents can be obtained easily.

![Fig. 9 ln\( \alpha_M \) versus \( M - M_0 \) curve on \( M_0 = 1.0\% \)](image)

![Fig. 10 ln\( \alpha_M \) versus \( M - M_0 \) curve on \( M_0 = 0 \)](image)

4 Conclusions

The effect of moisture content on mechanical property of macromolecule structure is studied experimentally. A series of experiments are completed on nylon-6 film and some conclusions can be made as follows:

1) The moisture content has a significant effect on mechanical property of polymer materials that was supported by a series of experiments on nylon-6 under different moisture. In particular, moisture can decrease the strength but increase the yielding stress of the polymer material. In the elastic stage the effect of moisture on material modulus is especially obvious.

2) A series of experiments about time-dependent mechanical properties under various moisture contents are systematically carried out for Nylon-6 materials for the first time. The generalized curves under various contents have been obtained quantitatively by the shifting
method. It is proved that there is an equivalence relationship between time and moisture for polymer Nylon-6 from the experiments.

3) The approximate shift factor and shift function of Nylon-6 can be determined from the experiments. With the shift function, the moisture-time superposition principle could be deduced for polymer material, which can be used for further predicting the material property under various environmental conditions or material time aging.

4) The equivalence relationship between time and moisture provides an efficient method for the investigation of long term behavior and aging behavior of polymer material under moisture or humidity environment. The extension of this work is possible such as the coupling effect of moisture-temperature on the property of polymer materials.

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