

## Characteristics of the Changes in the Compressive and Tensile Stress of the Construction Sealant under Cyclic Movement

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**Abstract.** *A compact fatigue testing machine to quantitatively evaluate the effects of this complex degradation of sealants and the load change of the sealant under dynamic fatigue has been developed. The developed fatigue testing machine is compact with dimensions of (width) 100 × (length) 135 × (height) 110 mm. It can be installed in an outdoor exposure test site or in a chamber. Thus, this machine can be used for performing various compounded accelerated degradation tests. We report the use of this testing machine to examine the effects of this complex degradation of sealants and the load change of the sealant under dynamic fatigue.*

**Keywords:** *Fatigue Testing Machine, Sealant, Joint, Fatigue Resistance.*

### 1 Introduction

The factors contributing to the degradation of the construction sealants used in exterior walls can be broadly classified into weathering (heat, ultraviolet rays, moisture, etc.) and joint movement and they work simultaneously in a complex manner. Especially, for dynamic joints, these factors work simultaneously and in a complex manner, and they continue to take effect from the moment that they are filled in the joint until the end of their life.

Current evaluation tests for the sealants mainly evaluate properties after curing in relation to a single degradation factor. No evaluation method for the effect of movement during curing process or one in which complex degradation can be applied had been established yet.

For this reason, we worked on developing a compact fatigue testing machine for the sealant to quantitatively evaluate the effect of complex degradation and load change in the sealants at the time of dynamic fatigue.

Using the developed compact fatigue testing machine the effects of the joint movement during curing on the physical characteristics and the shape of the sealant and the changes in physical properties of the cured sealants were evaluated. The changes in compression and tensile stress of the sealant when repetitive expansion/contraction fatigue (deformation) was applied to the sealing joints with variable fatigue cycle, displacement, and temperature were also measured and examined.

## 2 Overview of the Fatigue Test

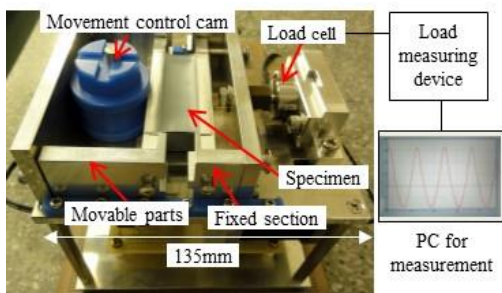
### 2.1 Overview of the Fatigue Testing Machine

Conventional fatigue test machines are all large devices with low versatility and high price. When developing the current fatigue machine, the following points were paid attention to (a) compact size, lightweight, installable in a chamber; (b) easy mechanism; and (c) the price range is such that concerned parties can use the machine in round-robin fashion.

An overview of the developed testing machine is shown in Figure 1 and Table 1. It comprises of (1) fatigue testing machine unit, (2) load measurement device, and (3) PC for measurement purposes. It is capable of measuring the stress (load) on the sealants simultaneously while applying repetitive expansion/contraction deformation.

The dimensions of the fatigue testing machine are 100 mm (Width) × 135 mm (Length) × 110 mm (Height) mm and it weighs only 1.3 kg and can be held by one hand. The device runs on AC 100 V power source or a DC 12 V battery, so it can be installed for outdoor exposure test and can also be placed in a chamber.

Two types of machines with different fatigue cycles were made. One was a fixed-cycle (one cycle/24 hrs) type, in which the number of rotations was controlled only by the combination of a motor equipped with a decelerator and a worm gear. Another was a variable cycle type, in which the number of rotations could be electronically changed with a stepping motor which was combined with the reduction gear ratio of the worm gear. The main unit is separated into the test unit on the upper fixed platform and that on the lower control unit. A test specimen was fixed between the movable section jig and the fixed section jig in the test section, and the load generated by the reciprocal motion of the compression and tension displacement of the movable section was detected by a load cell. In the control unit, high torque is realized by the motor equipped with the decelerator or the combination of the stepping motor and the worm gear, and it rotated within the specified range controlled by a displacement control cam attached to a rotation axis. The load method is explained as follows. In the displacement mode we used, the compression and tension displacement were applied alternately in a sine wave. The displacement was set at ± 1.2 mm (± 10%), ± 2.4 mm (± 20%), and ± 3.6 mm (± 30%) in relation to the joint width of 12 mm. For joint movement cycle, with this machine two levels could be selected, i.e., once per day (24 hrs) and 5 cycles/min (approximately 12 s). The latter is the range specified in JIS A 1439.



**Figure 1.** Compact Fatigue Testing Machine (Variable cycle type).

**Table 1.** Compact Fatigue Testing Machine Specification.

Testing machine type	Fixed Cycle type	Once per day: Decelerator-attached motor control
	Variable Cycle type	Once per day to 5 times/minute: Stepping motor+ electric control
Load method	Drive method	Motor+worm gear
	Displacement mechanism	Displacement control by cam eccentric motion
	Displacement mode	Compressed tensile displacement ± 1.2, 2.4, 3.6mm
	Cycle	Once per day; 5 times/minute (sine wave)
Load	Load resistance	Maximum 100N
	Load measurement	Tensile compression load cell (Max.200N)
Environment used	Temperature	-10 to +50°C (depends on motor spec)
	Power	AC100V, DC12V battery (for low load)
Others	Dimensions/weight	Width 100 × length 135 × height 110mm, 1.3kg

## 2.2 Sealants Used in the Test

Silyl-terminated polyether (STPE) type sealants having a silylated polyether main chain with reactive silyl terminal groups as the main ingredient, which forms siloxane bonds through moisture-curing and thereby exhibits rubber elasticity, were selected. It has excellent weatherability, durability, heat resistance, workability, and good paintability on the surface and is widely used for construction sealing materials and elastic adhesives. General structural formula of STPE is shown in Figure 2.

In the test, the two types of sealants were used, i.e., 1-component type (MS-1) and 2-component type (MS-2, F-25LM-9030), with tensile properties and relaxation rate shown in Table 2. The tensile properties were measured according to JIS A 1439 (tensile velocity was  $5.5 \pm 0.7$  mm/min). The stress relaxation rate was obtained from Equation 1. The larger the stress relaxation rate is, more is the reduction in tensile stress generated in the sealant with time.

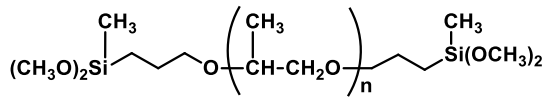


Figure 2. General structure of silyl-terminated polyether.

Table 2. Tensile test results and stress relaxation rate of the sealant used.

Sealant	$M_{50}$ ( $N/mm^2$ )	$T_{MAX}$ ( $N/mm^2$ )	$E_{MAX}$ (%)	Stress relaxation rate (%)
MS-1	0.06	0.25	580	68
MS-2	0.12	0.25	410	28

$$\text{Stress relaxation rate} = \frac{\text{Tensile stress immediately after 30\% tension} - \text{Tensile stress after 30\% tension being held for 15 hrs}}{\text{Tensile stress immediately after 30\% tension}} \quad (1)$$

## 2.3 Specimen Shape

As shown in Figure 3, the test specimen was an ISO type (W 12 mm  $\times$  D 12 mm  $\times$  L 50 mm) using anodic oxide coated aluminum as the substrate. The substrate was coated with a primer exclusive for sealants.

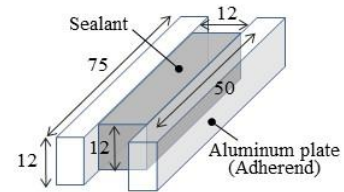


Figure 3. Specimen (ISO type) shape /dimensions (unit:mm).

## 3 Effect of Repetitive Deformation on Curing Sealants

### 3.1 Fatigue Test Method





Tests were carried out on two types of test specimens for MS-1 and MS-2, i.e., the cured test specimen in accordance with JIS A 1439 (also called specimen after curing) and the test specimen immediately after the sealants had been applied to the joints (also called specimen before curing). In order to measure the load change in the joint, backup material was not used in the specimen, and Teflon tape was attached to the bottom of the rear side so that the sealant could be peeled off. The deformation rate of the joint was set at  $\pm 20\%$ , and the test was started from the compression side. The cycle was set at once per day in accordance with the actual joint behavior. The test period was set to two weeks (total number of deformations: 14). Load (stress) changes in case of movement applied to sealants during curing were evaluated.

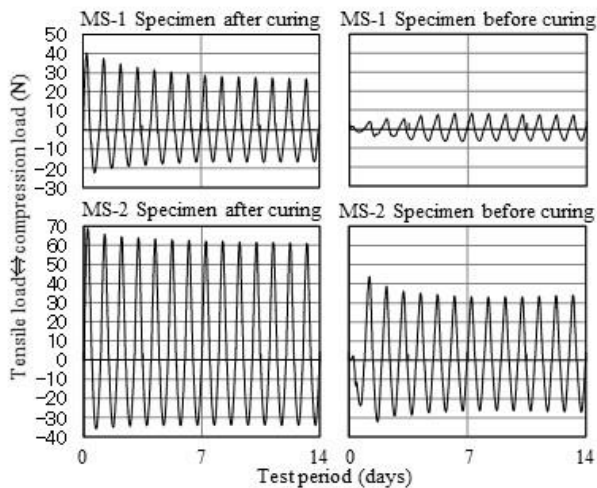
### 3.2 Fatigue Test Results

#### 3.2.1 Load changes and damage state of the sealant

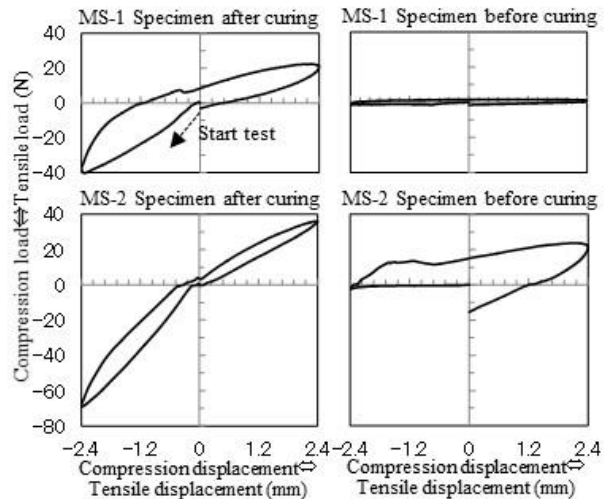
Figure 4 shows the load changes in each specimen related to the repetitive deformation. For both MS-1 and MS-2, we can see that the specimen before curing had a reduced load amplitude compared to the specimen after curing, and that it was affected by the movement during the curing. In particular, the MS-1 specimen before curing showed these tendencies prominently. The conditions of the front and rear face of each pre-cured specimen subjected to fatigue test did not show any change. Meanwhile, the front face of the specimen before curing swelled in a convex shape, as shown in Table 3. The MS-1 specimen before curing had a large hole in the center of the rear side. It was considered that the sealant was damaged due to significant effect of the movement applied during curing. Additionally, the rear face of the MS-2 specimen before curing was deformed to a convex shape.

**Table 3.** Surface/reverse for specimen before curing after

	MS-1 Specimen before curing	MS-2 Specimen before curing
Surface		
Side		



**Figure 4.** Changes in load against repetitive deformation.



**Figure 5.** Displacement and load hysteresis curve for the first repetitive deformation.

### 3.2.2 Hysteresis curve of the displacement and load after first fatigue cycle

Figure 5 shows the hysteresis curve of the displacement and load of the sealants after first repetitive deformation cycle. The initially uncured specimens were slow in expressing the strength compared to the cured specimens, and the load zero value before and after one fatigue cycle did not match. This may be due to change in shape of the sealants or due to damage. Meanwhile, for the cured MS-1 specimen, the difference in the load before and after the tension/compression round-trip was greater compared to that of the cured MS-2 specimen, presumably due to fatigue.

## 3.3 Observations Concerning Fatigue Resistance

### 3.3.1 Effect of curing state due to repetitive deformation

In case of the uncured MS-1 specimen, the sealants hardened gradually from the surface (Figure 6). Since the shape coefficient  $D/W$  ( $D$ : joint depth,  $W$ : joint width) decreases in the initial

curing period, the sealant was rendered into a state being easily deformed outward, as shown in Figure, once the compression movement was incurred during the curing. Additionally, when the movement occurred during the curing of MS-2, the compression/tensile load ratio changed (Figure 7). This also suggests that the change occurred similarly in the joint cross-section. That is, when it receives the movement during the curing, the subsequent fatigue resistance would be affected.

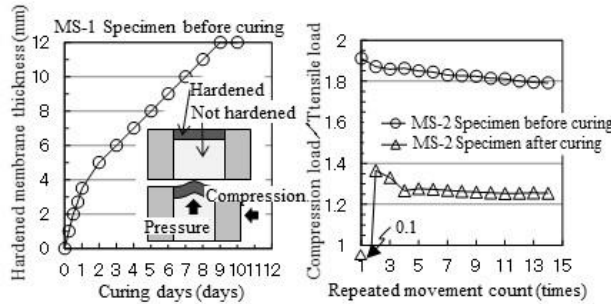


Figure 6. Changes in membrane thickness and joint cross-section change.

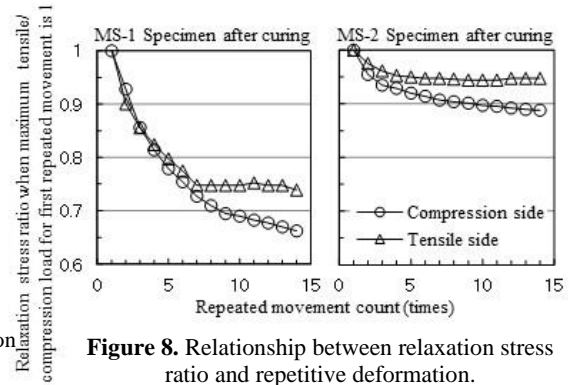


Figure 8. Relationship between relaxation stress ratio and repetitive deformation.

### 3.3.2 Effect of stress relaxation due to repetitive deformation

The relaxation stress ratio (fatigue stress ratio) has been defined as the ratio of the generated stress under the repetitive deformation to the maximum stress (load) at the first movement cycle expressed as the reference value 1. Its relationship with the number of repetitive deformations is shown in Figure 8 above. The reduction in relaxation stress ratio of the cured MS-1 specimen is larger, compared to the cured MS-2 specimen. Additionally, the relaxation stress rate greatly decreased after applying repetitive deformation. For both specimens, the decrease in the stress relaxation ratio on the compression side was greater than that on the tensile side, and it can be considered necessary to carry out repetitive fatigue tests to evaluate the effect of stress relaxation in the sealants.

## 4 Effect of Repetitive Deformation in Relation to Cured Sealant

Next, different repetitive deformation were applied to the cured sealant and the compression and tensile stress of the sealant were measured and observed.

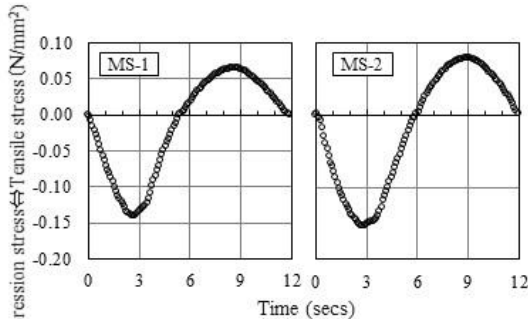
### 4.1 Fatigue Test Method

MS-1 and MS-2 described in Section 2.2 were used. The compression and tension deformation rate of the joint was 20% of joint width, and the fatigue test started from the compression side. The cycle was 12 s, and the maximum number of the fatigue cycles were 10,000.

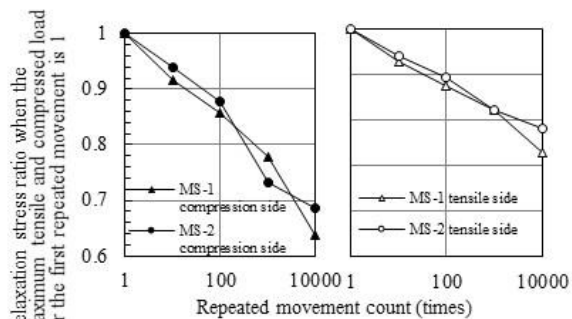
#### 4.1.1 Viscoelasticity Properties of Sealant

The changes in the stress of the sealant at the first fatigue deformation is shown in Figure 9. For MS-1, maximum compression stress was 2.2 times greater than the maximum tensile stress, and this ratio was 2 times for MS-2. For MS-2, at the displacement zero point (at 6 s

where the joint changed from contraction to expansion), the stress became zero, indicating the elasticity. Meanwhile, for MS-1, the changes in the stress preceded the movement, and the tensile stress was generated at the displacement zero point, indicating the tendency to easily undergo compressive setting and the viscoelasticity.



**Figure 9.** Sealant stress changes at first repetitive deformation (12-second cycle).



**Figure 10.** Relationship between relaxation stress ratio and the number of deformation (12-second cycle).

#### 4.1.2 Sealant Stress Reduction Characteristics in Relation to Repetitive Deformation

The relationship between the relaxation stress ratio and the number of the repetitive deformation (when maximum tension and compression load for the first repetitive deformation cycle = 1) is shown in Figure 10. For both MS-1 and MS-2, the stress relaxation ratio in the compression side became smaller compared to that in the tensile side as the number of the repetitive deformations increased. This is particularly prominent in the case of MS-1. Figure 11 shows the hysteresis curve of the displacement quantity and stress for each fatigue cycle.

When the repetitive deformation was applied once, the phase differences for both displacement and stress for both MS-1 and MS-2 were large. The difference was particularly large in MS-1, compared to MS-2. Additionally, in terms of the effect of the joint displacement, the effect of the compression side is greater than that of the tensile side. Therefore, MS-1 has more viscous properties (dashpot) and less elastic properties (spring) than MS-2. However, as the number of the fatigue cycles increased, phase difference became smaller.

#### 4.1.3 Effect of the Fatigue Cycle

Table 4 shows the relationship between the number of test days and total strain energy under test conditions. The 12-s cycle test had  $1/10^{\text{th}}$  the duration compared to 1-d cycle test, but the total strain energy was five times greater. Figure 12 shows the relaxation stress ratio for the 12-s and 1 day fatigue cycle tests. For MS-2, the stress relaxation ratio at the 14th fatigue cycle in both cases was almost the same. This is because the number of repetitions of the joint deformation may be dominantly influencing the MS-2 stress reduction characteristics, as shown in Figure 10. Meanwhile, for MS-1, the stress relaxation ratio at the 14th fatigue cycle in the 1-d duration cycle test is small, compared to that of the 12-s cycle. This is assumed to be because the fatigue loading time exerts a dominant influence on the MS-1 stress reduction characteristics.

From the above, MS-2 was able to bear the effect of 1 cycle/day fatigue (the actual cycle) based on the test method using a fatigue cycle of 5-6 cycles/min specified in JIS A 1439 under temperature conditions of  $23 \pm 2^{\circ}\text{C}$ . However, for MS-1, it is may be necessary to execute fatigue tests in accordance with the actual cycle.

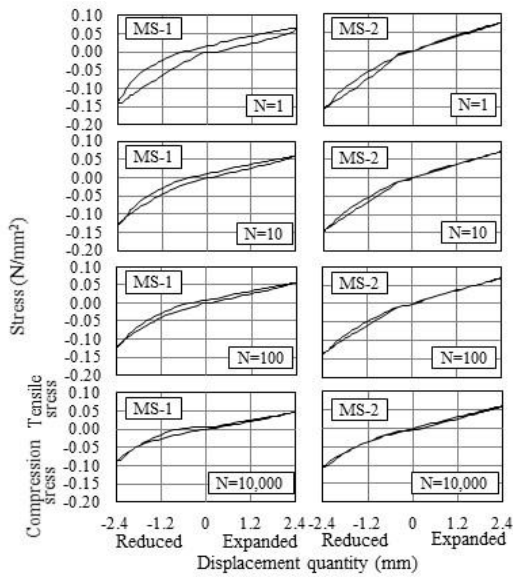


Figure 11. Hysteresis curve for displacement and stress (12-second cycle).

Table 4. Relationship between the number of test days and the strain energy under the load cycles and the maximum deformation cycle in this study.

Test conditions		Days (ratio)	Total strain energy
Cycle	Movement count (ratio)		
12 secs	10,000 (714 times)	1.4 (1)	5 times
1 day	14 (1)	14 (10 times)	1

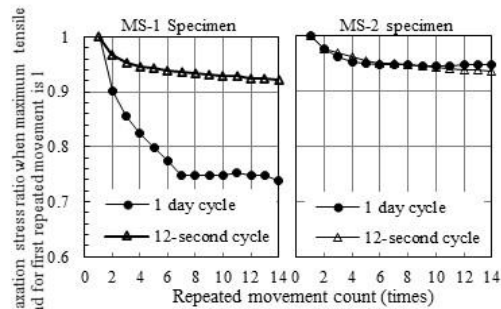


Figure 12. Effect on stress decrease in sealants

## 5 Effect of Displacement Quantity, Temperature Conditions and Repetitive Elongation/Reduction Deformation

Next, the changes in the compression and tensile stress of the sealant when the repetitive expansion/contraction reformation was applied to the cured sealants while changing the displacement and temperature were measured and examined.

### 5.1 Fatigue Test Method

After installing MS-2 specimen in the compact fatigue testing machine, it was kept for sufficient time under arbitrary temperature conditions (5, 23, 40°C). Then the repetitive expansion/contraction fatigue with a deformation rate of  $\pm 10\%$  or  $\pm 20\%$  in relation to the joint width was applied from the compression side. The repetition cycle was 12 s, and the maximum number of fatigue cycles were 8,000 to 10,000 (at 23°C,  $\pm 20\%$  30,000 times maximum).

### 5.2 Fatigue Test Results and Discussion

#### 5.2.1 Sealant Stress Reduction Characteristics in Relation to Repetitive deformation

The relationship between the relaxation stress ratio when the maximum tension stress (load) for the first repetitive deformation cycle was expressed as 1 and the number of the repetitive deformation is shown in Figure 13.

Under the deformation rates of both  $\pm 10\%$  and  $\pm 20\%$ , the relaxation stress ratio became lower for each repetition. Also, the deformation rate of  $\pm 20\%$  had a smaller relaxation stress rate compared to that of  $\pm 10\%$ . Meanwhile, no significant

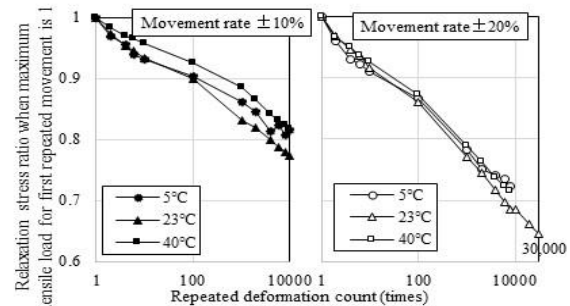


Figure 13. Relationship between relaxation stress rate and the number of deformation (12-second cycle).

temperature dependency was observed for the relaxation stress ratio.

### 5.2.2 Hysteresis Curve of Displacement Quantity and Load

The hysteresis curves of displacement and the load under various temperature conditions with the deformation rate of  $\pm 20\%$  are shown in Figure 14.

At  $23^\circ\text{C}$ , the displacement and the phase difference of the load were small up to a fatigue count of 8,000, whereas the phase difference became large at or above the fatigue count of 20,000. Meanwhile, at  $5^\circ\text{C}$ , the phase difference was large even at the fatigue count of 8,000, and it was larger than that at  $23^\circ\text{C}$  and  $40^\circ\text{C}$ .

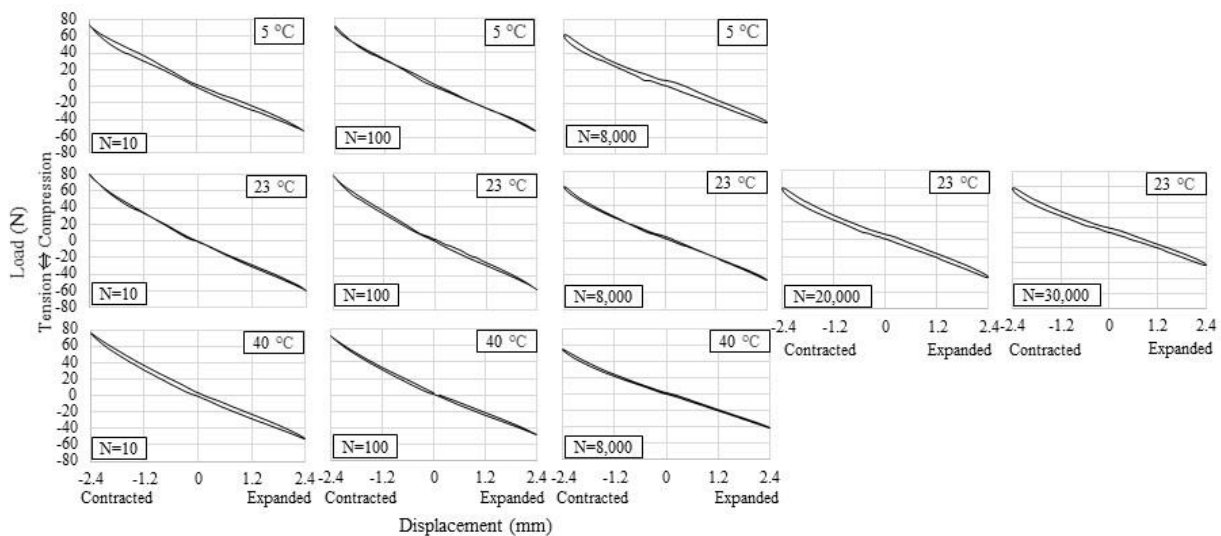


Figure 14. Hysteresis curve of displacement and load under various temperatures (deformation rate  $\pm 20\%$ ).

## 6 Conclusions

This fatigue testing machine was developed to evaluate the durability of sealants against degradation under outdoor environment. Various methods of utilization can be sought according to the user objectives. For example, the testing machine we developed reproduces the movement of the sealants and can be used in combination with outdoor exposure or in an accelerated deterioration test device. This way It is possible to perform a variety of complex degradation tests and further utilization for future sealing technology can be sought.

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