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QUANTIFICATION OF SURFACE CRACK DAMAGE OF CONSTRUCTION SEALANTS

Yoshiaki TAKEMOTO, Hiroyuki MIYAUCHI, Michael A. LACASSE, Noriyoshi ENOMOTO, Akihiko ITO and Kyoji TANAKA

ABSTRACT

Sealants used in construction on the exterior of buildings deteriorate with time and a consequence of this deterioration is the formation of surface cracks. Although the formation of surface cracks is an important indication of local failure that reflects the state of degradation of the product, until now assessing the degradation state has been performed by visual observation that provides only a cursory evaluation of the product. In this study, a new method based on fracture mechanics is proposed to quantify the surface damage of sealants and hence estimate their degradation state. Use of this method permits a comparison of the nature of surface cracks on the surface of sealants exposed for various periods of time and at different exposure sites.

INTRODUCTION

Sealed joints used in building construction are exposed to the outdoor environment and sealants are subjected to climate-driven loads such as sunlight, exterior temperatures and rainfall. Moreover, sealed joints must respond to joint movement in walls; that is, the expansion-contraction movement in the sealed joint that occurs repeatedly. Consequently over their service life, sealants gradually deteriorate by the combined deterioration effects of movement and weathering. When sealants deteriorate over their service life, cracks typically occur on the surface of the sealant. Because this crack-growth will in time influence the air and watertightness at the joint and considering that such cracks typically progress in the direction of the depth of the sealant joint, it is important to analyze the degree of cracking and rate of crack growth and propose a rating scale for the condition of the joint sealant.
The test method proposed for evaluating the degree of cracking of sealants is mainly based on an existing ISO method [1]. This method is reasonably useful to investigate the degree of cracking of sealants by visual observation, however the degradation rating scale depends on human factors such as experience and observation conditions. However, a more useful technique to develop would be one that permits investigating the relative degradation in an objective manner.

The most widely used method to evaluate the extent of deterioration of sealant materials is a test to rupture of the material [2]. Assessing the degree of extension to which a product can be expected to perform in-service is often estimated from comparison of the strength of new with that of a deteriorated sealant product. However, sealants are difficult to assess since one is not able to confirm the influence of the formation of surface cracks on the deterioration of the sealant bead as a whole because the progress in the degree of deterioration may vary considerably.

Enomoto et al. [3] have proposed an evaluation method for the extent of deterioration of sealing material that may also be capable of evaluating the progress of deterioration of the sealant. The crack is characterized by observing both the quantity (Q) and size (S) of cracks. The degree of increasing deterioration, based on the product of Q and S, can be classified, respectively, by six stages ranging from 0 to 5. However, the results from this evaluation method may be prone to variation depending on the skill of evaluator. As well, the depth of cracks is not at all considered.

In this study, sealants of the type typically used in Japan, were exposed to outdoor test conditions, and the crack width, area and depth of sealants were measured by optical microscope. The method for calculating the degree of deterioration of sealants is proposed by using basic concepts of fracture mechanics. By determining the changes in strain energy of sealants, the degree of damage to deteriorated sealants exposed to the outdoors could be categorized at different levels.

OUTDOOR EXPOSURE TEST

Test apparatus

As shown in Figure 1, two parallel anodized aluminum angle flanges (length 120-mm, flange height 15-mm; thickness 1.9-mm) spaced 20-mm apart, were fitted with eyelets about their mid-length allowing them to pivot about these points. The flange heights varied permitting the casting of 12 or 15-mm deep joints. Figure 1 shows the configuration for a 15-mm deep joint of 100-mm length. A sheet of polypropylene was placed on the base of the joint to act as bond breaker. The flanges could be fixed in predetermined positions with boards placed in slots located at their extremities. A singular feature of the test apparatus is that the joint width can be changed by pivoting the two flanges in opposite directions to one another. In such a manner, the test apparatus permits continuously changing the amount of expansion and contraction of the sealant material and additionally, one can compare the effects produced from subjecting the test specimen to states of tension, compression or of no movement.

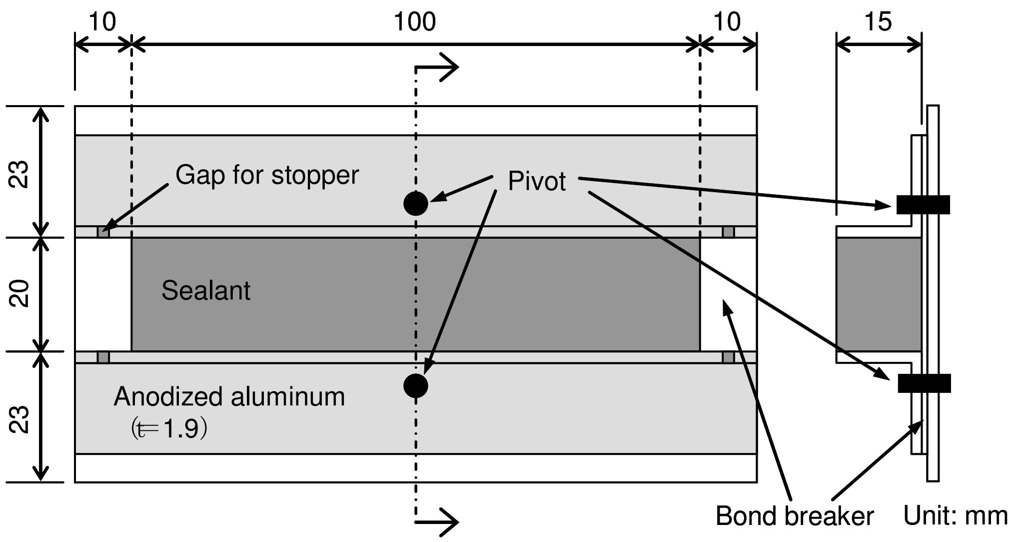


Figure 1. Variable movement test specimen

Sealants

Two kinds of sealant product were selected; a two-component modified silicone product, and a two-component polyurethane product. Table 1 provides information on the physical properties of sealants.

Table 1. Physical properties of sealant products based on JIS test methods

Sealant product type	Designation	Physical properties*		
		Tensile Modulus at 50% extension (N/mm^2)	Tensile stress (N/mm^2)	Maximum elongation (%)
Two-component modified silicone	MS-2	0.14	0.69	850
Two-component polyurethane	PU-2	0.07	1.03	1390

* Note: The cure conditions conform to JIS A1439 [2]; the tensile tests conform to JIS K6251 [4].

Curing of sealants and test method

A specimen was made by casting a sealant between two previously primed parallel aluminum flanges and onto a sheet of polypropylene acting as a bond breaker. The sealant was cured in accordance with conditions specified in JIS A 1439 [2].

After the sealant had cured to rigid state, a separator was installed on one side of the aluminum attachment flange, as shown in Figure 2, thus ensuring one side of the sealant was in a state of compression, and on the other in a state of tension. The compressed joint had a reduced joint width of 14-mm whereas the joint in extended mode was 26-mm. This corresponded to a 30% compression or extension of the sealant against the nominal 20-mm joint width.

Evidently joint movements in an actual joint occur once every a day [5], however it is impractical to carry out the same conditions as occur outdoors with the device. Sealant specimens were therefore repeatedly subjected to cycles of expansion and contraction (± 30%) in an outdoor environment by changing the position of the right and left separator every month.

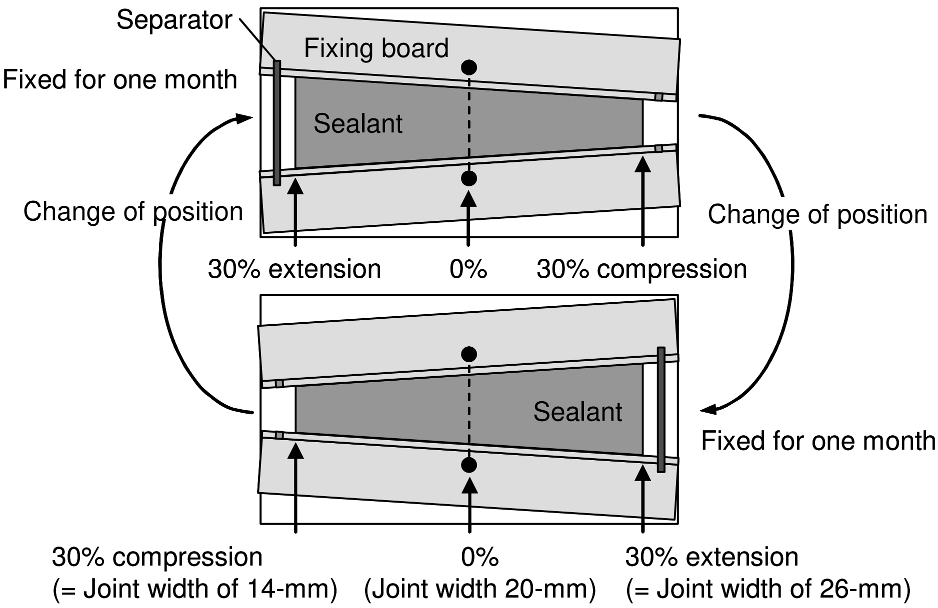


Figure 2. Sealant specimens subjected to continuous joint movement

Outdoor exposure sites

The outdoor exposure tests were carried out at three locations in Japan; in a Northern region, located at the Hokkaido Northern Regional Building Research Institute in Asahikawa, in a Central region of Hokkaido (Chiba), located at the Japan Weathering Test Center in Choshi, and the Southern region (Okinawa), located at the Japan Weathering Test Center in Miyakojima. The test period lasted 3 years from 2002 to 2005. Given the expectation that the test specimens would be affected by climate variations evident among the different exposure sites, the temperature, the amount of total rainfall, and total solar ultraviolet radiation over the exposure period was recorded as given in Table 2. Comparisons in respect to the environment at the different sites suggest that the climate of Miyakojima is more severe for organic based materials such as sealants. At the Miyakojima exposure site, the temperature and the amount of ultraviolet radiation is high in relation to the other two sites.

Table 2. Weather conditions of each exposure site*

Climate elements		Exposure site		
		Asahikawa	Choshi	Miyakojima
Temperature	Maximum	33.8	35.2	34.7
	Minimum	-23.3	-1.5	9.2
	Average	7.0	15.2	23.7
Total precipitation over 3 years (mm)		2,970	5,704	6,219
Total irradiation from ultraviolet rays over 3 years (0・MJ/m^2)		643	903	1,061

*Three year exposure, from 2002-10 to 2005-09.

METHOD OF ANALYSIS OF DETERIORATED TEST SPECIMENS

Digital photographs of surface of test specimens

Figure 3 provides digital photographs of the surface condition of the sealants observed after being exposed for 3 years to outdoor weathering at the respective exposure sites. It is evident from these photographs that cracks can be distinguished at the surface of the sealant from being subjected to expansion and contraction as well as the combined effects of solar radiation (i.e. ultraviolet rays, temperature) and moisture. The results show the progress in deterioration of the sealant based on changes at the surface of the material. Visual observation of the degree of surface deterioration of the sealants exposed to the 3 different sites indicated that their condition was characteristically different. Moreover, a large number of small cracks were evident on the surface of MS-2 whereas comparatively larger cracks were characteristic of PU-2. Therefore, the results, helped confirm the difference in response of the various materials to exposure at different sites. From this information is was proposed that the extent of deterioration could be evaluated on the basis of quantifying the number of surface cracks present on the surface of the sealant material in relation to the type of sealant product, the exposure site and the degree of extension to which the specimens were subjected.

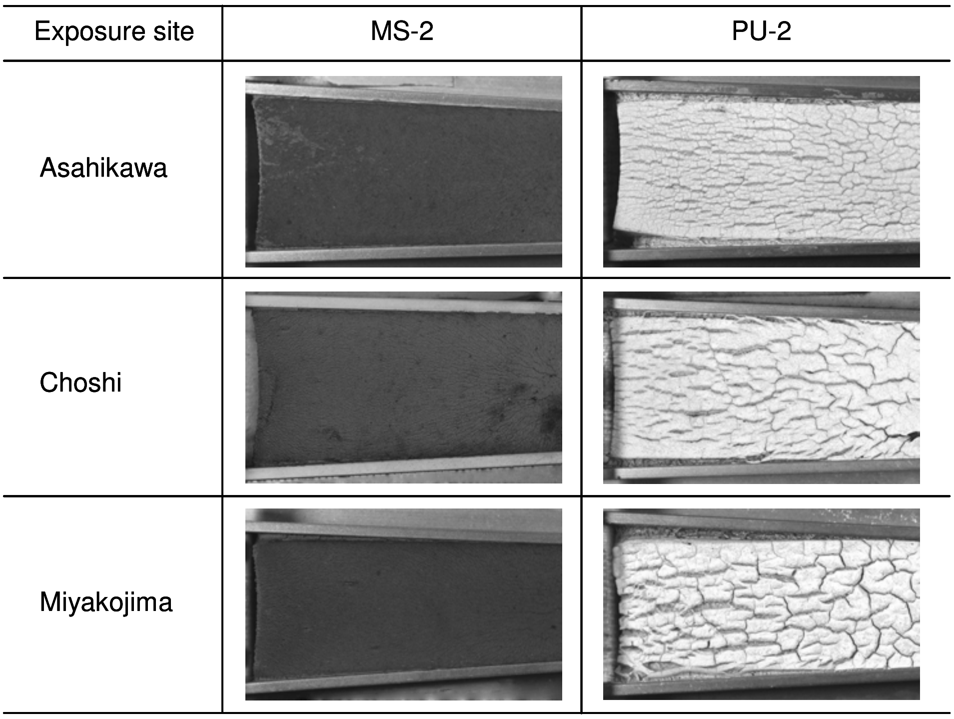


Figure 3. Surface cracks of MS-2 and PU-2 sealants exposed to different locations

Methods for quantifying the degree of crack formation

The following methods were used to quantify the degree of crack formation. The observation of crack formation was limited to the tension side given that in any case cracks were observed on either the compression or tension side of the specimen.

Average crack width - Using a digital microscope, crack widths on the surface of the sealant were observed 100 to 500 times actual size at the targeted degree of joint extension (i.e. 0, 15% or 30%) and an auto measurement device was used to determine crack widths from which an average was computed.

Crack area ratio - The method of measuring the ratio of crack area on the surface of the sealant was evaluated by using a light contrasting, binary process technique [6], in which cracks on the surface of sealant appear as a black image. The procedure of the measuring method is as follows: (i) A picture of the test specimen was taken with a high-resolution digital camera (6-Mega pixel). (ii) The level of brightness (ranging from 0 to 255) along a line on the surface of the sealant is measured as shown in Figure 4. An example of the value in brightness measured along the line is shown in Figure 5. The lowest values of brightness indicate cracks on the surface of the sealant. The mean value of the lowest 3 values of brightness along this line was the threshold level for which the binary process between black and white images could then carried out.

Figure 6 shows the resulting black-white contrasting image. The brightness levels higher than the threshold level appear white in the image whereas values below the threshold level are black. (iii) The crack area ratio was calculated on the basis of the black and white image; a measurement area of 8.8 by 16-mm (220 by 400 Pixels) was used at extensions of 0%, 15% and 30% as shown in Figure 7. The area of black pixels in the measurement area (Figure 8) was determined and the crack area ratio calculated based on the total area (140.8-mm^2).

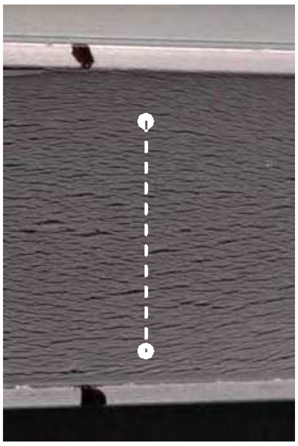


Figure 4. Measurement of brightness

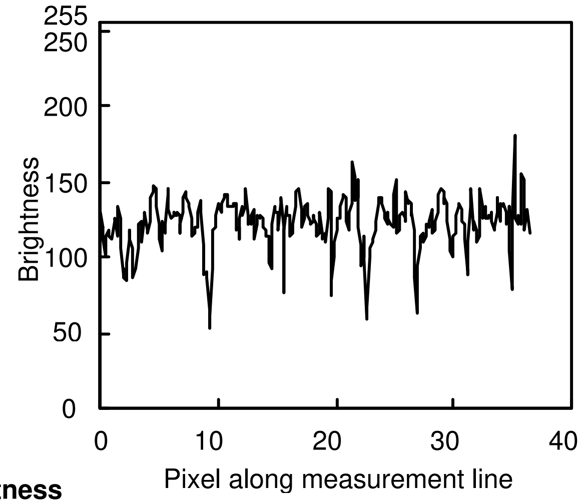


Figure 5. Degree of brightness measured in pixels along measurement line

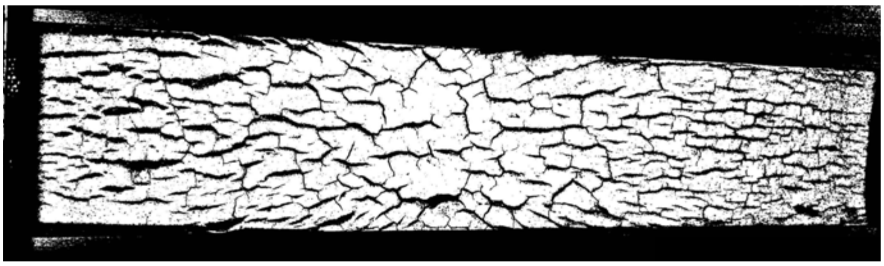


Figure 6. Surface condition of PU-2 sealant in Choshi exposure after the binaries process

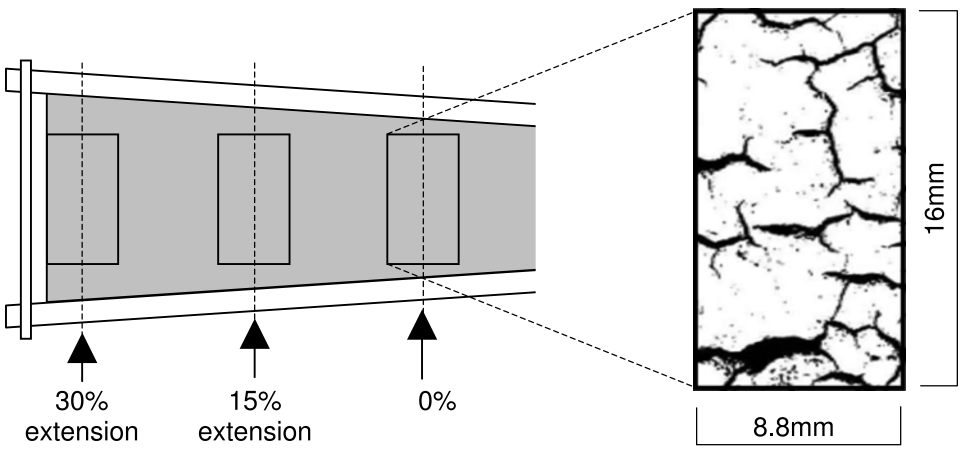
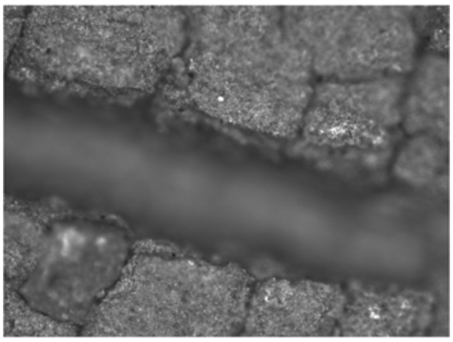


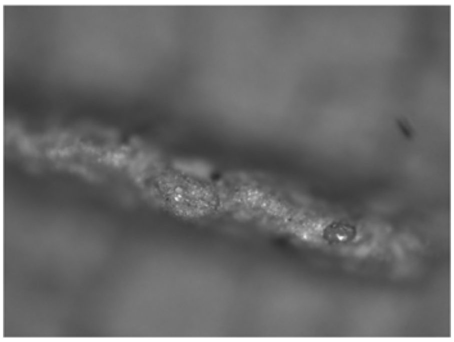
Figure 7. Measurement position of crack area of sealant

Figure 8. Crack condition of PU2 in Choshi exposure

Average crack depth - The average crack depth was determined for all cracks at the given extension ratio. Measuring crack depth was based on differences in focal length obtained when the camera was focused on the surface of the sealant and the bottom of the crack, as shown in Figure 9. The focal length is assumed to be 0 at the surface of the sealant. The difference in focal length was determined by focusing on the bottom of the crack and measuring the focal length at this location. The differences between focal length were related to the crack depth.



Focusing at the surface of the sealant



Focusing on the bottom of the crack

Figure 9. Measurement of crack depth

RESULTS

Figure 10 provides a comparison of results of the average crack width, area ratio and depth between the two different sealant products at given extension ratios and for the different exposure sites.

Average crack width - For the MS-2 product, the average crack width shows a tendency to increase in relation to the degree of extension, however, the average width is only about 0.1-mm even at 30% extension. The influence of the exposure site on the development of cracks is not evident from results of exposure of the MS-2 sealant product however, for the PU-2 product the crack width shows a tendency to increase to a comparatively significant crack size with a corresponding increase in extension. The tendency that following exposure, the crack width increases in order of the severity of exposure was evident from visual observations of products at each of the respective sites. Hence, crack width was found to increase from the least to the most severe exposure climate; i.e. Asahikawa < Choshi < Miyakojima.

Crack area ratio - Depending on the extension ratio, little or no change was observed in test specimens MS-2 and PU-2 subjected to the Asahikawa climate. However when in the extended mode (i.e. 15 or 30% extension), there was an evident tendency for the crack area ratio to increase for those specimens exposed to either the Choshi or Miyakojima climates. As well, on all the specimens there is an increase in crack area ratio for a corresponding increase in the degree of extension.

Average crack depth - For the MS-2 product the maximum crack depth observed after three years of outdoor weathering was about 0.2-mm whereas the maximum crack depth for specimens exposed to the Asahikawa climate is about 0.1-mm. There is little difference in terms of crack depth between different exposure sites however those at the least severe exposure site (Asahikawa) were not as significant as those obtained from exposure at either Choshi or Miyakojima. However, for all MS-2 specimens there is an evident tendency towards increased crack depth in relation to a corresponding increase in extension. The PU-2 product exhibits the deepest surface cracks, in particular specimens exposed to the Miyakojima climate for which about 0.9-mm deep cracks occurred at 30% extension.

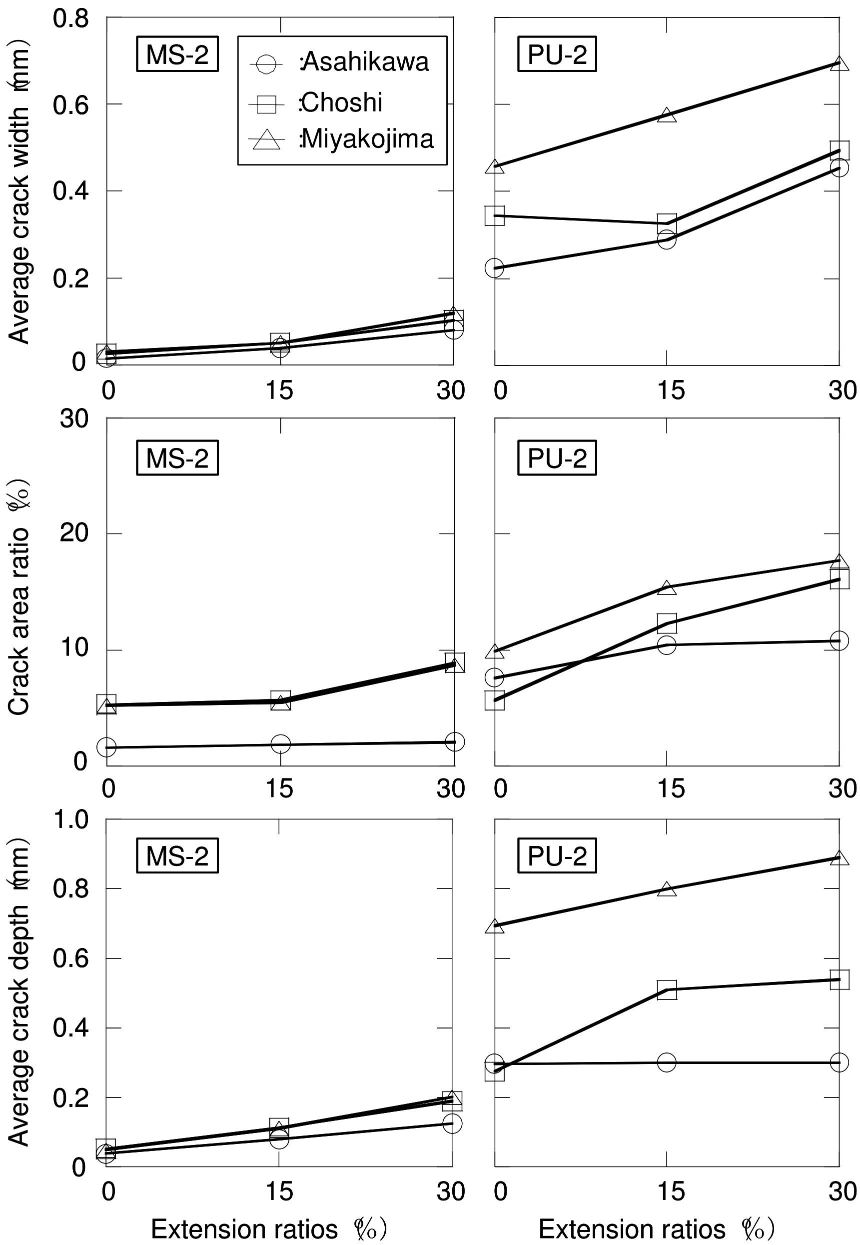


Figure 10. Results of surface condition of sealant after 3 years exposure

QUANTIFICATION OF SURFACE CRACK DAMAGE OF SEALANTS

Development of a crack deterioration index

Figure 11 shows the relation between the number of years of outdoor weathering and the average crack depth. The crack depth shows a tendency to increase with the passage of time in most measurement parts. The crack depth of damaged sealants is an important evaluation criterion because its function as waterproofing materials will gradually diminish as the crack depth of sealants grows from the surface to the back of the joint. However, a characteristic of surface crack formation of sealants is that the crack area ratio (i.e. number of cracks per unit area) increases as well as crack depth. Therefore to obtain more exact measure of the effects of deterioration, it is necessary when evaluating crack condition to consider all 3 dimensions; i.e., crack width, crack depth, and crack area ratio. From this discussion it follows that the surface of a smooth sealant material must require some measurable amount of strain energy for the formation of surface cracks and hence fracture mechanics should be considered in the development of a deterioration index.

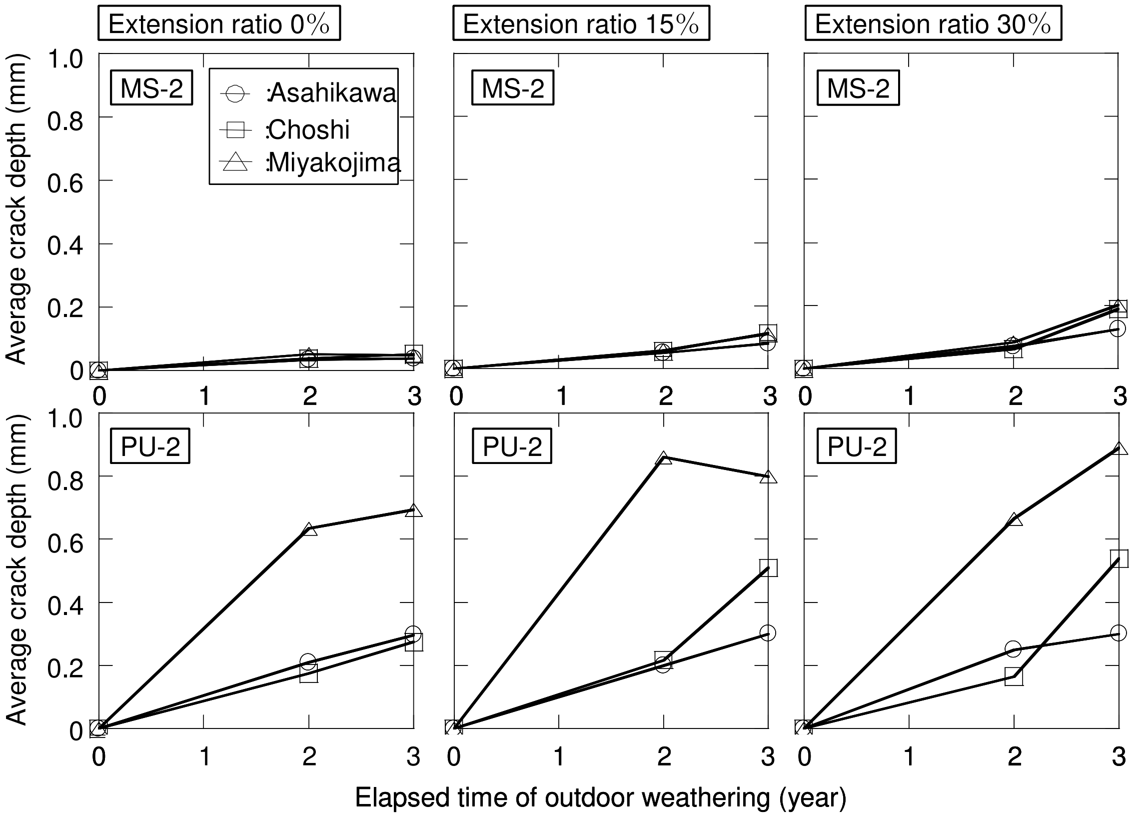


Figure 11. Relation between elapsed time and average crack depth of sealant

Evaluation of material deterioration by changes in strain energy

The deterioration of the sealants is a result of a break down occurring on its surface that ultimately will give rise to changes in strain energy [7]. When a representative unit cube of sealant undergoes a stress (σ), the elastic strain (ε) occurs in this element as shown in Figure 12. The energy brought about by strain on this cubic element is σ•ε / 2. When a crack of length (t) and depth (a) occurs, as shown in Figure 13, the stress is relieved (i.e. becomes 0) in an area defined by a semicircle of radius a. The total sum of strain energy U is obtained by considering the overall length of cracks (t) to be Σt using the following expressions (1).

$$U = \sigma \cdot \varepsilon / 2 \cdot (\pi a^2/2)\, \Sigma t \qquad \ldots (1)$$

It is extremely difficult to measure Σt (the overall crack length, t) because of the innumerable number of cracks occurring on the surface of the sealant. If, then, the area, of cracks (S) evident on the surface of the sealant is known or can be calculated, Equation (1) can be transformed into Equation (2) if one considers the crack area (S) as a product of the width b and length t.

$$U = \sigma \cdot \varepsilon / 2 \cdot (\pi a^2/2)\, S / b \qquad \ldots (2)$$
$$S = b \cdot \Sigma t$$

Where:
S : crack area (mm^2) ; a : average crack depth (mm); b : average crack width (mm) ;

The strain energy (σ•ε/2) is a characteristic value of the sealant whereas $(\pi a^2/2) \cdot S/b$ corresponds to the volume of the material where energy is released upon formation of a crack. The volume may be represented by a semicircular pattern as shown in Figure 13. Therefore, if this volume is defined as V_e, expression (2) can be rewritten as:

$$U = (\sigma \cdot \varepsilon / 2) \cdot V_e \qquad \ldots (3)$$

Where:
σ•ε / 2 : Strain energy (N/mm^2); V_e : Volume of material within stress-release zone (mm^3)

Using this expression, and based on the relationship between the volume of stress-release material and the formation of cracks, it becomes possible to determine the degree of damage to a product based on quantifying the formation of surface cracks in terms of average crack width (b), crack area (S) and crack depth (a). Additionally, V_e may change to a significant degree with crack depth progression given that it is related to the square of the crack depth.

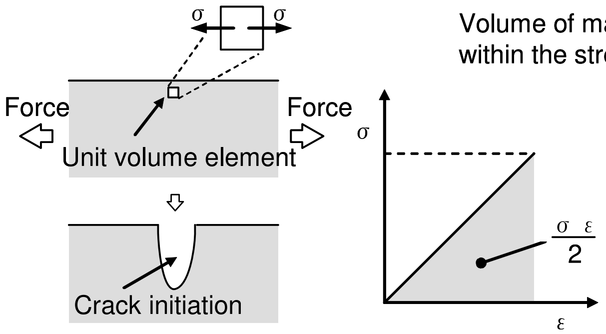


Figure 12. Strain energy of unit volume element

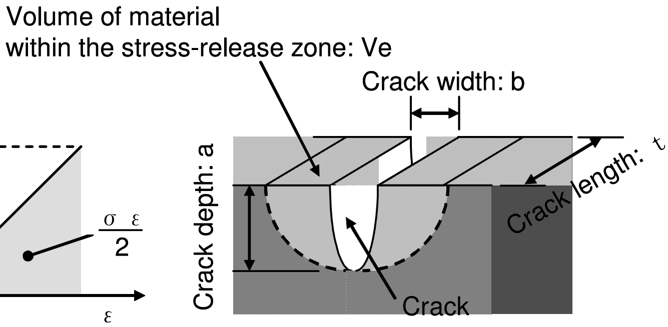


Figure 13. Schematic showing the volume of sealant within the stress-release zone

Progression of cracks quantified by V_e

Figure 14 shows the relation between the degree of extension (%) and V_e for each specimen examined and for the different sites at which they were exposed outdoors.

Values of V_e for PU-2 specimens exposed to conditions in Asahikawa do not relate to the extension ratio as compared to the MS-2 product as these values are almost the same for extended conditions; additionally, a lower value of V_e was obtained at an extension ratio of 30%. At 30% extension ratio, although the crack width is significantly larger than at 15% extension, the surface deterioration has not greatly advanced the crack depth.

It is observed that the tendency for V_e to increase in relation to increases in extension ratio is most significant for sealants exposed in Choshi and Miyakojima. This is most apparent for the PU-2 product exposed to the environment of Miyakojima where solar effects are most pronounced as shown by the singular increase in values of V_e as compared to any other exposure combination. After 3 years exposure the sealants shows the formation of cracks limited to a shallow portion on their surface. However plotting the progress of crack development over time could be obtained in a longer-term study. Measuring the state of change in crack formation in relation to crack width (b), depth (a), and area (S) would permit comparisons and possible correlations between long-term outdoor weathering and exposure to ultraviolet radiation in the laboratory.

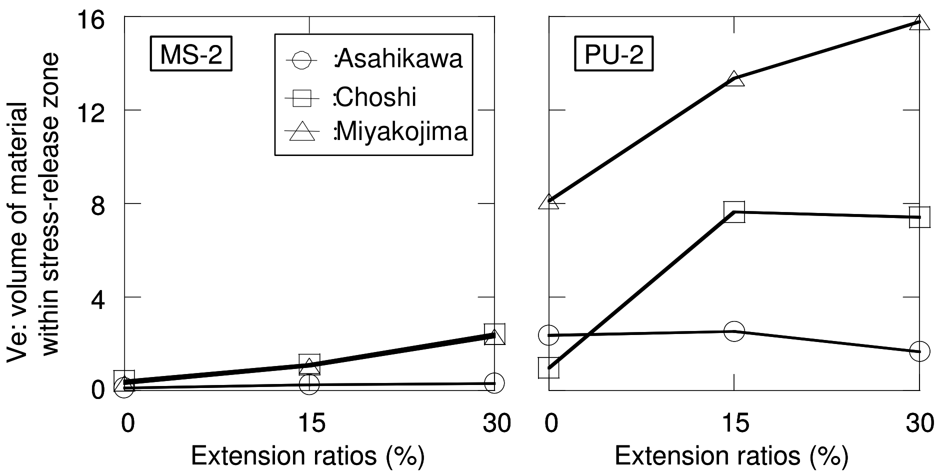


Figure 14. Result of calculation of the volume (Ve) within the stress-release zone (Exposure period, 3-years)

The evaluation of the degree of deterioration of the sealant by defining deterioration state becomes possible by comparison of initial to subsequent stages of deterioration based on the degree of change in strain energy or change to V_e. Moreover, it becomes possible to distinguish between the influence of physical effects on deterioration of the sealant affecting the value of V_e, such as expansion and contraction, and those due to chemical effects such as those induced by ultraviolet rays.

CONCLUSIONS

The following conclusions were obtained on the formation of surface cracks on different sealant materials when exposed outdoors at different locations in Japan.

(1) The volume of material within the stress-release zone (V_e), based on the crack width (b), area (S), and depth (a), was calculated for cracks occurring on the surface of different sealant materials, and the overall degree of surface damage on the respective sealants was quantified on the basis of the strain energy.

(2) The extent of damage of the sealant material through the formation of surface cracks was compared by calculating the volume of stress-released material (V_e). As a result, V_e increased in relation to the degree of extension to which the sealant was subjected and to the severity of the exposure conditions at the different sites at which products were placed; hence it was observed that there was a tendency for an increase in V_e for products exposed to increasingly severe climatic conditions in the order of: Asahikawa, Choshi, and Miyakojima.

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