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Advances in Test Methods to Assess the Long-Term Performance of Sealants

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ABSTRACT: In this review, a number of aspects related to sealant testing and evaluation will be addressed. Those factors that are most important in determining the useful life of sealants, as well as the choice of the most appropriate test methods to assess their performance are discussed. Some of the topics that are treated include, for example, studies undertaken to determine the amount and rate at which building joints move and their significance in relation to the effect of movement rate on the mechanical properties of sealants; the relevance of the failure envelope in evaluating the performance of sealants; the effect of daily cycling on the extended sealant; the use of strain-cycling movement when predicting sealant performance; the significance of light and moisture on the overall degradation of the sealant; the importance of movement in the deterioration of sealants joints. The nature of future research regarding the long-term performance of sealants is identified.

KEYWORDS: sealant, sealant evaluation, sealant performance, joint movement, mechanical properties of sealants, test methods sealant test apparatus, degradation of sealants

The outside envelope of a building undergoes cyclic movements as it responds to changing temperature and moisture conditions, the movement being accommodated at the joints. To prevent the passage of water, air, or dust, the joints are sealed with elastomeric based compounds called sealants. These materials are applied as liquids against a back-up material and harden through chemical or physical means to form rubber-like compounds capable of withstanding repeated cycles of extension and compression. In general, the sealant is extended at low temperature and expand with increasing temperature.

The demands on sealants are severe in climates such as those that exist in Canada because of the large temperature fluctuations on the outside of buildings. To determine the performance of sealants, test methods are required that provide an indication of their performance. To date, there is no standard laboratory test applicable to sealants that is derived directly from behavior on outdoor exposure. The existing CGSB and ASTM tests subject a sealant to various mechanical, temperature and immersion cycles that are not based on exterior exposure of sealants or observations of building joints. Furthermore, the existing tests call for curing of sealants and this, no matter how carefully chosen, does not reproduce the curing in a building joint. Even if the extent of movement is small, it is significant because previous investigations demonstrated that it is the most important factor influencing performance for silicone [1], polysulfide [2], and polyurethane sealants [3]. More recently, it has been further demonstrated that cyclic

movement during sealant cure has a significant affect on the mechanical properties of these products [4].

Other reviews have focused on establishing the state-of-the art of assessing the long-term durability of sealants [5,6]. Beech has provided an extended examination of the many different methods used to assess the movement capability of building sealants [5]. From this review it was apparent that the degree of cure of sealant specimen prior to assessing their performance was considered of particular importance since it is known that the degree of cure at any given time is also a measure of the extent to which the network structure has developed. Consequently similar sealants must be cured to the same extent in order that meaningful comparisons can be made. This suggests that a particular cure regime be established such that all sealants that cure under similar mechanisms can be evaluated on a equal basis. The other alternative is that sealants be evaluated as they cure, that is, they should undergo cycles of movements as soon as that are cast, as is known to occur in building joints. Beech [5] suggests that testing of slow curing sealants (that is, moisture cured sealants) be done on samples which have sufficiently cured. The periods of cure for such sealants would be 3 to 12 months or until stable properties have been achieved.

Another recommendation that was put forward was the necessity for attempting to collect and assess data related to determining the aging behavior of sealants. This was undertaken by Wolf [6] in a comprehensive study of factors causing degradation in building joint sealants. From this review, it was possible, by comparing the results acquired using different test methods, to demonstrate the inherent deficiencies of the accelerated aging methods currently in use, and to provide some guidance as to the type of studies which could be useful in establishing the long-term durability of sealants. In this regard, Wolf clearly states that cyclic movement is the preponderant factor in the aging of joint sealants. Suggestions for future work relate to the incorporation of cyclic movement to aging factors, as well as arriving at an appreciation of the effect of various sources of ultraviolet radiation on the degradation of sealants.

The focus of this brief review is to draw attention to the work undertaken over more than two decades at the laboratories of the Institute for Research in Construction (formerly the Division of Building Research) in the area of sealant life prediction. Particular emphasis will be given to the more recent contributions that relate to correlating the performance of sealants subjected to laboratory fatigue testing with those subjected to testing on a strain cycling exposure rack. Hence, this paper is to review some of the previous work in relation to the current research related to establishing suitable tests to determine the long-term performance of sealants, to briefly describe some of the more recent advances, and finally, to outline areas for future research.

Performance Testing of Sealants

Joint Movement and Sealant Characterization

Ashton has outlined some of the more important factors that should be taken into consideration when developing predictive tests for assessing the durability of building materials [7]. These are provided below with appropriate explanations:

- i) knowledge of the fundamental processes causing degradation;
- ii) the nature of the test conditions in relation to service conditions;
- iii) the transferability of tests developed for a particular material to another material;

A knowledge of the degradative processes that occur in materials is particularly important. A reliable accelerated test can only be developed based on an understanding that causes

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deterioration in a given material. Furthermore, acceleration of degradative factors must relate to service conditions to obtain meaningful results. Hence, a reliable means of accelerated testing is achieved by continuity of exposure to the appropriate factors at their maximum levels rather than by the use of excessive levels. This implies that the conditions to which a material is exposed in practice should be measured to provide a valid basis for the test. The more the test conditions depart from the natural levels, the more restricted the applicability of the test will be. Finally, tests developed for one material should not be applied to another without first establishing that the properties of the second are related to the basis for the test.

These principles are particularly important because they form the basis for establishing a useful performance test and this same process was adopted by Karpati in the development of a performance test to assess the durability of sealants.

In the case of joint sealants, it was recognized from the outset of the research program that the tests that come closest to performance testing of sealants are those that subject the sealant to cyclic movement and simultaneous temperature change [8]. It was, however, considered a complex test because in order to be successfully completed, it required a knowledge of the fundamental properties of the materials being tested as well as an understanding of the rates and amplitude of movement and the associated temperature range in which the materials are required to perform in the field. Hence initially, two avenues of research were simultaneously pursued to provide the required information: basic information related to the mechanical properties of the polymer based materials used in sealants was obtained by subjecting model sealant beads to tensile tests at various temperatures and strain rates and studies were undertaken to assess the nature of joint movement that occurs on the outside of a building.

The studies related to joint movement showed that joint between adjacent building elements correlated reasonably well with changes in surface temperature of the cladding material [9]. Furthermore, it was shown that the movements imposed on a sealant consist of daily cycles superimposed on yearly cycles. For example, in the case of a joint that moves $\pm 25\%$ of its width in a year, the daily movement would be, on the average, $\pm 4\%$ of joint width.

Another important observation obtained from these initial studies was that the rates of movement in the joints were comparatively small in relation to the rates at which sealants are commonly tested. This particular information was useful in adjusting the rate at which tensile tests were conducted such that meaningful properties could be obtained.

Failure envelopes are often used to characterize the nature of failure in polymeric based materials and are plotted as log strain against log stress. This was also done for the results obtained from tensile tests, however, it became evident that in the case of sealants, it is more relevant to plot results as log strain against log time when evaluating the performance of sealants because what is important is the extendibility of the sealant at a given time period. Furthermore it was determined, after having conducted a series of cyclic tests [10], that the results of these tests could also be plotted in the same manner as that used for tensile tests, thereby establishing a link between cyclic and tensile testing. It also provided a useful means of being able to interpret data from specimens placed on exposure racks and exposed to different levels of strain. What appeared complex in the initial research stages now became the basis for assessing the performance of sealants. What follows is a review of the methods utilized to assess the performance of sealants with cyclic movement as the main factor causing degradation.

Review of Methods Using Cyclic Movement

The use of cyclic devices to subject sealants to the type of movements that occur on the outside of the building envelope have been achieved in numerous ways and for the purposes of this review, have been categorized into three distinct classes: natural weathering exposure

rigs, manually adjusted vises and fully automated mechanical devices. Most natural exposure rigs were developed by the different research organizations as a tool to enable a more pertinent study of sealant durability whereas considerable monies have been expended by sealant manufacturers on the development of, in certain cases, very elaborate testing devices. An exhaustive review of the results from tests using the former test methods has already been reported [6] and will not be repeated here, although some of the more salient aspects of the results obtained from the use of the strain cycling exposure rack (SCR) at the IRC will be outlined. With respect to the test methods relating to mechanical devices, mention is made of the review provided by Cook [11] on such type of automated devices. Unfortunately, but understandably, very little information has been published on the results of fatigue tests on sealants from the use of automated devices. A brief outline of the few results that are available is provided in this section.

Natural Weathering Exposure Rigs—Brown [12] reports that the initial description of cyclic movement testers used in his study on joint sealants was provided in the papers of Ballantyne [13] and Ballantyne and Brown [14]. In these devices, the difference in thermal coefficients of expansion of timber and aluminum was used to impart the cyclic movement to a sealant specimen in shear. A diagram of the apparatus is shown in Fig. 1. The chief use of these durability tests was to provide some indication of the relative performance of the various types of sealants being evaluated. The devices were used to evaluate sealant specimens over a two-

FIG. 1—CSIRO cyclic movement tester [12].

year exposure period in Hightett, Australia. The type of failure as well as the time of failure are reported for the various classes of sealants being tested, which included: oil-based glazing compounds, butyl-based mastics and a number of elastomeric-based sealants.

This same device was used by researchers at the BRANZ [15,16] (Building Research Association of New Zealand) to evaluate the durability of a range of different types of sealants including single component silicones, latex and solvent based acrylic products as well as single and multiple component polyurethane and polysulfide-based products. Results from sealants subjected to natural exposure conditions (Judgeford, Wellington, N.Z.) for an initial period of 24 months [15] and thereafter a report after six years of natural weathering [16] indicated that the device was useful in determining the relative durability of the various types of sealants, producing the types of failures that occur in practice. It was further noted that exposure of the sealants without cyclic movement was not sufficient to reliably evaluate sealant durability.

Burstrom reports on the use of a natural weathering exposure rig which uses the differences in coefficients of thermal expansion of a relatively massive ($25 \times 900 \times 6000$ mm) concrete element and a pair of aluminum tubes running along the length of the element [17]. In this study, polysulfide, polyurethane, acrylic, as well as an oleo-resinous product, were evaluated on the basis of changes in mechanical properties in tension after various periods of exposure. It is not readily apparent from a review of this article the extent to which specimens were exposed, hence an evaluation of the usefulness of the natural weathering rig is not possible.

The Princes Risborough Laboratory (PRL), Building Research Establishment, UK, has devised a natural exposure movement simulation rig which uses black PVC driving bars to respond to temperature change and give rise to movement at a joint. The simulated sealant-filled joints exposed to weather on these rigs show daily and seasonal movement similar to those on buildings [18]. Reports on the usefulness of this device have yet to be published.

At the IRC, a weathering rack for sealants (Fig. 2) was developed to provide a test facility that could simultaneously subject sealant specimens to cyclic movement and temperature change, similar to that known to occur in various types of joints in buildings [19]. The

FIG. 2—Strain-cycling exposure rack [19].

movement is produced by using the differential movement between steel and aluminum. The rack can accommodate 216 specimens with imposed movements ranging from $\pm 9\%$ to $\pm 30\%$ joint width in three-quarters of the rack and the remaining 54 specimens move $\pm 19\%$. With this arrangement, movement above which a sealant starts to fail can be determined for a series of specimens exposed to various amounts of yearly movement. Those specimens that undergo identical movement can be subjected to repeated tests at given time intervals.

Results of tests on one-part chemically cured silicone sealants using this device indicate that strain-cycling movement is the predominant factor which causes failure during weathering of these sealants; outdoor weathering alone is negligible [1]. Failure is also influenced by the extent of movement, becoming more extensive at higher yearly strain cycles. Tensile tests reveal a notable decrease in strength beyond about $\pm 22\%$ movement.

In a similar study, a two-part polysulfide sealant formed cavities on the side sheltered from direct sunshine [2]. The same material, when weathered without cycling or stored in the laboratory, did not undergo permanent deformation. This underlines the importance of the effect of cyclic movement on the performance of two-part polysulfide sealants, revealing it as the most important factor in test methods intended to evaluate their performance.

The SCR was also used to assess the performance of low movement capability sealants that included various latex and solvent-borne acrylic sealant products and a chlorosulphonated polyethylene sealant [20]. In this study, the use of the rack provided a quick assessment of the movement capability of the sealant because failures started to occur after only a few months of exposure.

A procedure was also developed for the rapid evaluation of silicone sealants in which unsatisfactory products could be identified within a two-month period [21].

Finally, the rack was used to assess the performance of various types of polyurethane based sealants [3]. One single and three multi-component polyurethanes and one epoxy-polyurethane sealant were evaluated. Again, the results for these tests indicate, as was shown in other studies, that joint movement is the predominant factor in the failure of these products.

Mechanical Devices—A manually operated device (Fig. 3) was designed to enable individual sealant specimens to be subjected to cyclical movement [22]. Hence this inexpensive device,

FIG. 3—Cyclic movement device [22].

essentially developed as a means to imitate that which occurs on a strain cycling rack (SCR), can subject sealant specimens to extension and compression while exposed outdoors or to various artificially produced conditions [23]. Whereas in the case of the SCR, joint movement is continuous and automatic, this device must be adjusted manually to provide the necessary changes in joint width.

A number of studies were completed using this device [24–26] and in the case of the work carried out by Karpati [24,25], the results suggest that the laboratory test method, devised essentially as a fatigue test, can be correlated to those results obtained from sealant specimens exposed on a strain cycling exposure rack.

Initial work using this device was used to assess the performance of two-part polysulfide sealants which had been previously tested on the SCR [2]. In an effort to duplicate practice as closely as possible, newly cast specimens were exposed outdoors as soon as they could be handled. The vise widths were changed once a month, each change being one third of the total for the year, the total change ranging from $\pm 10\%$ to $\pm 80\%$ (Fig. 4). Based on the results of these trials, it was recognized that the polysulfide sealant underwent continuous change in appearance which, upon further examination, could be categorized into three distinct stages of permanent deformation. The first stage represents the largest joint width movement ($\pm \%$) at and below which permanent deformation is negligible; the second stage is characterized by the formation of lengthwise bulges in sealant specimens; the third stage provides an indication of the smallest movement ($\pm$ joint width change, $\%$) at and above which holes develop (Fig. 5). The observed stages of permanent deformation are shown as a function of the number of winters of exposure. Stages one and two of specimens exposed on the SCR from the previous study [2], are represented by a sinusoidal line marked SCR1 and SCR2 at the approximate time in which they occurred. The stages of observable deformation develop in these sealant specimens at lower movements because these undergo diurnal movements on the SCR that is

YME: YEARLY MAXIMUM EXTENSION

YMC: YEARLY MAXIMUM COMPRESSION

FIG. 4—Time schedule of joint width changes [24].

FIG. 5—Stages of permanent deformation [24].

in the order of one-fifth the yearly movement and hence, the same degree of cumulative damage occurs for a given time, at lower annual movements.

Based on these initial studies, it was concluded that it was possible to produce with hand-operated vises the same permanent deformation of sealant specimens that occurs on the SCR. Another observation was that any elastomeric based sealant could be evaluated using this technique provided the processes of permanent deformation were similar to those observed to occur in the two-part polysulfide sealant.

It was apparent that on the basis of previous weathering tests, the most important factor leading to permanent deformation and eventual failure of the joint was cyclic movement. Hence, it was useful to know whether failure produced by cycling during natural weathering would also result solely from cycling in the laboratory [25].

Sealant specimens of the same two-part polysulfide sealant as in the previous studies [2,24] were mounted after accelerated curing (4 d at 30°C), on vises and extended and compressed to different amplitudes (from ± 10 to $\pm 80\%$) and at three cycling rates (1, 2.5 and 7.5 cycles/week). Results from these tests presented in Fig. 6, indicated that all three stages of permanent deformation, previously observed on specimens mounted on vises and exposed outdoors on a SCR, were produced using this laboratory test method. Furthermore, the results of any of the stages, including stage three (i.e. sealant perforation) could be plotted in such a manner as to provide an indication of the long-term performance of the sealant. For example, the best-fit lines of stage three of the laboratory fatigue tests give movements of $\pm 19\%$ when extrapolated

FIG. 6—The three stages occurring at 7 1/2 cycles per week [25].

to 20 years (Fig. 7). It is to be noted that the results obtained from these fatigue tests are consistent with those obtained from sealants subjected to outdoor exposure and cyclical movement, the movement being achieved either through the use of vises or the SCR (Fig. 8).

It remains to be determined, however, if the degree of cure of specimens used in this experiment would necessarily change the extent to which results can be correlated with that of work carried out in the outdoor exposure tests.

Lacasse [26] used hand-operated vises similar to that devised by Karpati with the exception that up to six specimens could simultaneously be subjected to joint movements. Thirty-six testing devices, of the type shown in Fig. 9, were used to subject two commercially available polyurethane based sealants, cured for two months in the laboratory, to a cyclic test program comparable to that undertaken by Karpati in the laboratory fatigue test of a two-part polysulfide sealant [25]. The sealants in this study were subjected to 7.5 cycles per week in amplitudes of ± 25 to $\pm 80\%$ of the joint width in steps of 5%. Triplicate specimens were used at each amplitude. Figure 10 depicts results of sealant specimens at the various stages of deformation, described earlier. The progressive deterioration of the sealant bead is clearly noticeable for specimens A2 subjected to $\pm 70\%$ width change after 2, 3, 4 and 4.5 cycles respectively. A more gradual degeneration is observed at smaller strain amplitudes as shown in the subsequent sequence of photographs depicting type A3 sealants undergoing movements of ± 40 , 50 and 60% respectively. Based on the results of this test and using the same technique to predict performance as that used by Karpati [25], a twenty-year life expectancy (to stage 3) is achieved for the A3 sealant if the strain program does not exceed the $\pm 15\%$ joint width range. It must be stated that these results have not been correlated to long-term outdoor exposure tests, as was the case in the aforementioned studies by Karpati. This would necessarily be required in order to validate the prediction of durability resulting from the interpolation of data acquired from the fatigue test.

Another aspect that has practical implications is the possibility of increasing the test rate without unduly affecting the nature of the results. This is particularly relevant in the development

FIG. 7—Stage three results from 7 1/2 cycles per week [25].

of an automated fatigue testing device capable of subjecting sealants to much higher rates of cyclic deformation than can be achieved using manually adjusted vises. It is evident that there exists a potential to reduce the amount of time required to assess the performance of sealants in using such a device.

Many mechanized testing rigs have been devised over the years and, as mentioned earlier, Cook [11] has described a number of different types of devices built by testing agencies, manufacturers of testing equipment or again, sealant producers. More recently, the BRE has developed an apparatus for testing the movement capability of building sealants. It is capable of evaluating up to 40 specimens (BSI standard with a $50 \times 12 \times 12$ mm bead) in compression or extension by 50%. An environmental chamber houses the test rig and can be maintained at temperatures ranging from -20 and $+70^\circ\text{C}$. The entire testing mechanism is computer controlled and the test temperature is adjusted according to the direction of travel, whereby the chamber is cooled when the specimens are being extended and heated when specimens are being compressed. Results on the use of this device have yet to be published.

In fact, few results are available on the cyclic fatigue of building sealants. Matsumoto [28] does however, report on the use of a cyclic test device complete with environmental chamber (-10 to 100°C) capable of subjecting up to 22 sealant specimens to a cyclic program of 300 cycles per minute. The report suggests that sealants can readily be classified on the basis of their fatigue resistance, evaluated on the basis of the resilient energy (toughness) of the sealant before and after being subjected to cyclic movement. Although this method is reportedly capable of ranking the sealants in terms of their cyclic durability, it does not provide an indication as to how long sealant materials might expect to remain functional in practice. No further work using this device has been reported.

FIG. 8—Tensile and laboratory fatigue test results [25].

FIG. 9—Cyclic movement device capable of accommodating up to six sealant specimens [26].

FIG. 10—Composite photograph showing various stages of deformation for three types of polyurethane based sealants [26].

Lacasse [26] produced a similar device as that developed at the BRE in that up to 36 sealant specimens could be subjected to simultaneous cyclic movement in an environmental chamber. The testing frame and hydraulic press were part of an existing test platform otherwise used for testing concrete cylinders, but in this case fitted with a sealant test rig, as shown in Fig. 11. The press was connected to a hydraulic power unit as well as the necessary control apparatus and central processing unit (CPU), such that a given extension-compression program could be set up directly from the CPU. This testing system was used to assess the cyclic

FIG. 11—Thirty-six specimen sealant test rig [26].

performance of various polyurethane-based elastomer formulations and subjected replicates of six specimens for each polyurethane type to a series of five strain amplitudes ranging from ± 25 to $\pm 60\%$ of the joint width. The device was useful in being able to rank the performance of the various sealants in terms of their resistance to cyclic fatigue. A similar device is currently being developed at the IRC for eventual use in the study of the fatigue resistance and long-term performance of various polymeric based sealant materials.

Areas for Future Research

A review of previous developments made to determine suitable performance related tests for sealants suggests that future research should be centered in two distinct areas:

- i) durability of sealants to cyclic movement;
- ii) development of analytical methods to evaluate the durability of sealants.

Durability of Sealants to Cyclic Movement

Work undertaken by Karpati has shown that cyclic tests undertaken in the lab can be used to produce deformations in sealants consistent with those obtained from an exposure rack and hence comparable to that known to occur in sealants used in building joints. The results

obtained from these tests suggest that provided the type of cycle is properly chosen, cyclic tests can be used to predict the durability of a given type of sealant. Of interest then are the consequences of varying the type of cycle on the deterioration of the sealant bead. Initial results have shown that the rate of cycling can be significantly increased without changing the nature of the results. It would be useful to know the extent to which the rate could be increased before the sealant no longer deteriorates under the same influences as that which causes sealants to degrade in joints. It might also be of interest to determine if further improvements in the test method can be achieved if testing is undertaken under simultaneous temperature control. Finally, tests using the SCR should continue such that the degree to which cyclic movement contributes to the degradation of a sealant in relation to other factors known to cause distress can be estimated for the various types of sealants.

Use of Analytical Techniques

Artificial aging, using various types of weather-o-meter devices, is often used as a method to accelerate the degradative effects brought about by UV radiation, heat and moisture. A sealant has an intrinsic durability to a given degradative action whether it be cyclic movement or the other aforementioned factors. The action of individual effects can be isolated by the proper choice of apparatus and aging conditions and these can be investigated using analytical techniques such as differential scanning calorimetry, dynamic mechanical analysis, thermogravimetric analysis and Fourier transform infra-red analysis. These techniques have been successfully employed in numerous studies related to the degradation of polymeric based materials and more recently have been employed to investigate the aging process in roofing materials [28]. Their use in the study of aging of sealants is less well documented. Wolf [6] cites a study by Maurer and Brazier (see Ref. 6) using thermomechanical analysis which indicated that this method can be used to characterize the mechanical properties of sealant samples before and after aging. Such type of analytical techniques can be used as a basis for investigating the synergistic effects of various combinations of aging factors.

Summary

A considerable body of knowledge exists related to assessing the long-term durability of sealants. Initial studies focused on determining whether a specific mechanical parameter could readily be used to predict sealant performance. Although advances were made in this area, the usefulness of this approach was considered limited in consideration of the complexity of the test and attention was then placed on observing the physicomachanical degradation of sealants subjected to natural weathering on an exposure rack. Such type of racks had been used by researchers in the past; however, few efforts were made to establish a link between laboratory testing and cyclic testing, although it was known that such testing was most representative of that which occurs on the outside of buildings. The first investigations established a fundamental aspect related to sealant testing in that it was apparent that the most significant factor in the degradation of sealants was cyclic movement. This provided a means by which cyclic movement was obtained using manually adjusted vises. Results of these trials formed the basis of laboratory fatigue tests that indicated that the results of these types of tests, undertaken in the laboratory under controlled conditions and in a relatively short period of time, could be correlated to those observed to occur on the exposure rack and by extension, simulate that which occurs in a joint on the outside of a building. This was achieved for silicone, polysulfide and polyurethane based sealants of the types currently used to seal joints. Recent advances in assessing the performance of sealants have centered on using these and related cycling techniques in an effort to refine and further improve the test procedure. Future

research should endeavor to continue studies related to cyclic movement capability and should also consider the investigation of aspects related to the use of analytical techniques to further enhance the understanding of the interrelationship between factors causing degradation in sealants.

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