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Development and Verification of a Method to Determine the Long Term Load Carrying Performance of a Double Sided Pressure Sensitive Adhesive Tape

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DEVELOPMENT AND VERIFICATION OF A METHOD TO DETERMINE THE LONG TERM LOAD CARRYING PERFORMANCE OF A DOUBLE SIDED PRESSURE SENSITIVE ADHESIVE TAPE

by

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Acrylic foam pressure sensitive adhesive (PSA) tapes are used in various applications as an alternative of mechanical fasteners, especially in areas like structural bonding which requires demanding bond strength and durability.

This research focuses on comparing design values of acrylic foam PSA using static shear test method and dynamic shear test method in accordance of J0MP0164 standard specification. Static shear test has lots of disadvantages; but on the other hand it is the test that mimics the real life usage of a tape in a real life application. Dynamic shear test is a faster way of testing and gives a full insight of the PSA tape deformation behavior.

The relationship between static load and failure time at various loads obtains a mathematical model to predict long-term load carrying performance of a PSA. That model is compared to dynamic shear mathematical models to check differences in obtained design values.

The peak stress and time at peak stress on a stress-strain diagram at various shear rate tests were used to manipulate a mathematical model to compare it to the static shear model and see how the two models correlate.

Two other dynamic shear models were investigated. The first model presents the relationship between peak stress and actual rupture time, and the second model is relationship between peak stress and theoretical rupture time. These two models did not show a noticeable differences in estimated design values. On the

other hand, the design values obtained from these models were 10-15% higher than static shear design values.

It was found that the estimated design values using a dynamic shear method is only 3% higher than the estimated design values from static shear method. Not only that, the differences in design values are consistent when predicted for 1 year to 25 years.

The results support using dynamic shear test method as an industrial technique to predict long-term carrying performance of PSA tape as an alternative method to static shear test.

ACKNOWLEDGMENTS

I would like to begin sharing the thanks and blessings to all the mothers in my life that because of them, I would have never reached to where I am now. To the mother of all mothers, my home, the holy land of Palestine. To all the mothers who have lost and still losing their beloved lives in wars and tragedies.

To my mother, every time I felt down or depressed I find happiness and peace in your voice, I know I was in your prayers every single day since I left, and I surely know I would have never been a successful man without my faith in God and your faith in me.

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I extend my gratitude to the best family a man can ever ask for. To my father, my hero, the man who always supported me and believed in me, the man who raised me to believe that I can reach the moon and beyond. To my brothers, my best friends and buddies. The same way I want to be successful and happy in my life, I want the exact same thing for you and even more.

To my grandparents, I love and miss you dearly, you are the sunshine of my life, may God give you more and more years of joyful and happiness. To my friends, to everyone I have met and had a positive addition to my life, thank you. Thank you for making me feel welcomed and warm.

I'd like to thank my supervisor, Dr. Andrew Kline for his time and effort to help me go over this stack of papers, I appreciate everything you have done to make this happen. I'd also thank my committee members, Dr. James Springstead and Dr. Said Abubakr who have the credit for starting my Master's here at WMU.

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Rahal Rasheed

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CHAPTER 1

INTRODUCTION

1.1 Background

Pressure sensitive adhesives (PSA) historically have been used for temporary bonding of substrates. However, with recent developments in technology, PSAs are finding applications in long-term bonding of substrates with moderate load carrying capacity. PSAs are comprised of polymeric materials which are viscoelastic in nature. Consequently, PSAs exhibit both elastic as well as viscous behavior. Therefore these materials creep when subjected to stress. The extent of creep is a function of loading, time, and temperature. Creep ultimately leads to a failure in the bond and of the parts that are held together by the adhesive. One of the frequently asked questions –especially from building supplies customers- is how long can a double sided pressure sensitive tape hold a load before it fails? Different methods are used to determine holding time of a tape before failure. Both static shear and dynamic shear tests are used to predict long term performance of a tape. In a static shear test, one end of the pressure sensitive adhesive tape is bonded to a surface, and the other end is subjected to a constant load vertically where the load is freely hanging and the time to failure is recorded. While in a dynamic test, the bonded parts are pulled at a constant speed and the peak stress for failure is recorded, it is an indirect but faster method of testing. Accordingly, customers are interested in design values for the adhesive systems. Design value is a system used to predict the failure time of the bonded area stressed at a specified load. It is practical to use static shear test when the bond fails within a reasonable time period. However, long term e.g., one year or more, takes at least a year to make the measurement. Therefore, it is customary to predict medium and long term behavior by extrapolating the short term results. Dynamic shear is a rapid alternative technique to make long term predictions in very short term experiments. In the currently used method the dynamic shear results can be correlated to the static shear for some adhesive systems. However, it fails to uniformly predict short and medium-term performance for some other adhesives. The design values predicted using static shear and dynamic shear differ. The objective of this work is to make improvements in the current predictive system; so that short term dynamic shear test can be used as an industrial standard testing.

1.2 Objectives

The objective of this work is to make improvements in the current predictive system; so that short term dynamic shear test can be used as an industrial standard testing. If static shear and dynamic shear methods can both approach to predict a comparative design value, then static shear method can be replaced with a faster and more accurate testing method.

Another goal this study is looking to achieve is to determine the best geometry of a PSA to withstand stress for a longer period of time before its end use. Geometries to be studied are machine direction (MD) and cross direction (CD). MD is the direction of the materials parallel to its forward movement on a machine, e.g. extruder, whereas CD is the direction at right angle (90° degree) to the machine direction. Figure 1.1 shows the product used for this research with a scheme of MD and CD.

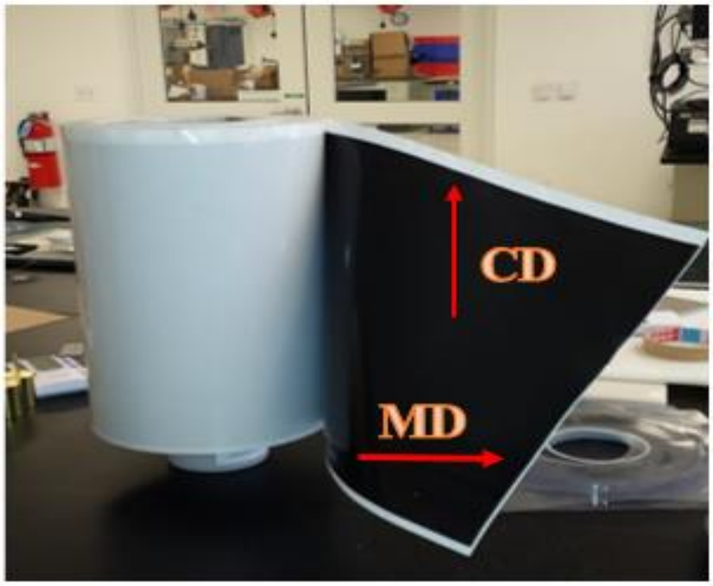

Figure 1.1: Machine Direction and Cross Direction on a Roll of PSA Tape

1.3 Applications

The results presented in this thesis provide knowledge of shear strength of acrylic foam tape. These results can be directly applied as design values for applications such as structural bonding and signage mounting. Furthermore, this study can prove how reliable the currently used long term predictive systems are.

1.4 Limitations of Study

Although the study's objective is developing a prediction method for PSA tape long term performance, all the testing is done under lab standard conditions and on standard substrates. This does not reflect real life applications unless further testing under aging conditions are implemented and taken into consideration. Also a factor of safety should be considered to extend the expected load capacity the PSA tape can handle for long terms.

Moreover, this research conducted testing on shear direction (y-direction) of a PSA tape, so design values are only applicable for similar applications. Using a PSA in tensile direction (z-direction) requires more investigation.

CHAPTER 2

LITERATURE AND BACKGROUND

2.1 Introduction

Pressure sensitive adhesive (PSA) is adhesive that requires pressure to form a bond between the adhesive and the substrate.

PSA's are used to join two solid parts together either permanently or temporarily. Tapes are the most common product of PSAs, these products can be used in varies applications like mounting, packaging, repairing, surface protection, etc.

Dr. Horace Day, a surgeon, was the first who developed a pressure sensitive tape in 1845 by devising a method of applying a natural rubber adhesive to strips of cloth, thus producing a kind of surgical tape which he used in his practice [1]. For a few decades, PSA applications were limited to medical uses. PSA tapes are now everywhere and used in different industries like automotive, building supplies, electronics, appliances and more. The demand on PSAs is increasing every year. The pressure sensitive adhesives market is projected to grow at a rate of 5.8% from 2013 reaching an annual volume of about 3,460 kilotons by 2018 [1].

PSA tape is a combination of two components: backing and the adhesive. Backing is the material carrying the adhesive, it can be any flexible material that is being used for its characteristics depending on the application it is used for. Backing can be paper, polypropylene, cloth, acrylics, and more. Adhesive can be coated on one side (single sided) or both sides (double sided) of the backing. Moreover, double sided PSA tapes can have a release liner that is used to protect the adhesive from containments to its point of use. Figure 2.1 illustrates a scheme of a double sided PSA tape structure with an acrylic core backing. The relative importance of the backing and adhesive can vary greatly according to the application the PSA tape used for. Properties such as peel, shear strength, and tack are used to determine the performance of PSA tape depending on the application it is used for. The balance of these properties governs its time-dependent responsibilities and bonding strength [2].

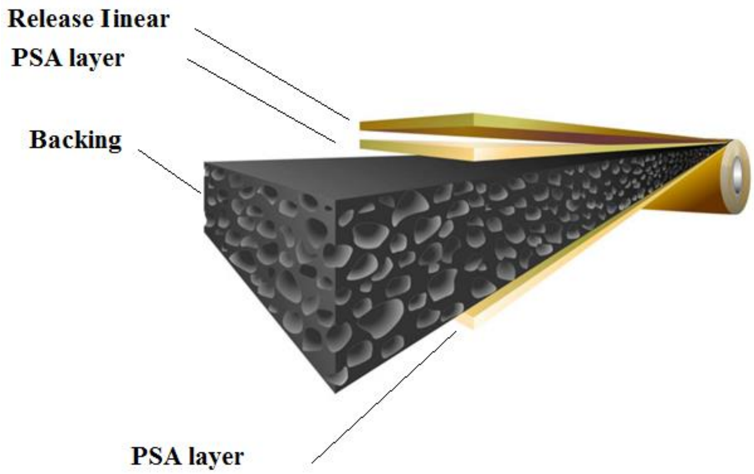

Figure 2.1: A Scheme of Double Sided PSA Structure [3]

This research will focus on the mounting applications for a PSA. PSAs are comprised of polymeric materials which are viscoelastic in nature. Moreover, PSAs exhibit both elastic as well as viscous behavior. When a PSA tape is subjected to stress or load, the tape will creep and ultimately leads to a failure in the bond and of the parts that are held together by the adhesive. The creep response can be expressed as load versus time or as modulus versus time. Modulus is the ratio of stress to strain. Adhesive bond failures are most commonly divided into adhesive and cohesive failures. Adhesive failure is the separation of adhesive bonds from the bonded surface, while cohesive failure is the breakage of the internal bonds of the adhesive. Shear resistance will be the investigated property for mounting applications**.** Shear is the ability of an adhesive to resist creep or slippage under load or force.

2.2 Methods Used

There are different methods to determine the long-term performance of PSA's, these methods can be classified under two criteria:

1) Method analyzing characteristics of PSA, which can ultimately lead to a prediction of the shear resistance behavior.
2) Application testing of a PSA.

2.2.1 Methods Analyzing Characteristics of PSA

Rheology, using small amplitude oscillations, may be used to test adhesives throughout the whole viscoelastic profile. A rheometer can be used to apply small amplitudes (frequencies) on a circular PSA sample, which causes the shear stress to be proportional to the shear strain, a necessary condition for linear viscoelasticity [4].

Another method was developed by Williams Plasticity. The concept is determining the rheology of a PSA via dynamic mechanical analysis to predict all aspects of adhesive performance including adhesion and cohesion [5, 6]. Utilizing a temperature sweep of both G' (elastic modulus) and G" (viscous modulus), predictions of adhesion can be made via the viscoelastic window technique, and cohesion can be predicted by tracking G' as a function of temperature [7, 8].

2.2.2 Application Testing of a PSA

This section will focus only on static shear and dynamic shear test methods. In a static shear test, one end of the pressure sensitive adhesive tape is bonded to a surface, and the other end is subjected to a constant load vertically where the load is freely hanging and the time to failure is recorded. In a dynamic test, the bonded parts are pulled at a constant speed and the peak stress for failure is recorded. A dynamic test is an indirect but faster method of testing. Figure 2.2 illustrates schemes of static shear test setup. Two test plates are bonded using a double sided tape applied to the end of the plates and a constant load is freely hanged to the other end of the plate and the time to failure is recorded.

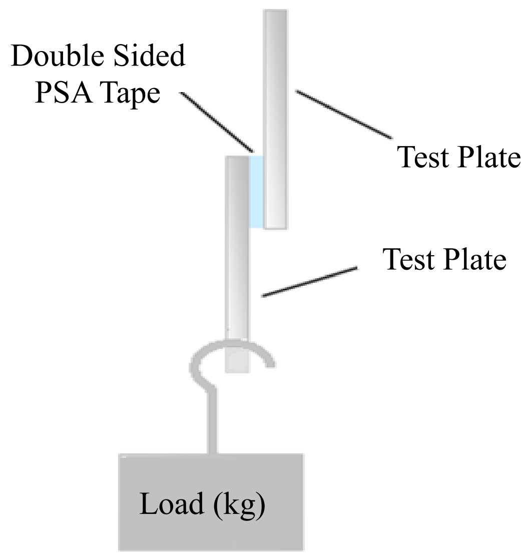

Figure 2.2: Static Shear Test Setup Scheme

Figure 2.3 illustrates a dynamic shear test setup. A double sided tape is used to bond two test plates, and the end of the plates are fixed in a tensile machine that pulls the upper test plate at a constant speed vertically. The peak force and failure time are recorded.

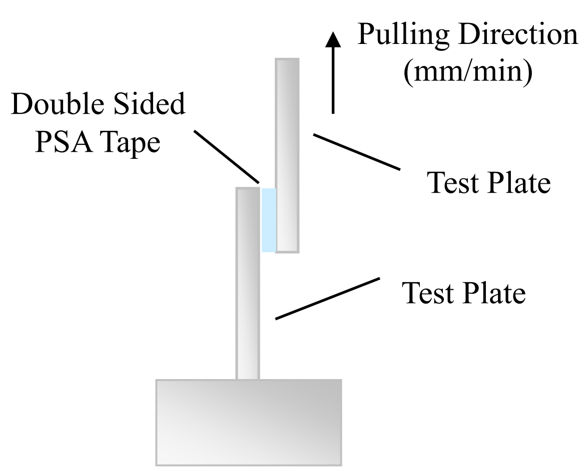

Figure 2.3: Dynamic Shear Test Setup Scheme

CHAPTER 3

PRELIMENARY WORK AND EXPERIMENTAL PLAN

3.1 Sample Preparation

The pressure sensitive adhesive used in this study is a tesa tape acrylic foam, which is an acrylic foam tape with acrylic adhesive, total thickness of 1,200 µm. Samples will be taken in two geometrical directions, machine direction and a cross direction. Machine direction is the direction along the width of the roll, and cross direction is the direction along the length of the roll or perpendicular to the machine direction.

Standard stainless steel panels “25 mm x 50 mm” will be used for both static and dynamic shear tests. Each sample will be replicated 5 times to account for variation and have consistent results. Tape samples used for this research are die cuts to eliminate dimension variation.

3.1.1 Static Shear Samples

Stainless steel panels and tape will stay in laboratory environment (23 ±1 °C, 50% ±5 relative humidity) for at least 24 hours before preparing samples. All stainless steel panels used for this test are new and used for the first time for the purpose of this project and will not be reused to prepare other samples for this project. Stainless steel panels are cleaned with a tissue saturated with acetone and wiped several times. Tape will be centered in the panel and pressured according to the internal specification procedure of tesa tape, specification number J0MP0164 (Appendix A). Each 1 cm^2 requires 100 N for 1 minute, so samples will be pressured at 260 N for 1 minute. Pressurization will be done using Baltec assembly press. Samples will be let to dwell at room temperature for 72 hours before hanging weights. Figure 3.1 shows attached loads to static shear samples.

When load is hanged on the samples, the timer turns on. One end of the pressure sensitive adhesive tape is bonded to the stainless steel surface, and the other end is subjected to a constant load vertically where the load is freely hanging. Eventually the PSA tape fails, and the timer goes off. Loads used are 1.02, 1.52, 2.02, 2.52, 3.02, 3.52 and 4.02 kg. Selected loads are random and chose to cover failure time ranges from a few hours to months. Failure time versus stress are plotted on a graph. Figure 3.1 shows attached loads to static shear samples. Samples are hung on a hook connected to a timer. When the load is on, timer turns on, when the load fall, the timer turns off.

Figure 3.1: Static Shear Test Lab Setup

3.1.2 Dynamic Shear Samples

Samples were prepared using the same procedure as static shear samples. Tape dimensions used for this test are the same as static shear test to eliminate variables that affect final results. One end of the test panels will be fixed, and the other end will be pulled vertically at a constant speed and the peak stress for failure is recorded using a material testing machine that is used to determine the strength and deformation behavior of materials shear. Machines being used are Zwick / Z 2.5 and Instron 33R4464 as shown in Figure 3.2 a. and b. respectively. Speeds that will be used to perform test are 0.005, 0.05, 0.5, 5, 50 and 500 mm/min. Speeds were chosen to capture a range of failure times from a few seconds to several hours. Failure time versus stress are plotted on a graph to create a mathematical model. Figure 2.3 illustrates a scheme of dynamic shear test setup.

Depending on the correlation, the tape area needed to hang a constant load for a long term period, e.g. 25 years, will then be estimated using extrapolation.

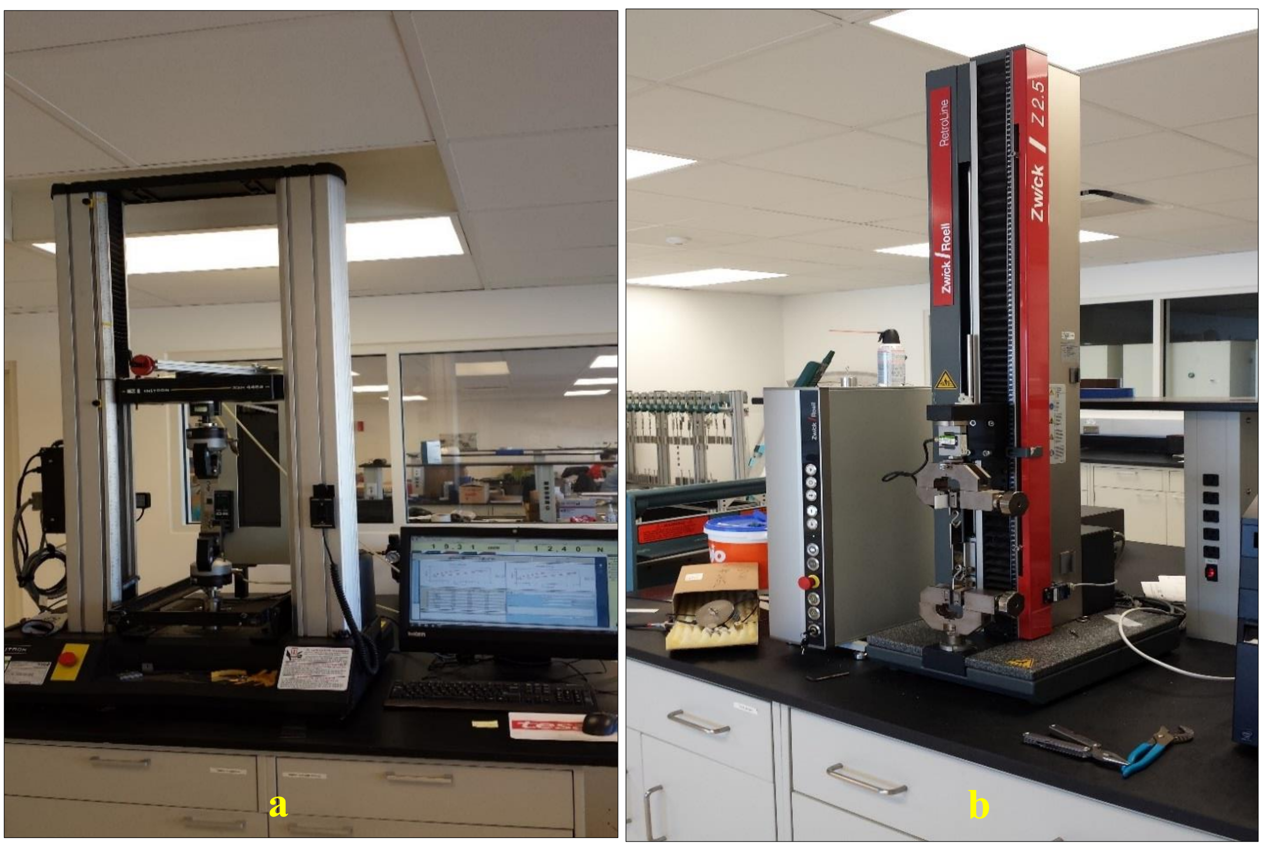

Figure 3.2: Tensile Machine Testers a) Instron 33R4464 Test Machine. b) Zwick / Z.2.5 Test Machine

3.2 Advantages and Disadvantages

As mentioned before, this research focuses on static and dynamic methods to improve prediction of long term performance of a PSA tape. This study will perform testing using these methods in order to develop a long term performance using dynamic shear method as a replacement for the static shear method if ultimately it can lead to similar design values for both methods. The approach of long-term carrying performance will be based on improving dynamic and static shear test methods, so that design values obtained from both tests are equivalent. This will make the dynamic shear method a powerful industrial technique to predict long-term carrying performance of PSA tape.

Static shear test is more realistic to real life applications and is easy to setup. But on the other hand, there are several drawbacks to static shear. Even under precise sample cutting and sample preparing, the results are often highly variable because sample may involve random fracture mechanisms which may cause the results to be highly deviated. Moreover, the duration of shear testing can lead to issues regarding product development and production quality control [8].

Dynamic shear test is a faster way to dominate PSA tape cohesive characterization, it also lead to more precise results in short time, and it also gives more information about the rheology profile of the tested material. But dynamic shear hasn’t been used as a method to determine long term failure time. Table 3.1 shows advantages and disadvantages of both methods.

Table 3.1: Advantages and Disadvantages of Static and Dynamic Shear Methods

	Advantages	Disadvantages
Static Shear	• More realistic to real life applications • Can be done under different conditions	• Significant variation in results • Not practical testing for long term periods
Dynamic Shear	• Faster method of testing • More accurate results	• Less realistic to real life applications • Needs further clarification

3.3 Comparing Models

Plotted graphs represent the relationship between stress and versus failure time. Logically both graphs should lead to the same design values. In other words, both graphs should give the same correlation, but according to previous experimentations by Lars Conneberg, the graphs had poor correlation [9]. Although both methods were compared with shearing PSA tape in the same direction and same conditions, they found no correlation between the two methods.

The ultimate goal of this project is to find a reliable relationship between dynamic shear and static shear methods in order to improve prediction of a PSA performance.

Industry would then be able to use results from the dynamic shear test model to correlate or represent long term tape performance. This could be used as additional information to support marketing efforts to potential customers.

Cross machine direction static shear samples were noticed to have significantly higher failure time than the machine direction geometry. This research focuses on both static and dynamic shear test methods, but since the static shear samples are taking so long, and some sample are still hanging over 6 months, it was decided to terminate the cross direction part from this thesis.

3.4 Failure Modes

Adhesive bond failures are most commonly divided into adhesive and cohesive failures. Adhesive failure is the separation of adhesive bonds from the bonded surface, while cohesive failure is the breakage of the internal bonds of the adhesive [10]. A scheme of failure modes is shown in Figure 3.3.

If a PSA specimen fails adhesively, it will be excluded from calculations and considered not valid; because an adhesive failure does not measure a true shear resistance property.

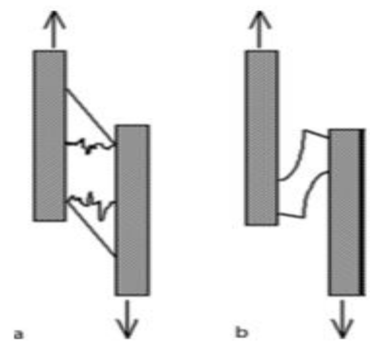

Figure 3.3: Schematic Illustration of Characteristic Failure Modes in Creep Experiments, a) Cohesive Failure. b) Adhesive Failure [10]

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

Static shear test is more realistic test to real life usage of a PSA; but the method itself is time consuming and results usually are unreliable because of inconsistent failure times. Therefore, it is preferred to use dynamic shear test method to predict long term performance of a PSA.

4.1.1 Static Shear Method

Static shear tests under low stress, 1.02 kg (38.49 kPa) take an average failure time of 107 days, this is just an example of how long a static shear test takes with low shear stress. Figure 4.1 shows a summary of static shear test results. The graph shows the relationship between log failure time in seconds and the constant shear stress in kPa. The shear stress is the total weight added to the PSA sample (hanged load + shear plate weight) over the PSA area. Each set of stress is a combination of 5 replicates to show how consistent the results are. The red diamond points represent the average log failure time (s) and the constant shear stress (kPa). The average points show a trend line to a power regression function with $R^2 = 0.987$ which indicates the model is a good fit.

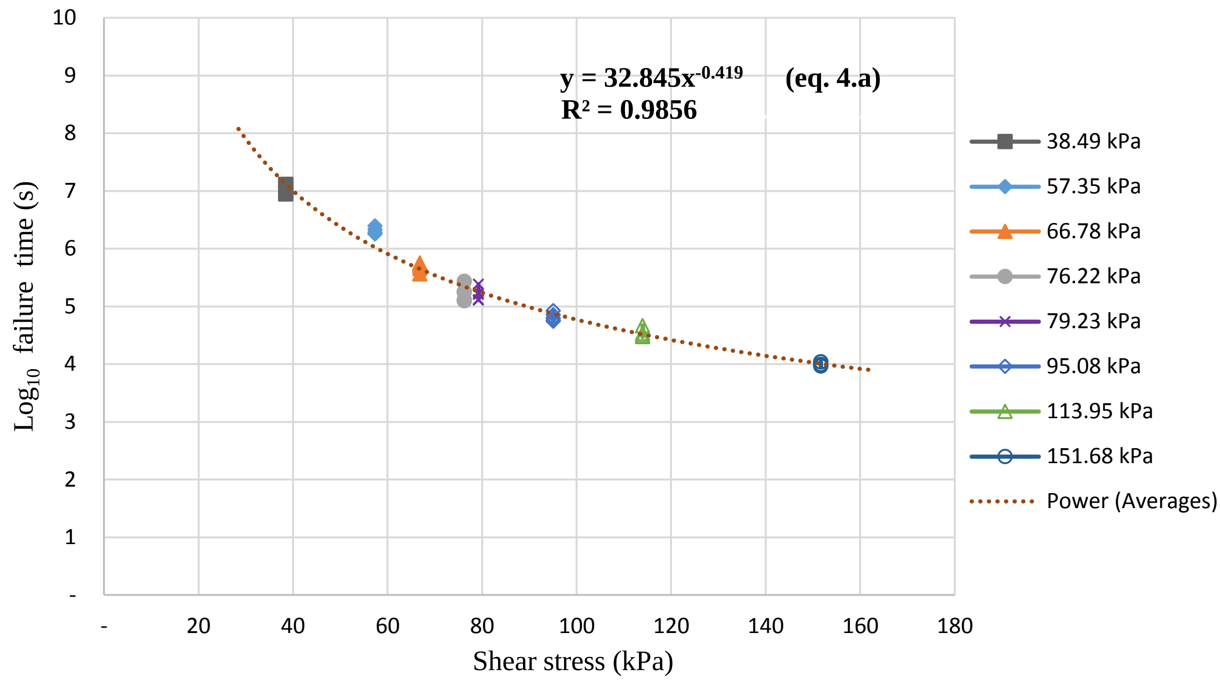

Figure 4.1: Static Shear Test Results of Various Constant Stresses

To see static shear experimental data in detail, check Table B.2 in Appendix B.

4.1.2 Dynamic Shear Method

Dynamic shear test has the advantage of less test time and more accurate results. The testing is done using a tensile machine which provides several mechanical properties of the PSA, deformation phases from initial shearing to rupture, stress-strain diagram of the PSA, failure time and time at peak stress. A typical stress-strain diagram of a PSA is illustrated in Figure 4.2. The test is done at a constant test speed. The PSA sample continuously resists shear stress and the maximum shear stress is recorded. Point "a" on Figure 4.2 shows the peak stress of a specimen. The sample continuously deforms until rupture, and the rupture point indicates the maximum strain a PSA sample can reach. Rupture point "b" is shown on Figure 4.2.

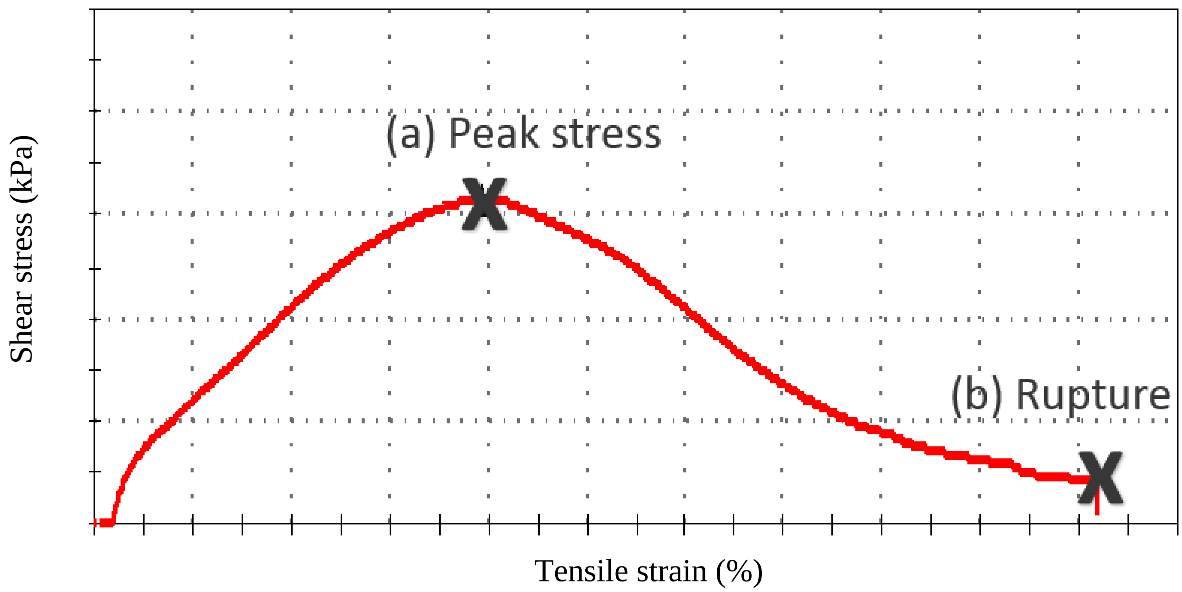

Figure 4.2: Typical Stress-Strain Diagram of a Viscoelastic Material

The lowest shear speed tested is 0.0008 mm/min. The theoretical rupture point is when the sample travels the whole PSA sample length (20 mm). Failure time $= \frac{Distance}{Speed} = \frac{20\ mm}{0.0008\ mm/min} = 25{,}000\ \text{min} \approx 17\ \text{days}$. See Figure B.3 to review stress-strain diagram of tesa acrylic foam PSA at test speed of 0.0008 mm/min. The purpose of doing a dynamic shear at a slow shear speed is to check if the curve follows the trend of the data. For future work, slow shear speeds will not be used in dynamic shear test because it is a waste of time and energy.

Dynamic shear tests were implemented using Instron model no. 33R4464. The testing capability of Instron under slow shear speeds is limited, and therefore some samples were tested using Zwick / Z 2.5 which has the capability to run slow speeds.

Stress-strain diagram of various test speeds is shown in Figure 4.3. This diagram shows the behavior of a PSA at increased stress. The peak stress is the maximum stress the specimen can withstand before it breaks, after peak stress point the specimen have very minute strength to face further stress. Afterwards stress drops and sample keeps deforming until rupture. Time is recorded at peak stress point and rupture point. More experimental data at various test speeds are shown in Table B.1 in Appendix B.

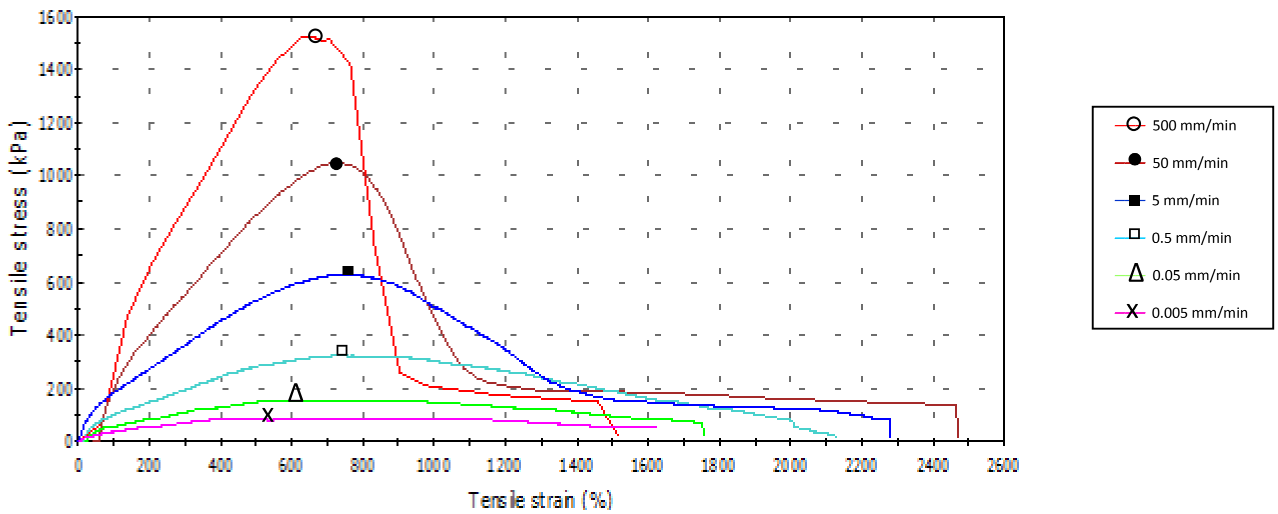

Figure 4.3: Stress-Strain Diagram of Acrylic Foam PSA in MD at Various Shear Speeds Using Instron Model No. 33R4464

From stress-strain diagram at various test speeds, two mathematical models can be obtained to compare to the static shear model. The models are as follows:

4.1.2.1 Dynamic Shear Model Using Peak Stress and Rupture Time

This model assumes that the failure of the specimen is when the PSA samples breaks. This assumption can also be classified as theoretical failure time and actual failure time. Theoretical failure time is the time when the overlap length is fully traveled, which can be calculated using the simple speed equation, $\text{time (s)} = \frac{\text{distance (mm)}}{\text{speed (mm/min)}}$. Whereas the actual failure time is the time when sample breaks, which can involve some elongation.

The difference between theoretical and actual models is the time needed for the specimen to rupture. Theoretical model theoretically ends when the overlap length is traveled, where as in actual test, PSA specimen elongates until rupture.

Figure 4.4 a. and b. represent the average peak stress versus average log actual rupture time and average peak stress versus average log theoretical rupture time respectively. The average set points show a trend line to a power regression function with R^2 = 0.79 and 0.80 for actual model and theoretical model respectively, which indicates the model is an acceptable fit.

The model have similar scatter of points with minor difference in the mathematical equations. The models will be compared to the static shear model to measure differences in design values. To review all experimental data see Figure B.1 and Figure B.2 in Appendix B.

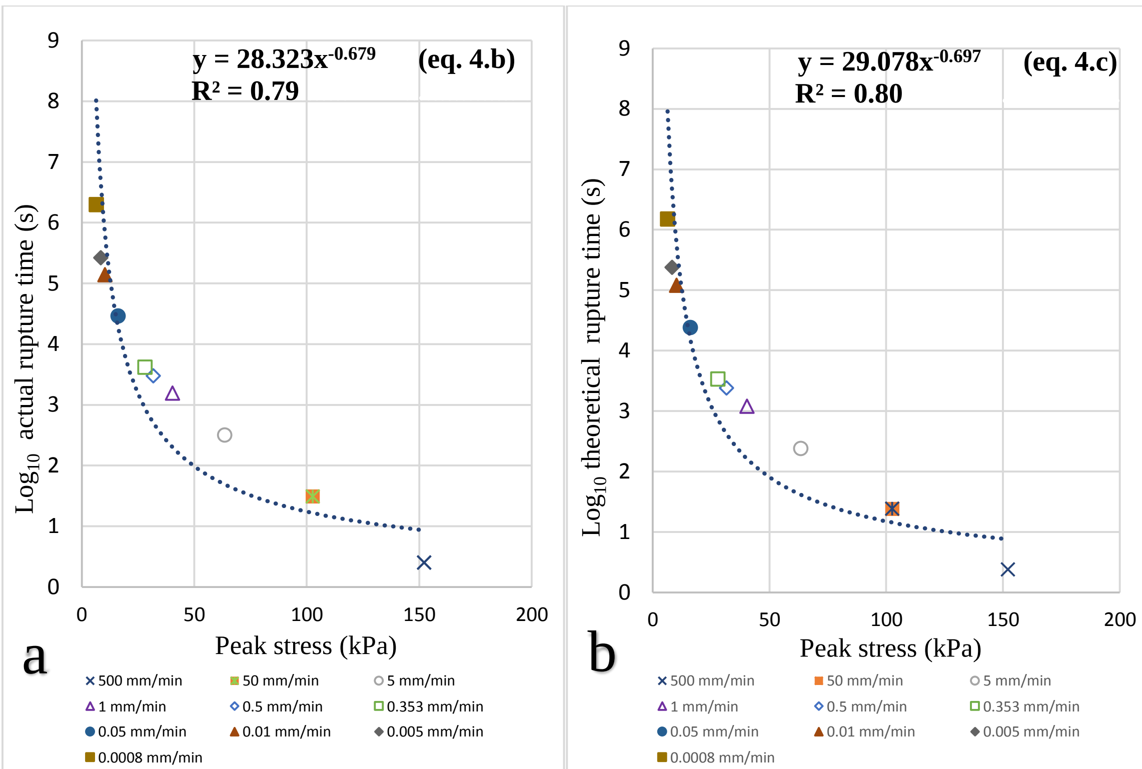

Figure 4.4: Dynamic Shear Models at Rupture Point. a) Actual Rupture Point b) Theoretical Rupture Point

4.1.2.2 Dynamic Shear Model Using Peak Stress and Time at Peak Stress

This model considers the failure of the specimen in an earlier stage before rupture. This assumption is safer to build design values on since the failure time here is the time the maximum force a PSA is reached. It was noticed that the distance range where the peak stress is reached is 6.5 to 10.5 mm. Keep in mind the length of the specimen is 20 mm, so the peak stress is reached at 32.5 to 52.5% of the original specimen length. As a result, the failure time is expected to be 32.5 to 52.5 % less than the theoretical rupture time.

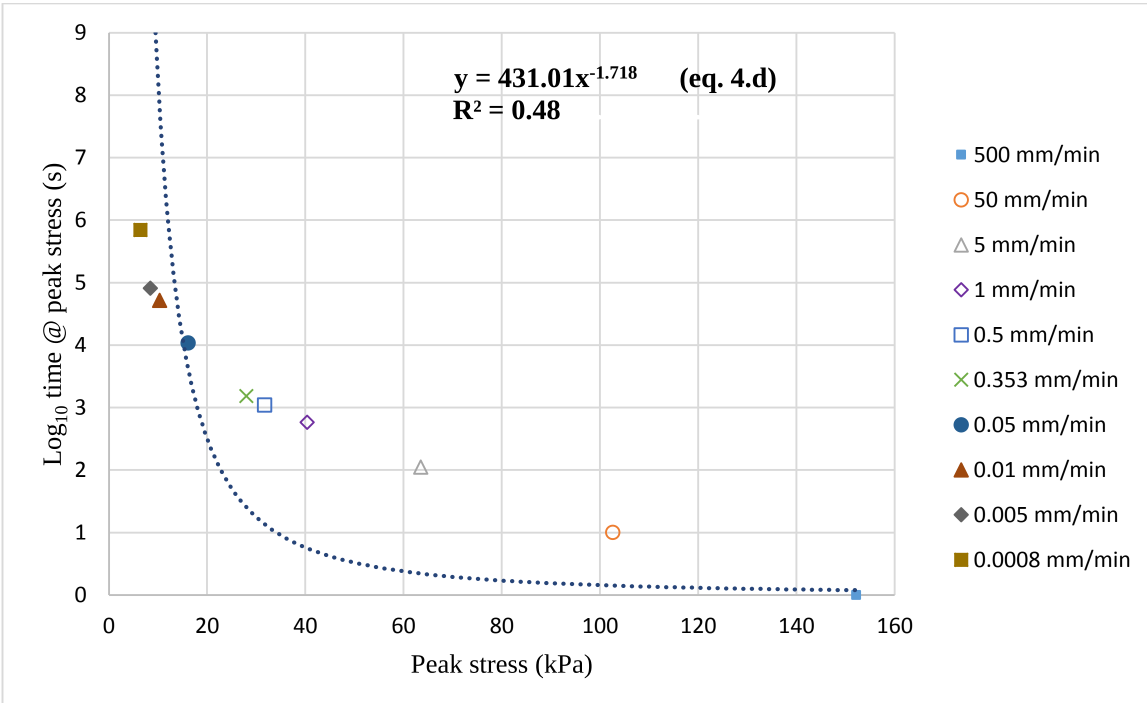

Figure 4.5: Dynamic Shear Model at Peak Stress

Figure 4.5 shows the average peak stress versus average log time at peak stress. The average set points show a trend line to a power regression function with R^2 = 0.48. The points are poorly fitting the curve and so the confidence of the model is not reliable. The full data series is shown in Table B.1 in Appendix B.

Obtaining stress values at various test speeds with a huge range of 500 to 0.0008 mm/min can lead to such results. Because PSA sample is a viscoelastic material, that is, their mechanical characteristics are temperature and time dependent. The temperature is constant for all tested samples, so the focus is on the function of time on viscosity, and the effect of viscosity on the shear stress.

At low shear rates, there is an interval called zero-shear rate viscosity. This is an interval where viscosity does not depend on shear rate. At higher shear rates, the viscosity has a linear or nonlinear function on the shear rate [11]. That fact can also be supported by Phan-Thien, “for most fluids with long chain microstructure, the viscosity is a decreasing function of the shear rate, sometimes reaching of the zero-shear rate viscosity. This type of behavior is called shear thinning.” [12].

The apparent viscosity η is the shear stress τ divided by the shear rate $\dot{\gamma}$, it has units of Pa . s = 1,000 cp.

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad \text{(eq. 4.1)}$$

Shear stress τ is maximum force recorded divided by cross sectional area.

$$\tau = \frac{F}{A} \qquad \text{(eq. 4.2)}$$

Where:

τ: is peak shear stress (kPa)

F: maximum force (kN)

A: cross sectional area (m^2)

The shear rate $\dot{\gamma}$ is the rate of a PSA specimen held between two flat parallel plates, one of which is moving relative to the other plate at a constant speed. In other words, it is the pulling speed divided by distance between plates.

$$\dot{\gamma} = \frac{\upsilon}{h} \qquad \text{(eq. 4.3)}$$

Where:

$\dot{\gamma}$: shear rate (s^{-1})

υ: pulling speed (mm/min)

h: distance between plates or thickness of the PSA specimen (mm)

To visualize the behavior of the tested PSA; shear stress is plotted versus shear rate to check the effect of shear rate on viscoelasticity. Apparent viscosity is the slope of a trend line, which is shear stress divided by shear rate. Figure 4.6 illustrates the viscosity behavior of PSA sample under various shear rates. The calculations of shear rate and viscosity can be found in Appendix C.

As noticed in Figure 4.6, there are two linear slopes detected based on the data points, short dash trend line covers the crowded points into the left-hand axis which are tests at slow shear rates. Whereas long dash dot trend line represents the high shear rates tests. The viscosity of the data at low shear rate test is 34.10 MPa.s, which is significantly higher than the viscosity of PSA samples tested at high shear rate, viscosity at high shear rate is 0.08 MPa.s. The slope gives the apparent viscosity values.

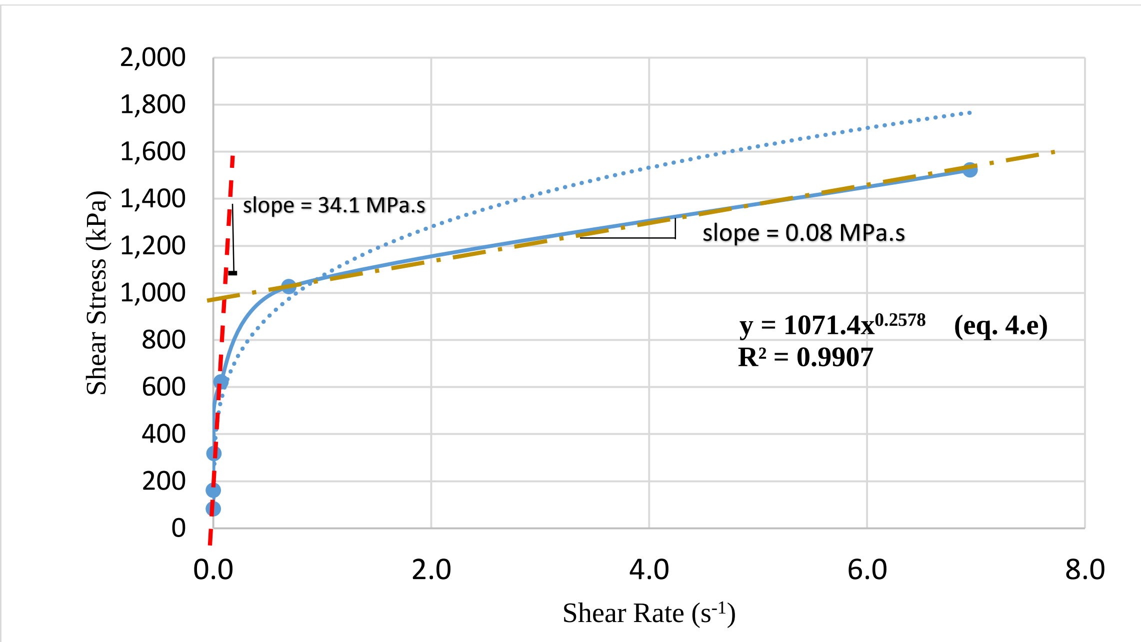

Figure 4.6: Response of a PSA with Shear Stress as a Function of Shear Rate

The relationship between shear stress and shear rate is non-linear which categorizes the PSA sample to be considered as a non-Newtonian fluid. The power-law fluid equation is a generalized equation to determine shear stress (τ) due to viscosity [13].

$$\tau = K\left(\frac{\partial u}{\partial y}\right)^n \qquad \text{(eq. 4.4)}$$

Where:

K: is the consistency index

n: is the flow behavior index

$\frac{\partial u}{\partial y}$: is shear rate

In Equation 4.4, *K* and *n* are empirical curve-fitting parameters. Based on power-law fluid equation, fluids can be classified into three types based on the n value [13].

For $n < 1$, the fluid shows pseudoplastic behavior.
$n = 1$, the fluid shows Newtonian behavior
$n > 1$, the fluid shows dilatant behavior

Using Equation 4.4 fitted to the data in Figure 4.6, the curve shows a *K* value of 1071.4 kPa.s and *n* value is less than one, $n = 0.2578$, which supports the fact that the viscosity is a decreasing function of shear rate and so it behaves as a pseudoplastic fluid.

With that being said, it is necessary to distinguish between low shear rate and high shear rate tests to obtain a reasonable design model for dynamic shear test method. High shear rates shown in Figure 4.6 are the two points lay on long dash dot trend line, which express dynamic shear rates of 1,026.2 s^{-1} and 1,522.1 s^{-1}. The stress values obtained from these two shear rates should be excluded from the design models of dynamic shear method, it makes sense to exclude these points from design model for the fact that these speeds are unrealistic to real life applications of the usage of a PSA.

Back to page 17 and 19, there are two dynamic shear models in Figure 4.4 and Figure 4.5 that included all shear rate testing. Figure 4.7 and Figure 4.8 show the dynamic shear models at rupture point and at peak stress respectively excluding the stresses at high shear rates. More tests at various shear rates were added to the models to modify curves and have a better fit. The modified models of dynamic shear at actual rupture time and theoretical rupture time are shown in Figure 4.7 a. and b. respectively. Figure 4.8 shows modified dynamic shear model with time at peak stress.

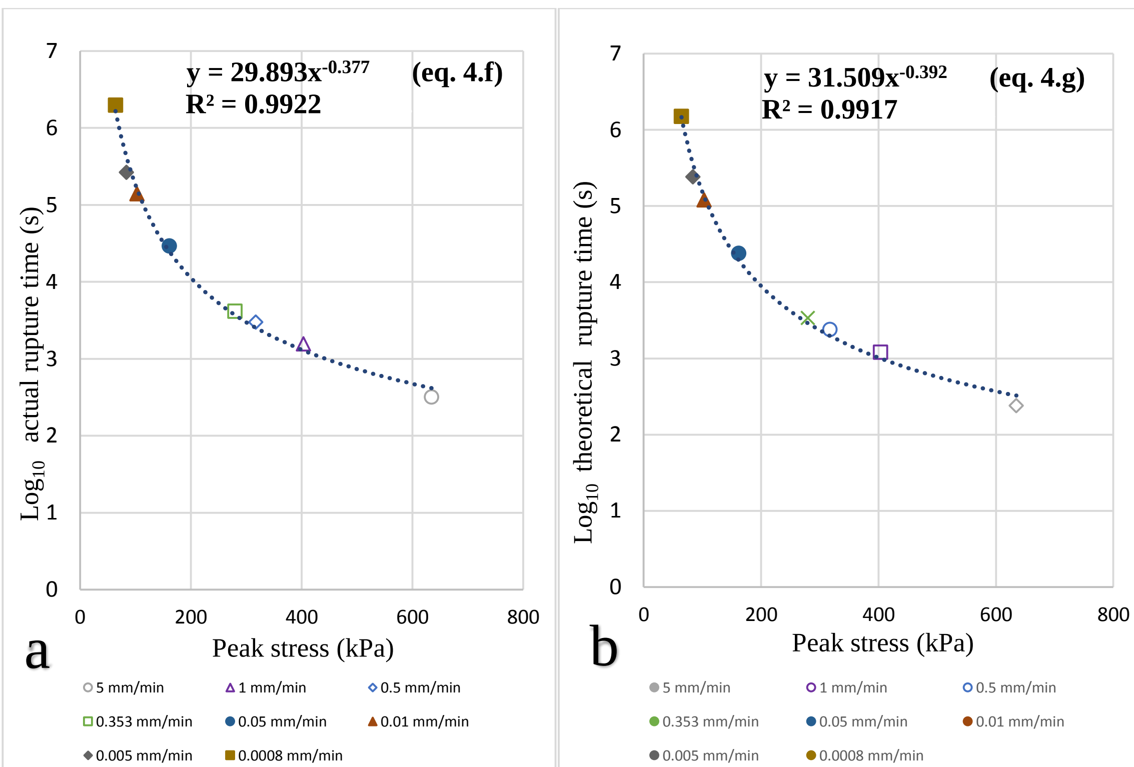

Figure 4.7: Dynamic Shear Models at Rupture Point Excluding High Shear Rate Measurements. a) Actual Rupture Point b) Theoretical Rupture Point

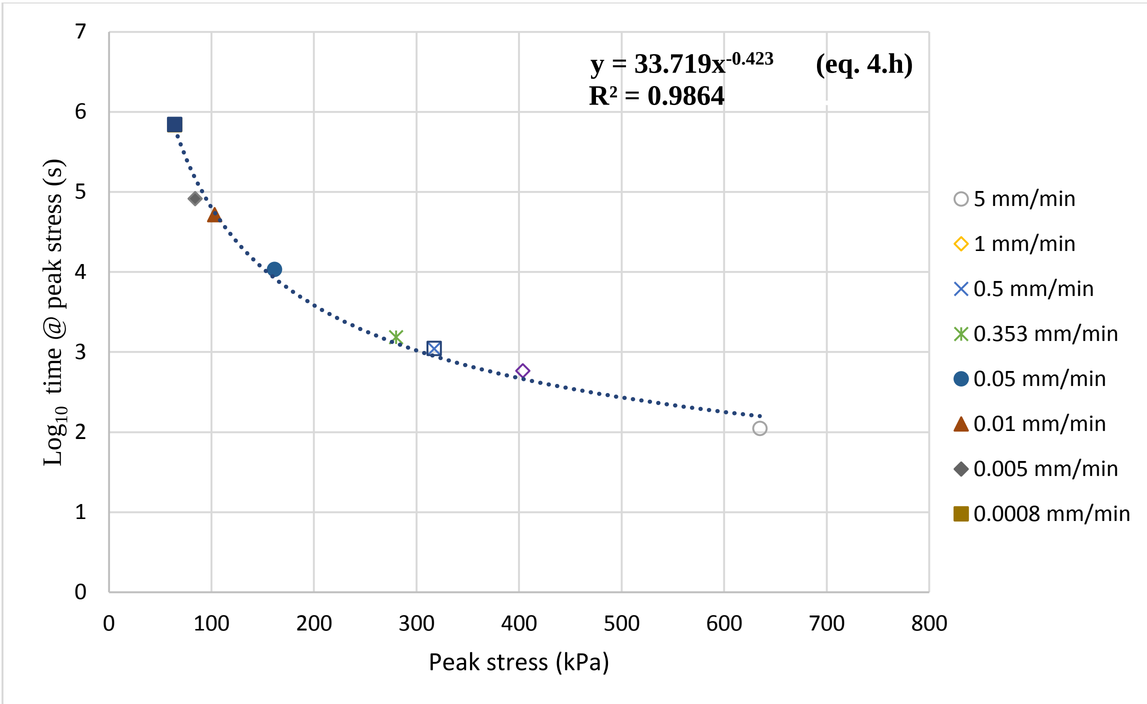

Figure 4.8: Dynamic Shear Model at Peak Stress Excluding High Shear Rate Measurements

General speaking, all curves fit better after excluding high shear rate values. The R^2 has significantly improved in Figures 4.7 and 4.8, and the mathematical models are more accurate and confident. These dynamic shear models can be compared to the static shear model to check compatibility.

4.2 Comparison

Static shear design model will be compared to the two dynamic shear models. Equations obtained from each test method will be used to estimate long term design values. Design values of each time period estimated using design models will be compared to each other.

Firstly, an individual comparison will be done between each dynamic shear model and the static shear model. Then all the models will be compared at the same chart for an overall comparison.

4.2.1 Static Shear Model versus Dynamic Shear Model - Actual Rupture Time

Figure 4.9 shows comparison of static shear model and dynamic shear model at actual rupture time. Design values are compared using Equation 4.a from Figure 4.1 for static shear model versus Equation 4.f from Figure 4.10 for the dynamic shear model at actual rupture time. Figure 4.9 shows a chart compares stress design values from year 1 to year 25. Further explanation of how to use the design values will follow in Chapter 5.

Static shear design value at year 1 is (34.0 kPa) 15% less than the design value from the dynamic shear at actual rupture time model (39.2 kPa). The difference decreases to 10% at year 25 (22.1 kPa and 24.3 kPa, respectively).

The percentage values are used to measure the difference between dynamic shear models to the static shear model during a period of time.

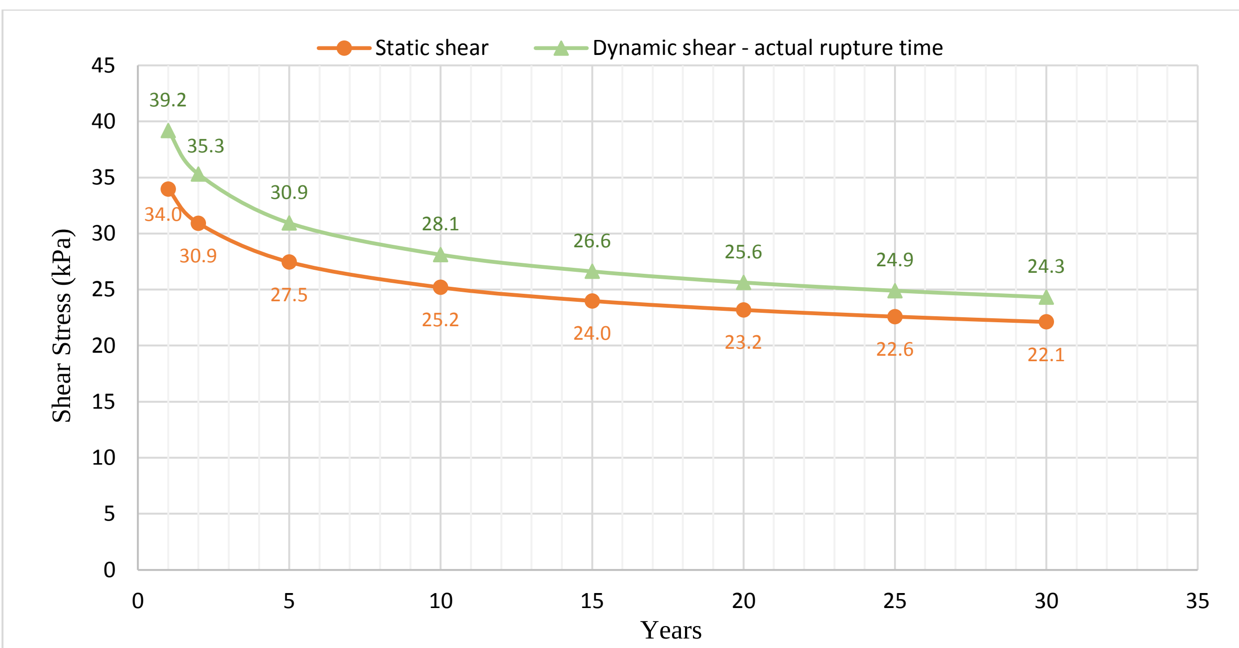

Figure 4.9: Comparing Design Values of Static Shear versus Dynamic Shear - Actual Rupture Time

4.2.2 Static Shear Model versus Dynamic Shear Model - Theoretical Rupture Time

Figure 4.10 shows comparison of static shear model and dynamic shear model at theoretical rupture time. This model can be beneficial that it is not necessary to complete the test to rupture, which can save about 50% of the actual test time.

Static shear design value at year 1 is 15% less than the design value of dynamic shear at theoretical rupture time (34.0 kPa and 38.9 kPa, respectively). The difference decreases to 11% at year 25 (22.1 kPa and 24.6 kPa, respectively). The design values obtained from dynamic shear method at actual and theoretical rupture time are very comparative due to the agreement of their percentage different values versus time, and can be used interchangeably.

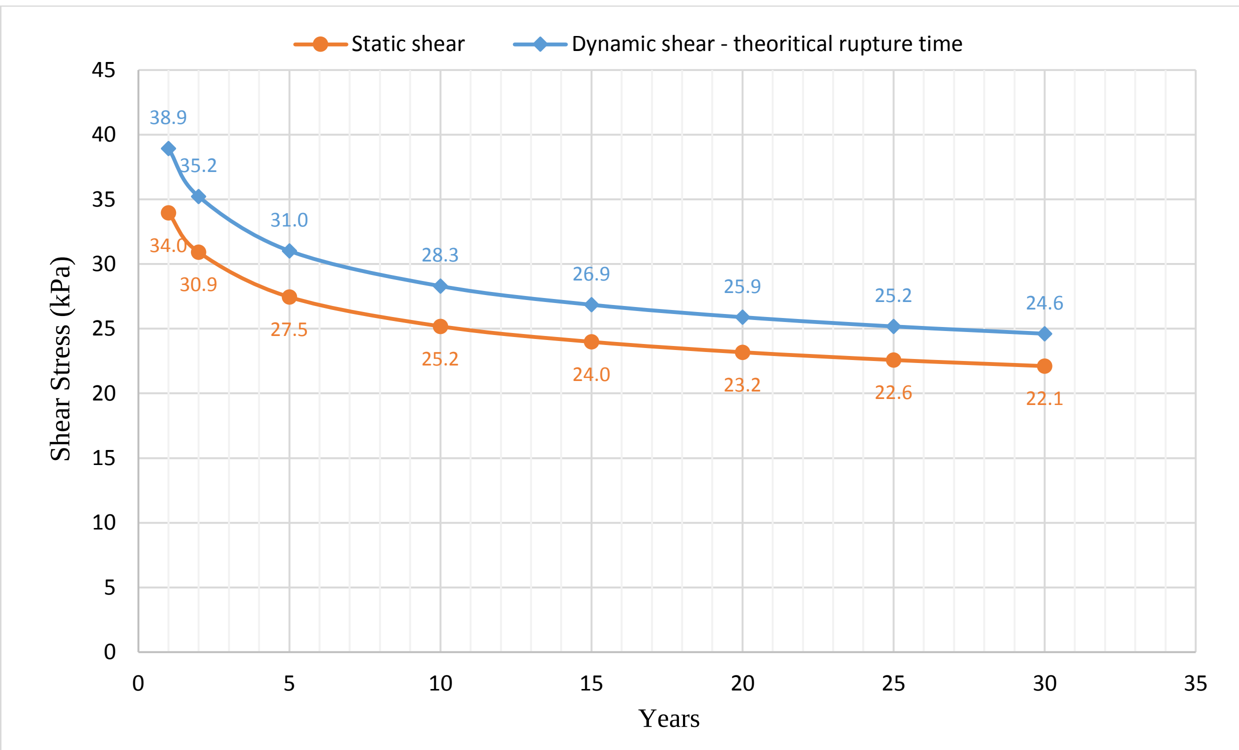

Figure 4.10: Comparing Design Values of Static Shear versus Dynamic Shear - Theoretical Rupture Time

4.2.3 Static Shear Model versus Dynamic Shear Model - Time at Peak Stress

Figure 4.11 shows comparison of static shear model and dynamic shear model - time at peak stress. Static shear design value at year 1 is only 3% less than the design value of dynamic shear - time at peak stress (34.0 kPa and 35.0 kPa, respectively). The difference stays constant at 3% through year 25 (22.1 kPa and 22.8 kPa). This comparison not only has closer design values between the two methods, it also has consistent difference during long term period of time. This is the only model explored which shows this consistency.

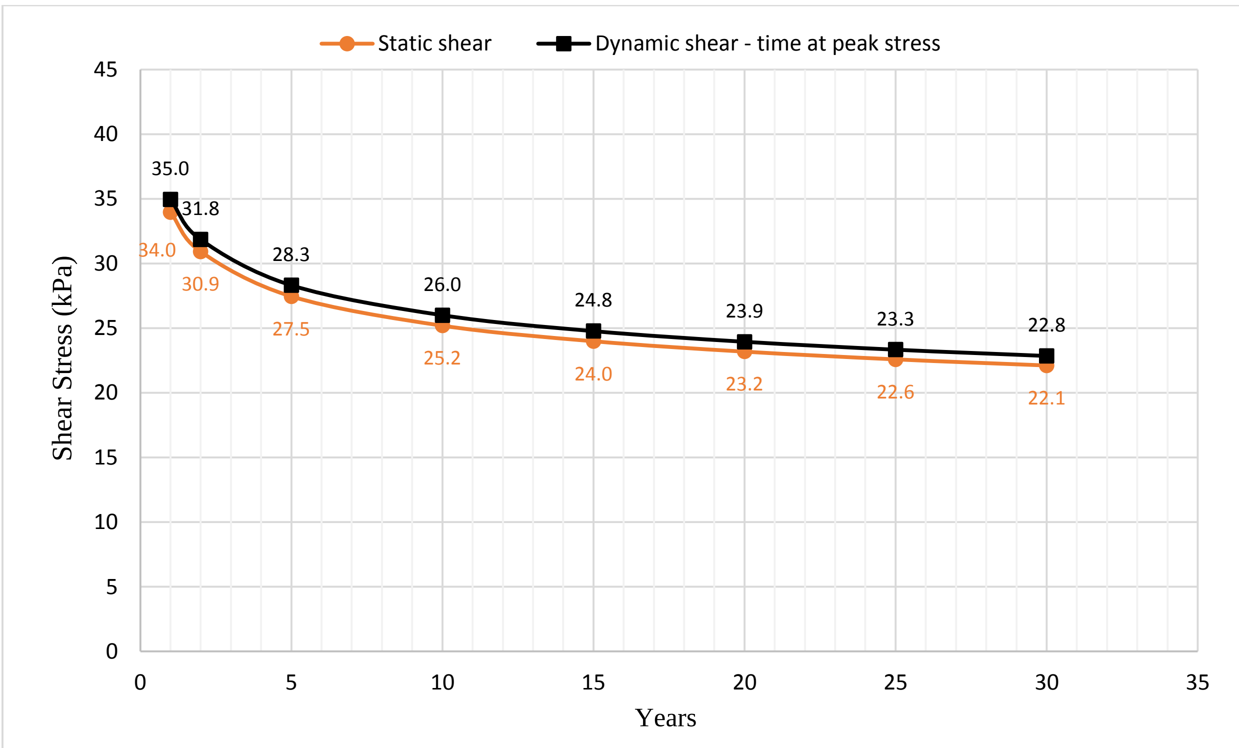

Figure 4.11: Comparing Design Values of Static Shear versus Dynamic Shear - Time at Peak Stress

The overall comparison of the static shear and the two dynamic shear models are shown in Figure 4.12. It summarizes what was concluded earlier:

- Theoretical and actual rupture time dynamic shear models are similar and can be used interchangeably.
- Dynamic shear method with time at peak stress model shows relatively close design values to the static shear model. The difference is only 3% and it is consistent during long period of time.

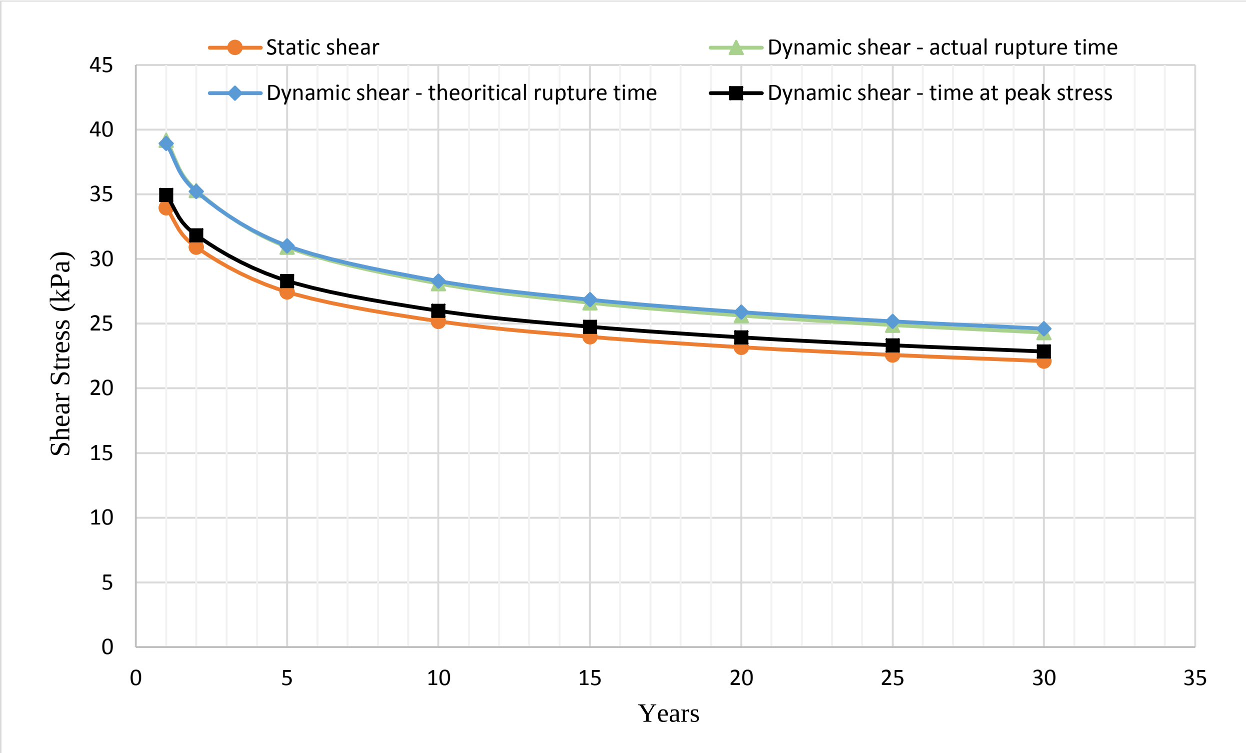

Figure 4.12: Overall Comparison of Design Values of Static Shear Model versus Dynamic Shear Models

4.3 Specimens Failure

Failure modes of PSA specimens were alike for both test methods. All specimens showed cohesive failure. Cohesive failure is when the PSA specimen breaks between the two test plates as illustrated in Figure 3.3.

Figure 4.13 and Figure 4.14 show dynamic shear and static shear samples failure modes respectively. All samples showed cohesive failure, the PSA specimen left a black layer of adhesive on both test plates after they pulled apart.

Figure 4.13: Failure Mode of Dynamic Shear Specimens at Various Test Speeds

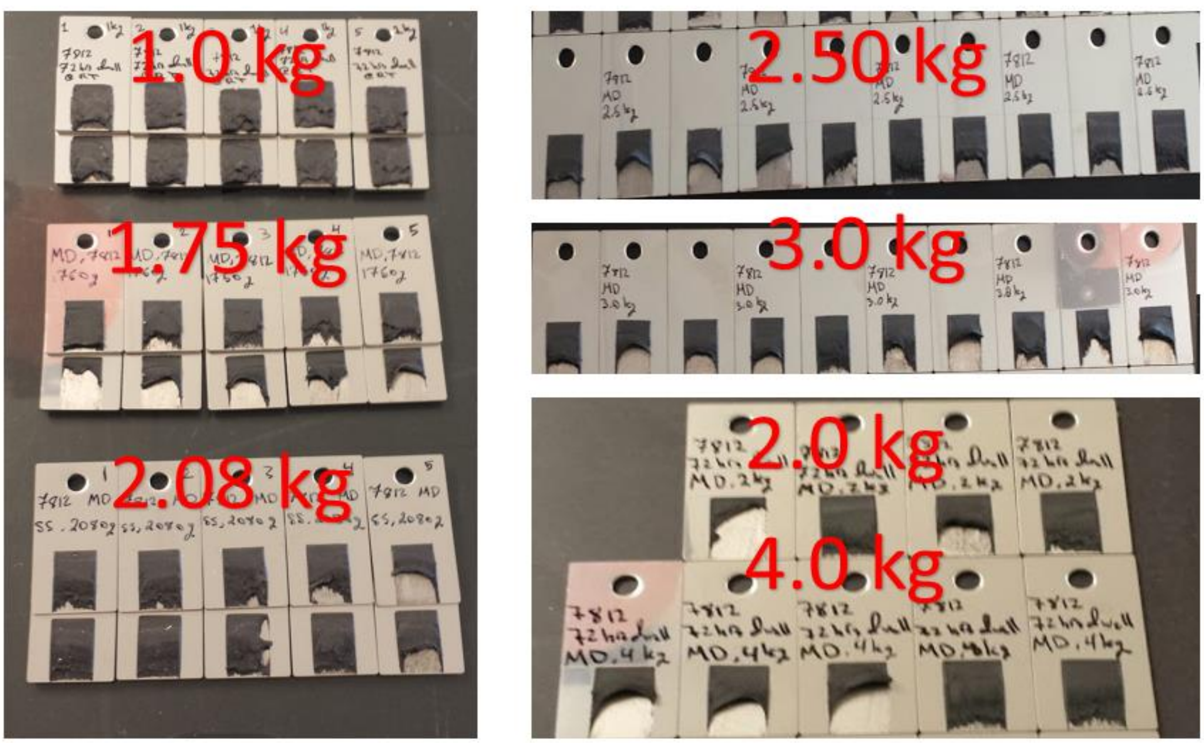

Figure 4.14: Failure Mode of Static Shear Specimens at Various Test Speeds

CHAPTER 5

DATA ANALYSIS

5.1 Validation of Static Shear Method Test Results

From a statistical stand of point, how reliable are the static shear method failure times especially with high and variable failure times? For example, taking the failure times of 38.49 kPa failure times of the replicated samples, some samples failed few days before the others, so in order to question or not question the reliability of the results; the coefficient of variance statistical tool will be used to make the judgment.

Coefficient of variation (CV) measures of distribution of data points in a data series around the mean. CV permits the comparison of variants free from scale effects which is the case in the static shear test results that covered failure times from few hours to few months [14].

CV is the ratio of standard deviation to the mean. Distributions with a CV ratio less than 1 are acceptable, whereas distributions with a CV ratio greater than 1 are noted to be high variance [14]. Table 4.1 shows standard deviation, mean and CV of the static shear data series tested. CV was calculated using Eq. C.1 in Appendix C.

Table 5.1: CV Values of Static Shear Test Results

Stress (kPa)	Mean failure time (s)	Standard deviation	CV
38.49	9.22E+06	6.28E+05	0.07
57.35	2.04E+06	2.87E+05	0.14
66.78	4.85E+05	7.81E+04	0.16
76.22	1.77E+05	5.90E+04	0.33
79.23	1.68E+05	4.60E+04	0.27
95.08	6.65E+04	1.19E+04	0.18
113.95	3.46E+04	6.84E+03	0.20
151.68	1.01E+04	7.72E+02	0.08

All CV values are lower than 1; so all data series are low variance. It means static shear test results are reliable and valid to use in a mathematical model.

This research provides a solid experimental results, analysis and comparisons of testing method used to test shear resistance PSA's. Continuing investigations on the presented future work topics can expand the applications an acrylic foam PSA used for.

5.2 Future Work

Based on the positive results obtained from this work, here is a list of some ideas for further investigation need to be looked at:

- First on the list is to finish testing the cross machine direction samples to see the relationship between MD and CD.
- Check whether the correlation between the models is true for other acrylic foam PSA's. It is also recommended to test same PSA tape with different thicknesses.
- Acrylic foam PSA's are most common products used in structural applications; but it would be useful to investigate in other materials such as, filmic tapes and polyethylene core tapes.
- Factor of safety also requires lots of investigations because it also depends on adhesive property more than a backing property. There are some standard technical specifications to add the appropriate safety factors, for example, ETAG 002 is a guideline for structural sealant glazing systems that also valid for acrylic PSA's.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

Static shear test method is the test that mimics the real life application of a PSA under static load, but that method is not the most efficient method of testing and it takes long time to provide required data. That is why this research focused on finding an alternative, faster and more reliable method of testing to replace the static shear test and to be taken as an industrial predictive system for long-term performance of a PSA.

The model obtained from the static shear method is the relationship between the constant stress and recorded rupture time, this model is the reference model that dynamic shear method is approaching. Dynamic shear test is done using a tensile machine that draws the deformation behavior of the PSA specimen once it starts shearing until it ruptures. The dynamic shear model is relationship between peak stress and failure time. The definition of failure is not clear here, it can be the time the PSA specimen ruptures, or failure can be the maximum stress a PSA specimen can take. Based on that, three dynamic shear models were studied:

i. Relationship between peak stress and actual rupture time.
ii. Relationship between peak stress and theoretical rupture time.
iii. Relationship between peak stress and time at peak stress.

Testing at different ranges of shear rates can lead to poor and unreliable models, it is very important to distinguish between "high" shear rate and "slow" shear rate. There isn't really a line between what is high and what is low, but drawing the relationship between shear stress and shear rate can show the full picture of viscosity response when shear rate changes. The focus of this study was on low shear rates testing because it is the reflection of the PSA usage in real life.

The first two models show unnoticeable differences when compared to each other. On the other hand, comparing design values from these models to the reference model (static shear model); the dynamic shear models are 10-15% higher than the static shear model.

Dynamic shear model from peak point (peak stress and time at peak stress) showed a closer design values to the static shear model. The difference significantly dropped to 3%.

Estimating long-term performance of a foam acrylic PSA can be done using dynamic shear model of stress peak and time at stress peak. It shows highly reliable results, consistent theoretical differences during times from 1 to 25 years, and building a new model for other acrylic foam PSA’s will only take few days instead of few months using a static shear method.

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APPENDICES

A. Standard Specifications Used

A.1 Static and Dynamic Shear Test Methods (J0PM0164-E)

tesa	Test Method	Ident.no.: J0PM0164-E Version : 002 Valid since: March 2012
Shear Test Plate-Plate, static/dynamic		Page 1 of 5

Printout - the online document takes precedence!

Table of contents

1. Purpose and Scope of testing

For AXCplus a.o. DS tapes. In contrast to the usual tesa shear test the tape is attached between 2 test plates.

2. Principle of the Method

The tape to be tested is attached between 2 steel plates and pressed for 1 Minute with 100 N/cm² tape area. After the specified dwell time (typically 3 days at room temperature) the static or dynamic test is conducted.

Static test: The test piece is loaded with the specified weight at the specified temperature. Result is the holding time in minutes until falling down.

Dynamic test: The test piece is torn in a tensile tester at 50 mm/min. Result is the maximum force measured in N/cm².

Signatures on original German document:		
Created: 9110 – Dr. Kahl	Checked: 9110 – M. Mies	Authorized: 9110 – M. Mies
Contents identical with German original document: 9110 - Dr. Kahl		

3. Test Equipment and Conditions

- Shear test plates, steel, 2 x 25 x 50 mm, not grinded, as for tesa shear test J0PME002, RA = 25 – 75 nm.
- Pressing device with force measuring dauge.
- Stopwatch
- Static Test: Holding power counters in climate room or in heat oven
- Dynamic Test: Tensile tester, strong hooks (4 mm diameter, hardened)

Testing climate: 23 ± 1 °C, 50 ± 5 % rel. Humidity

4. Materials

Acetone and tissue paper for plate cleaning

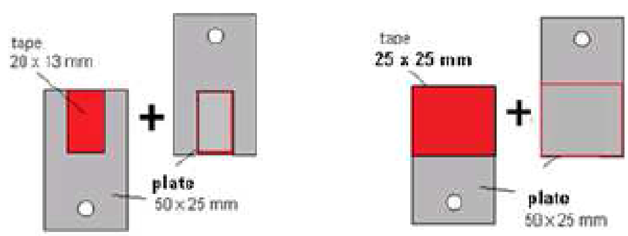
5. Test Specimens

Static Test: Strips of 13 mm width.
Dynamic Test: Strips of 25 mm width.

6. Procedure

Prepare 3 test pieces per tape sample.

- Clean both plates intensively with Acetone. Let dry 1 – 10 minutes.
- Attach tape to one plate. Avoid air inclusions, cut to be flush with edge of plate. No pressing with fingers to avoid dimples in the tape.
- Attach 2nd plate to form the test piece.
- Press test pieces in the pressing device.



Pcture 1: static dynamic

If not stipulated otherwise, use the following standard test parameters.

Parameter	Standard static	Standard dynamisch
Adhesive area	20 x 13 mm	25 x 25 mm
Pressure	0,260 kN (= 100 N/cm²)	0,625 kN (= 100 N/cm²)
Pressing time	1 minute	
Dwell time	3 days at 23 °C	
Test velocity	-	50 mm/min

Mark open and covered side if required

In contrast to conventional tesa-shear test here, the open and the covered side of a tape are tested at the same time. In order to be able to assess the failure mode foe each side, indicate the tape side on the plates.

6.1 Static Test

No adapter plates are used to hang the weight pieces. (see photo).

The test ends when the specified minimum holding time is reached or all test specimens fell down

Test in oven

When tested in an oven, first hang the test pieces alone and let warm up for 15 minutes, then attach the weight pieces.

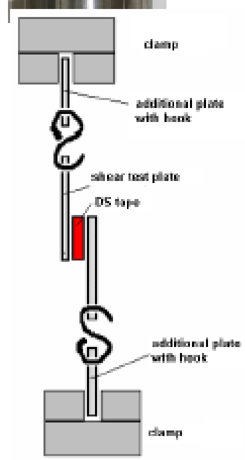
6.2 Dynamic test

Attach the test piece to the upper clamp of the tensile tester using an additional plate and a hook.

Then zero the load cell.

Attach the test piece in the same way to the lower clamp.

Start the machine. Result is the maximal force measured.



7. Calculation and Evaluation

Evaluation of Failure Mode

If required (in F & E, the rule) also evaluate the failure mode.
For example, open side adhesive failure, cohesive failure, etc.

7.1 Static Test

Routine test holding time

Take the Median of 3 single results.

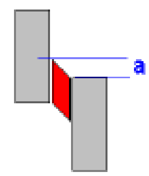
The test may be stopped after 2 test pieces fell down. The holding time of the 2nd is the result.

Hint for Hausbruch plant: If the QS-software cannot calculate the median, you can use the mean of three results.

Testing for product properties or round robin tests
The number test pieces per samples depends on the needs. For statistic evaluation take the logarithm of the single results.

Examples : 720 Min. = log(720) = 2,857 logMin.
4552 Min. = log(4552) = 3,658 logMin.

Measuring Creep of aborted tests
If required (in F & E, the rule): If the test is stopped before all specimens have fallen, measure the shear displacement **a**.
Calculate the mean of the single results.



7.2 Dynamic Test

Calculate the arithmetic mean of the 3 single maximum forces in N/cm²

8. Reporting Results

Static Test
Result is the holding time in minutes.

With the result report:
- Test type static
- Deviations from the standard parameters in paragraph 6
- When testing in R & D: the failure mode
- When testing in R & D: Time until test end and creep in mm

Example 1: tape A, shear test plate-plate, static, 1000 g, 70 ° C: 720 min

Example 2: tape B, ST plate-plate, static, 2000 g, 23 °C, after 1 h 60 °C: 720 min
→ Here a non standard dwell time was used.

Example 3: tape C, ST plate/plate, static, 2 kg, 23 °C: >22.000 min, creep 4.5 mm.
→Here the test was stopped after 22,000 min and an average creep of 4.5 mm was measured.

Dynamic Test
Result is the mean of the measured maximum forces N/cm².

With the result report:
- Test type dynamic
- Deviations from the standard parameters in paragraph 6
- When testing in R & D: the failure mode

Example 1: tape A, shear test plate-plate, dynamic, 105 N/cm².

9. History

Ver. 2 March 2012: Significant changes: The method for the dynamic shear test has been integrated. The name of the method changed from “Shear Test Plate-Plate” to “Shear Test Plate-Plate, static/dynamic”

Ver. 1 March 2010

10. Notes

B. Experimental Data

Table B.1: Dynamic Shear Test Results

#	Rate (mm/min)	Max.Load (N)	Max. Load/ Area (N/cm^2)	Time at peak(sec)	Rupture Time (sec)	Extension at peak(mm)	Final Extension (mm)	Tensile strain at peak (%)	Tensile stress at peak (kPa)	Final Tensile Strain (%)
1	500	372.08	143.11	0.90	1.82	7.50	15.15	625.00	1,431.07	1,262.50
2	500	395.69	152.19	1.10	3.18	9.17	26.53	764.17	1,521.87	2,210.83
3	500	399.10	153.50	1.00	2.18	8.33	18.17	694.17	1,535.00	1,514.17
4	500	383.17	147.37	1.00	2.28	8.33	19.02	694.17	1,473.73	1,585.00
5	500	428.67	164.87	1.00	3.01	8.33	25.05	694.17	1,648.72	2,087.50
6	50	241.37	92.83	9.20	32.39	7.67	26.99	639.17	928.33	2,249.17
7	50	261.41	100.54	9.90	29.40	8.25	24.50	687.50	1,005.42	2,041.67
8	50	273.28	105.11	10.50	35.56	8.75	29.63	729.17	1,051.09	2,469.17
9	50	275.25	105.87	10.30	22.85	8.58	19.04	715.00	1,058.67	1,586.67
10	50	282.72	108.74	10.60	35.18	8.83	29.32	735.83	1,087.37	2,443.33
11	5	144.05	55.40	96.30	303.24	8.03	25.27	669.17	554.03	2,105.83
12	5	168.42	64.78	109.40	346.20	9.12	28.85	760.00	647.78	2,404.17
13	5	169.35	65.14	114.20	324.36	9.52	27.03	793.33	651.36	2,252.50
14	5	162.95	62.67	109.40	328.20	9.12	27.35	760.00	626.74	2,279.17
15	5	164.35	63.21	113.50	293.52	9.46	24.46	788.33	632.10	2,038.33
16	5	160.17	61.61	111.60	297.24	9.30	24.77	775.00	616.05	2,064.17
17	1	104.99	40.38	581.30	1,559.45	9.69	25.99	807.50	403.81	2,165.83
18	1	104.99	40.38	581.30	1,559.45	9.69	25.99	807.50	403.81	2,165.83
19	0.50	82.44	31.71	1,145.90	3,079.20	9.55	25.66	795.83	317.07	2,138.33
20	0.50	84.52	32.51	1,267.60	3,171.60	10.56	26.43	880.00	325.06	2,202.50
21	0.50	83.28	32.03	1,036.60	3,064.80	8.64	25.54	720.00	320.29	2,128.33
22	0.50	80.61	31.00	1,001.50	2,583.60	8.35	21.53	695.83	310.04	1,794.17
23	0.50	81.54	31.36	1,065.70	3,048.00	8.88	25.40	740.00	313.61	2,116.67
24	0.353	72.84	28.02	1,530.50	4,144.80	9.02	24.41	751.67	280.15	2,034.17
25	0.353	72.84	28.02	1,530.50	4,144.80	9.02	24.41	751.67	280.15	2,034.17
26	0.050	39.84	15.32	9,475.20	25,248.00	7.90	21.04	658.33	153.22	1,753.33
27	0.050	40.70	15.65	13,607.60	31,356.00	11.34	26.13	945.00	156.53	2,177.50
28	0.050	41.24	15.86	9,769.70	30,089.10	8.14	25.07	678.33	158.62	2,089.17
29	0.050	41.77	16.07	12,629.00	29,875.70	10.50	24.90	875.00	160.65	2,075.00
30	0.050	46.33	17.82	8,560.80	29,400.00	7.10	24.50	591.67	178.19	2,041.67
31	0.050	41.24	15.86	9,769.70	30,089.10	8.14	25.07	678.33	158.62	2,089.17

32	0.010	19.32	7.43	20,768.30	21,344.20	3.46	3.56	288.33	74.31	296.67
33	0.010	27.27	10.49	44,815.30	141,244	7.47	23.54	622.50	104.88	1,961.67
34	0.010	27.70	10.65	58,917.40	134,917	9.82	22.49	818.33	106.54	1,874.17
35	0.010	27.27	10.49	44,815.30	141,244	7.47	23.54	622.50	104.88	1,961.67
36	0.010	27.70	10.65	58,917.40	134,917	9.82	22.49	818.33	106.54	1,874.17
37	0.005	22.28	8.57	78,733.50	234,360	6.56	19.53	546.67	85.68	1,627.50
38	0.005	22.17	8.53	81,600.00	240,002	6.80	20.00	566.67	85.27	1,666.67
39	0.005	21.88	8.42	79,320.00	264,120	6.61	22.01	550.83	84.15	1,834.17
40	0.005	19.76	7.60	88,200.00	253,301	7.35	21.11	612.50	76.00	1,759.17
41	0.0008	16.69	6.42	795,000.0	1,725,000	10.60	23.00	883.33	64.19	1,916.67

Table B.2: Static Shear Test Results Related to Figure 4.3

Loads (kg)		1.02	1.52	1.77	2.02	2.10	2.52	3.02	4.02
Force (N)		10.01	14.91	17.36	19.82	20.60	24.72	29.63	39.44
Force/area (N/cm^2)		3.85	5.74	6.68	7.62	7.92	9.51	11.39	15.17
Stress (kPa)		38.49	57.35	66.78	76.22	79.23	95.08	113.95	151.68
Specimen #	1	8.78E+6	1.81E+6	3.67E+5	1.25E+5	1.29E+5	5.55E+4	2.99E+4	9.24E+3
	2	9.67E+6	1.83E+6	4.52E+5	1.31E+5	1.31E+5	5.78E+4	3.13E+4	9.69E+3
	3	1.02E+7	1.91E+6	5.05E+5	1.76E+5	1.62E+5	6.30E+4	3.14E+4	9.85E+3
	4	1.26E+7	2.14E+6	5.34E+5	1.80E+5	1.73E+5	7.14E+4	3.40E+4	1.09E+4
	5	1.29E+7	2.49E+6	5.66E+5	2.72E+5	2.42E+5	8.47E+4	4.66E+4	1.10E+4
Failure time	Average (s)	1.08E+7	2.04E+6	4.85E+5	1.77E+5	1.68E+5	6.65E+4	3.46E+4	1.01E+4
	Standard deviation	1.82E+6	2.87E+5	7.81E+4	5.90E+4	4.60E+4	1.19E+4	6.84E+3	7.72E+2
	log10 failure time	7.03	6.30	5.68	5.24	5.22	4.82	4.53	4.00

Table B.3: Shear Rate and Apparent Viscosity Results Summary

Test speed (mm/min)	Shear rate (s^{-1})	Shear stress (kPa)	Apparent viscosity η (MPa.s)
500	6.944444	1,522.08	0.22
50	0.694444	1,026.18	1.48
5	0.069444	621.35	8.95
1	0.013889	403.81	29.07
0.5	0.006944	317.22	45.68
0.35	0.004908	280.15	57.08
0.05	0.000694	161.41	232.44
0.0100	0.000139	104.88	755.17
0.0050	0.000069	82.78	1,191.97
0.0008	0.000011	64.19	5,777.31

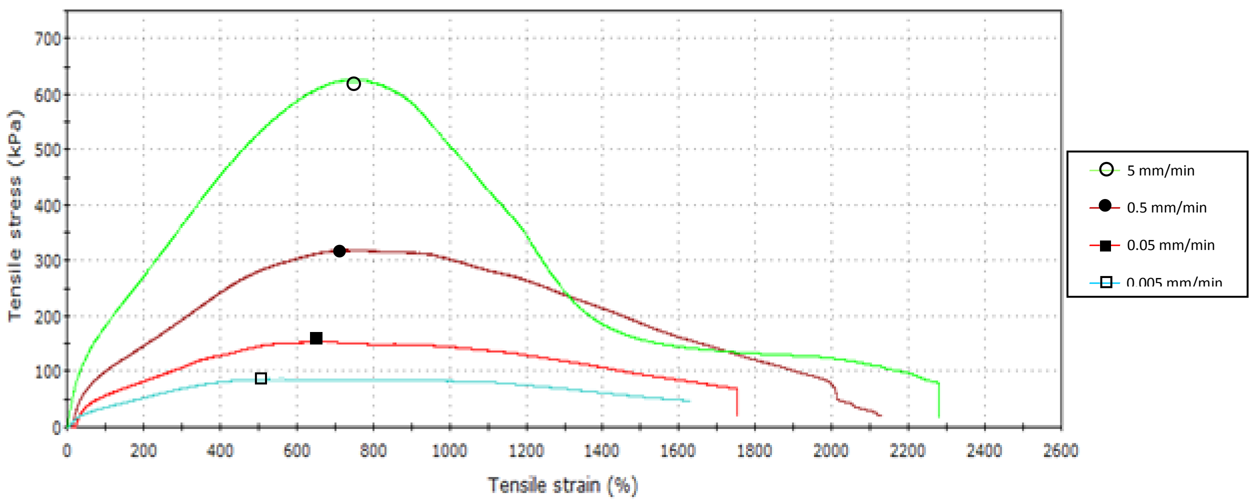


Figure B.1: Stress-Strain Diagram of Tesa Acrylic Foam PSA in MD at Low Test Speeds Using Instron Model No. 33R4464

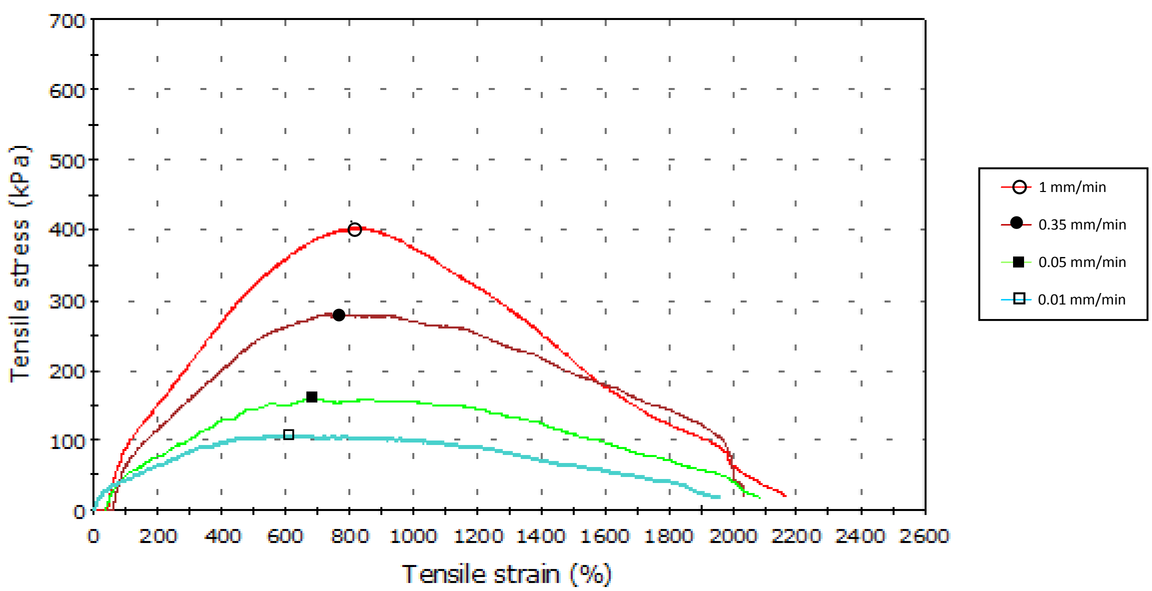


Figure B.2: Stress-Strain Diagram of Tesa Acrylic Foam PSA in MD at Low Test Speeds Using Instron Model No. 33R4464

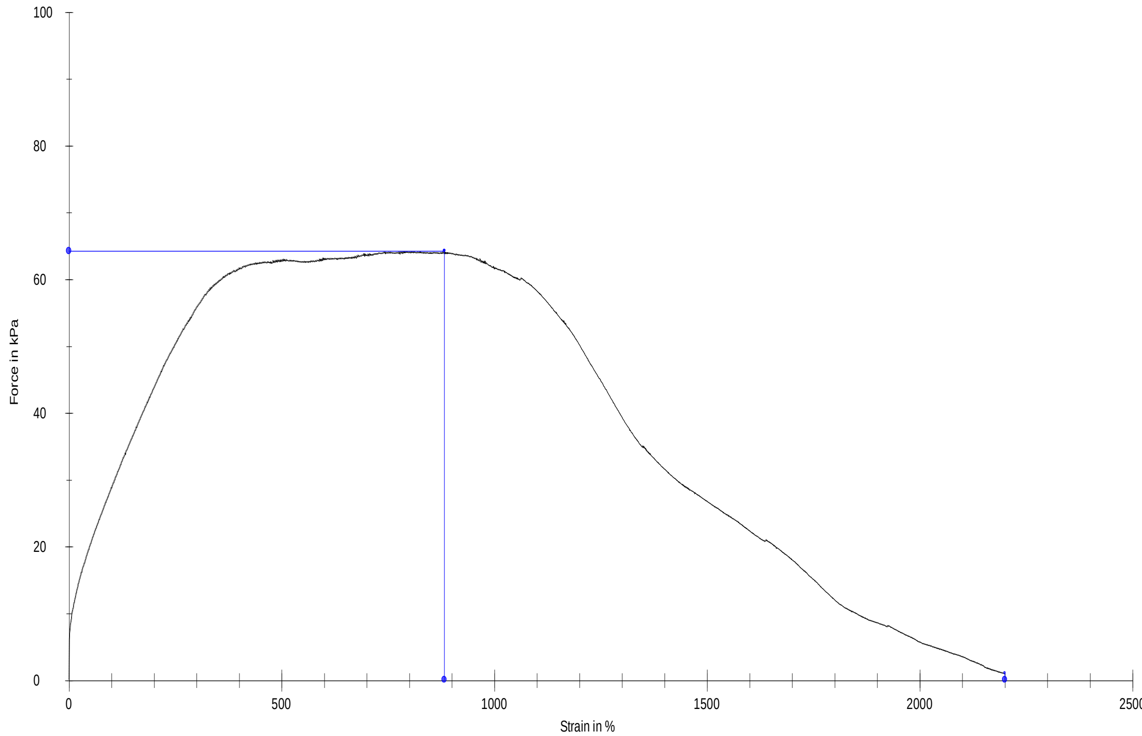


Figure B.3: Stress-Strain Diagram of Tesa Acrylic Foam PSA in MD at 0.0008 mm/min using Zwick / Z 2.5

C. Calculations

C.1 Example of Using Design Values

Acrylic foam core tapes are used in structure applications. Design values are becoming more and more required by building supply customers, especially for mounting applications. One of the direct applications is signage mounting.

For example, a customer wants to hold a sign weighs 50 kg using tesa's acrylic foam PSA. The customer want to know how much tape to use (bonding area) to hold the sign for at least 25 years. The design value provide acceptable performance for shear applications, while incorporating safety factors typical of the industry.

Solution:

To hold a load of 50 kg for 25 years, the design value obtained from static shear model is 22.60 kPa, and design value using dynamic shear model with time at peak stress is 23.30 kPa, to be in the safe side, the lower design value is used to calculate required bonding area. So 22.6 kPa is then the ultimate design value. The ultimate design value is the stress value manipulated based on a lab scale and lab environment testing. A factor of safety will be added to the theoretical calculations.

For acrylic foam tapes used in long-term holding applications, engineers typically use a safety factor of 12 or more in their designs [15]. And the structural design value is the design value used after adding a safety factor to assure that failure is never reached during the designated period of time.

Ultimate design value: $22.6\ kPa = 22.6\frac{kN}{m^2} \times \frac{1\ kg}{9.81\times10^{-3} kN} \times \frac{1\ m^2}{100^2\ cm^2} = 0.23\frac{kg}{cm^2}$

Using Eq. C.3, Structural design value = $\frac{\text{Refernce design value}}{\text{Safety factor}} = \frac{0.23\ {kg}/{cm^2}}{12} = 0.0192\frac{kg}{cm^2}$

To calculate the required bonding area:

$0.0192\ kg \rightarrow 1\ cm^2$

$50\ kg \rightarrow x\ cm^2$

So bonding area needed to hold a 50 kg load for 25 years is 2,604.16 cm^2. Based on the structural design value, a safe stress can be assured to the final end use of a PSA.

C.1 Equations Used

$$\text{Time} = \frac{\text{Distance}}{\text{Speed}} \qquad \text{(eq. C.1)}$$

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad \text{(eq. 4.1)}$$

η: apparent viscosity (Pa.s)

- τ : shear stress (Pa)
- $\dot{\gamma}$: shear rate (s^{-1})

$$\tau = \frac{F}{A} \qquad \text{(eq. 4.2)}$$

- τ: peak shear stress (kPa)
- F: maximum force (kN)
- A: bonding area area (m^2)

$$\dot{\gamma} = \frac{\upsilon}{h} \qquad \text{(eq. 4.3)}$$

- $\dot{\gamma}$: shear rate (s^{-1})
- υ: pulling speed (mm/min)
- h: distance between plates or thickness of the PSA specimen (mm)

$$\tau = K\left(\frac{\partial u}{\partial y}\right)^n \qquad \text{(eq. 4.4)}$$

- K: consistency index
- n: flow behavior index

- $\frac{\partial u}{\partial y}$: shear rate

$$\text{Coefficient of variance} = \frac{\text{Standard deviation}}{\text{mean}} \qquad \text{(eq. C.1)}$$

$$\text{Structural design value} = \frac{\text{Refernce design value}}{\text{Safety factor}} \qquad \text{(eq. C.2)}$$

$$\text{Shear strain} = \frac{\text{Extension}}{\text{Thickness}} \times 100\ \% \qquad \text{(eq. C.3)}$$

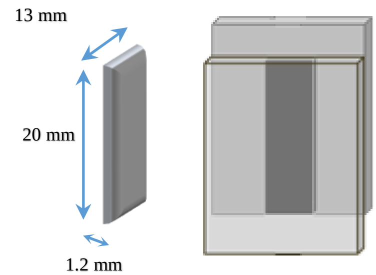
- Extension: any point during deformation.
- Original length: 1.2 mm.

C.2 Sample Calculation

Specimen geometry, 13 mm x 20 mm x 1.2 mm

Bonding area = 2.6 cm^2

Calculations based on, specimen number 19 from Table B.1.



$$\text{Time} = \frac{\text{Distance}}{\text{Speed}} \qquad \text{(eq. C.1)}$$

$$\text{Theoretical failure time} = \frac{20\ \text{mm}}{0.5\ \text{mm/min}} = 40\ \text{min} = 2{,}400\ \text{seconds}$$

$$\tau = \frac{F}{A} \qquad \text{(eq. 4.2)}$$

$$\tau = \frac{F}{A} = \frac{82.44\ \text{N}}{2.6\ cm^2} = 31.71\ \frac{N}{cm^2} \times \frac{100^2 cm^2}{m^2} = 317{,}100\ \frac{N}{m^2} = 317.1\ \text{kPa}$$

$$\dot{\gamma} = \frac{\upsilon}{\mathrm{h}} \quad \text{(eq. 4.3)}$$

$$\dot{\gamma} = \frac{0.5\ ^{mm}/_{min}}{1.2\ \mathrm{mm}} = 0.417\ min^{-1} = 0.00694\ s^{-1}$$

$$\eta = \frac{\tau}{\dot{\gamma}} \quad \text{(eq. 4.1)}$$

$$\eta = \frac{317.1\ \mathrm{kPa}}{0.00694\ \mathrm{s}^{-1}} = 45{,}691.64\ \mathrm{kPa.s} = 45.69\ \mathrm{MPa.s}$$

$$\text{Coefficient of variance} = \frac{\text{Standard deviation}}{\text{mean}} \quad \text{(eq. C.1)}$$

Samples series number 19 to 23 from Table B.1:

$$\text{CV} = \frac{\text{Standard deviation}}{\text{mean}} = \frac{5.82}{317.21} = 0.02$$

$$\text{Shear strain} = \frac{\text{Extension}}{\text{Thickness}} \times 100\ \% \quad \text{(eq. C.3)}$$

$$\text{Shear strain at rupture} = \frac{25.66}{1.2} \times 100\ \% = 2{,}138.33\ \%$$