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Evaluation of Pavement Joint Sealants:

A New Testing Technique

A Thesis in

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by

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ABSTRACT

A new method to evaluate the performance of sealants, used in rigid pavement joints, was developed. A special fixture was designed to transfer cyclic in-line deflection, applied by a testing machine, to cyclic normal and shear deflections on a sealant sandwiched between two-2 x 2 x 2 in. portland cement mortar cubes. The normal and shear deflections were applied simultaneously at a specific ratio controlled by the developed fixture. The new testing method simulates field conditions, where shear deflection is caused by vehicle loads while normal deflection is caused by slabs contraction or expansion due to temperature variation. The developed fixture was used to evaluate the performance of three commercially available one-component sealant types: (A, B, and C), A is a low modulus sealant, B is a self leveling type, while C is a sealant which is used with primer.

The effect of joint width on sealant performance was investigated using two joint widths (0.25 in. and 0.75 in.), while the weathering effect was evaluated by exposing specimens to 50 cycles of rapid freezing and thawing prior to testing.

Analysis of test results indicated that performance of

sealant C was the best, while performance of sealant B was the least. Sealant B showed incomplete curing although it was cured for 30 days prior to testing. All sealants performed better in compression than in tension.

Exposure to freezing and thawing cycles reduces the number of loading cycles to cause failure for sealant A and C and increases it for sealant B. Sealant B showed a better curing after being exposed to freezing and thawing cycles. The three sealants experienced a higher rate of stress reduction over the number of loading cycles after freezing and thawing conditioning. Sealant performance was found to be greatly affected by joint width. Joint width of 0.25 in. offers higher sealant failure resistance than 0.75 in. joint width.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL

The low tensile strength of concrete makes it necessary to provide joints for many concrete structures including rigid pavement. Rigid pavement joints may be classified into three categories: transverse joint (expansion and contraction joints), longitudinal joints (center line and edge joints), and construction joints.

In 1903, jointed concrete was first used as a paving system in the United States. Since then, wood, tar, asphalt, rubber, inorganic-elastometer, and many other materials have been used to seal the joints (Collins *et al.*, 1986).

Joints may fail if one of the following problems in the sealant occurs: adhesive failure, cohesive failure, extrusion or intrusion failure, and/or impregnation of incompressible materials. Failure in joint systems normally causes service life reduction of rigid pavements. A high percentage of deterioration in concrete pavements occurs at or near the transverse contraction joints due to inadequately sealed or failed joints (Capas and Pennock, 1973).

The increasing use of deicing salts in the United States is also causing serious damage to pavement joints. The intrusion of salt and water through failed joints causes the dowels and tie bars to corrode due to chloride intrusion with the presence of oxygen and water. The expansive steel corrosion products (around six times the original product) lead to increase buildup of internal stresses which crack the joint concrete.

Shear movements, resulting mainly from traffic and occasionally from temperature variations, contribute to sealant failure, especially if the sealant initially does not possess sufficient elastomeric properties or if it has lost these properties. The level of loss on these properties depends mainly on temperature, weathering, joint width, and load repetition.

At present, pavement engineers can choose from among hundreds of sealants. Extensive research has been conducted on the use of joint sealants in concrete pavements. However, the acceptable sealing of joints continues to be one of the most debatable issues in concrete pavement design and maintenance (Kuenning, 1962).

An examination of available literature shows that sealant acceptance specifications require only laboratory testing which ignores the effect of shear deflection due to vehicle loads. This may explain the poor field performance of some sealants that had previously met the laboratory testing specifications.

1.2 PROBLEM STATEMENT

As part of the national pavement management system, a better understanding of sealant performance is needed.

It is well recognized that joint-sealant failures are caused by repeatable normal pavement joint opening and closing due to slab expansion and contraction caused by variation in temperature. However, researchers have failed to address sealant failure resulting from vertical shear in the joint caused by heavy truck trafficking. Currently, there is no American Society for Testing and Materials (ASTM) standard to evaluate the performance of sealant in a manner which simulates field conditions.

1.3 OBJECTIVES

The objective of this study is to develop a new testing technique to evaluate joint sealant performance. This technique will be used to evaluate the potential field performance of three types of joint sealants. The sealants are to be exposed to simultaneous cyclic shear and normal deflections at different temperatures. In order to simulate field conditions, joint sealants are also to be exposed to freezing and thawing cycles prior to cyclic deflections. As the joint width may have an influence on joint performance, two different joint widths are considered for evaluation. The research variables are presented in detail in the research approach of this study.

1.4 RESEARCH SCOPE

A series of tests were performed by applying shear and normal deflections to sealant sandwiched between two 2 X 2 X 2 in. mortar cubes. Cyclic deflections were applied by an Instron machine model 1331. Special attachments and fixtures were designed to apply the simultaneous application of dynamic normal and shear deflections.

Three types of sealants were evaluated under deflection controlled conditions using the following criteria: 1) a normal deflection of 0.166 in. for a 0.75-in. joint width, and 2) a normal deflection of 0.056 in. for 0.25-in. joint width. Two other parameters were considered: temperature, and environment (freezing and thawing) effects.

The temperature effect was studied by conducting the tension tests at 25 °F, since the pavement slabs contract at low temperature. This ensured that the joint would open and that the sealant was under tension. The compression tests were conducted at 104 °F, because the pavement slab expands at this temperature, ensuring that the sealant would be under compression. Joint width was investigated by using two joint widths (0.25 and 0.75 in.). Also the environmental effect was studied by exposing specimens to freezing and thawing cycles, then comparing test results with results from tests on unconditioned specimens.

CHAPTER TWO

LITERATURE REVIEW

2.1 BACKGROUND

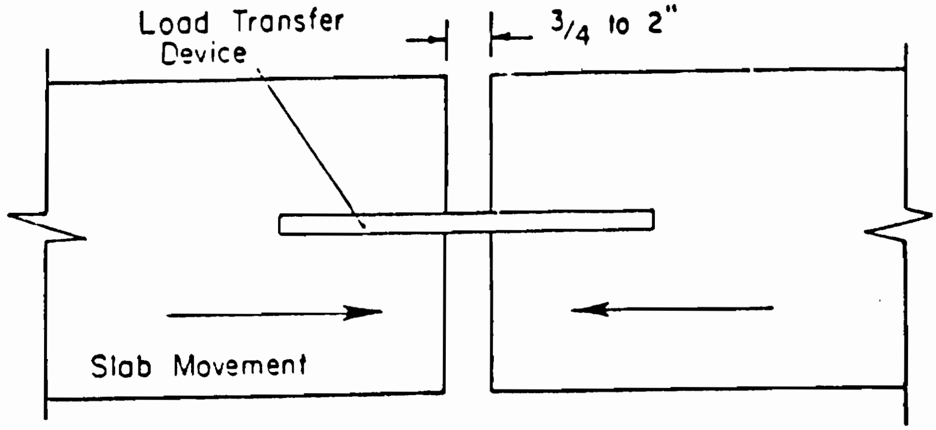
The importance of rigid pavement joints arises from their ability to minimize stresses from environmental changes (temperature and moisture) which result in expansion and contraction, to facilitate construction, and to control cracks by accommodating vertical and horizontal pavement movements. Concrete pavement joints may be classified as follows: transverse joints (expansion and contraction joints), longitudinal joints (center line and edge joints), and construction joints.

Expansion joints provide space for slab expansion and anticipated progressive horizontal movement from the gradual shoving of an adjacent slab. The joints are usually 0.75- to 2-in. wide and are spaced frequently up to 600 ft. Compressible filler material is installed in full depth between the slabs (Capas and Pennock, 1973). Regularly spaced dowels are used at these joints to help in transferring vertical loads from one slab to the next, as shown in Figure 2.1.

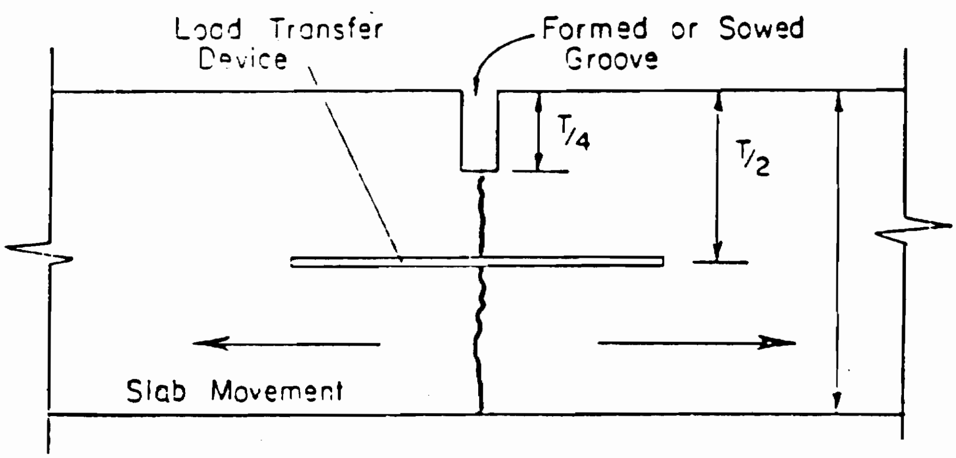
Contraction joints are designed to control random cracking of pavement due to thermal shrinkage and warping stresses. The depth of these joints should be at least one fourth of the slab thickness, 0.25- to 0.75-in. wide, and spaced at 15 to 60 ft. However, joints can be spaced as frequently as every 10 ft. if load transfer devices are not used.

Longitudinal joints are located between lanes or between lanes and shoulders of the pavements. This type of joint prevents lateral movement and relieves warping stresses; therefore, tie bars are usually used. Center line joints are used at the center line of two pavement lanes cast in a single operation in order to reduce stresses that may push the concrete slab from its initial plane. These stresses are usually due to temperature and moisture differentials between the top and bottom slab surfaces. These stresses, combined with vehicle loads, may cause pavements wider than 16 ft. to crack near the center lines if the joints are not provided (Collins *et al.*, 1986).

Edge joints, which are relatively new to rigid pavements,



Typical Expansion Joint



Typical Contraction Joint

Fig. 2.1 Expansion and Contraction Joints

(Collins *et al.*, 1986)

are longitudinal joints between pavements and concrete shoulders. Tie bars sometimes are used to prevent separation and to preserve the sealant. However, it is difficult to tie asphalt into concrete, and sealing joints is a major problem in this case.

Construction joints are used to join adjacent pavement lanes that are constructed separately. These are full-depth joints with abutting smooth faces and resemble expansion joints (Capas and Pennock, 1973). Transverse construction joints are used when the construction is stopped for a period of time. In that case, the joint should be located at expansion or contraction joints and built to conform with the specifications of these joints.

Joint construction is a critical factor in sealant performance. If the joints are not properly prepared and sealed, adhesive failure may occur as soon as the slabs contract.

2.1.1 **JOINT CONSTRUCTION**

A weakened joint is simply a joint created by weakening the cross section of the pavement. Generally, one of three methods is used to create the weakness: an insert is placed in the wet concrete surface, a groove is formed in the fresh concrete surface, or a groove is made by sawing shortly after the concrete has set (Capas and Pennock, 1973).

In the case of an insert, the weakness is created by inserting a thin plastic strip. The strip usually is placed automatically by a machine following the finisher. The float then passes over the surface without disturbing the embedded strip. An alternative to the machine placement is vibrating a lane width strip or total pavement width strip into the concrete. The plastic strip is folded over the edge of the bar which is then positioned by workmen. The assembly is vibrated into the fresh concrete, and the bar is then withdrawn, leaving the plastic strip embedded. Metal or other rigid inserts are placed in a similar manner. In some cases, it may be necessary to part the fresh concrete with guides, trowels, or grooving bars prior to placing the insert (Capas and Pennock, 1973).

Sometimes, metal or fiber inserts are installed with a provision for sealants to be placed above the insert. In other cases, expanded polyurethane or other material is inserted into the fresh concrete. After the concrete has set, it is sawed to permit seal installation.

Grooves in the wet concrete can be made by vibrating or working a T-shaped grooving bar into concrete. The bar should have a trapped web to permit withdrawal and should be embedded full depth, i.e., to the flange. It should be coated with form oil or another appropriate release agent. After concrete is stiffened sufficiently to prevent flow, the grooving bar is withdrawn, and the groove is edged. Even when joints appear to be well formed, some edging is desirable due to the tendency to disturb the edges when the bars are withdrawn. However, this hand work often produces rough joints (Capas and Pennock, 1973).

Sawed grooves are made after the concrete has attained sufficient strength to enable cutting through aggregates with minimum aggregate pullout. The timing of the sawing is critical; the appropriate time may be as soon as four hours after concreting if the day is warm and windy, or it may exceed eight hours under cool moist conditions. Cuts are made with a single blade or with a gang saw blade for early cuts. The second top groove must be widened to accommodate the seal and leveled slightly to reduce raveling. The width of this reservoir varies, but the depth is usually in the range of 1 in. The reservoir may be sawed simultaneously with groove cuts by spacing blades of different sizes (Capas and Pennock, 1973).

A backer rod is normally used in joints. The primary function of the backer rod is to act as a bond breaker, preventing three-sided adhesion of the sealant while at the same time forming the desired cross section of the sealant. Failure to utilize a backer rod will allow the sealant to bond to the bottom of the joint. The backer rod should be approximately 25 percent oversized so that it fits tightly into the joint; a loose backer rod will be pushed deeper into the joint when the sealant is installed (Dow Corning Corporation, 1991).

2.1.2 **SEALANT MATERIALS**

Since the joints are used in concrete pavement, wood, tar, asphalt, rubber, inorganic elastomeric and many other materials are used to seal these joints to stop the infiltration of incompressible materials. Usually joints are sealed by hot poured sealants, cold poured sealants, or preformed seals (Collins *et al.*, 1986).

Hot-poured sealants are usually asphalt mastic filled with latex, butyl, or reclaimed rubbers, all of which lose their elastic properties when overheated. The application directions suggest slow heating and then rigid control of temperature between specified limits. Initial heating to pouring temperature usually requires several hours. Hot-poured sealants are injected into prepared reservoirs through nozzles shaped to penetrate the space. In cold weather, fresh sealant level should be slightly below the pavement surface (Capas and Pennock, 1973).

Cold-poured sealants are one or two component polymer systems mixed at the job site. Some of these sealants are polyurethanes, polysulfides, and modified epoxies. Preparation of reservoirs for cold-poured sealant parallels that for hot-poured reservoirs, with the added stipulation that the concrete surface be dry. A final application of protective tape over the joint is sometimes necessary when cold-poured material is used, since its curing process is slow (Capas and Pennock, 1973).

The preformed sealants are pre-molded strips of styrene, urethane, polycholoroprene, neoprene, or other synthetic rubbers. The sealant must be selected to fit each reservoir, or the slab length and reservoir must be designed to fit the seal. Immediately before installation of the seal strip, the walls of the reservoir must be cleaned and coated with a temporary lubricant that will serve later as an adhesive. The strip is then pre-compressed and inserted by a machine or a special tool. Sealant elongation at insertion should not exceed five percent. If the maximum compressibility limit is exceeded, the cells will be locked, or if the minimum allowable compression is not maintained, the seal will be lost.

Polymer advantages, such as increased extensibility, reduced temperature sensitivity, and good adhesive and cohesive strength, are offset somewhat by high material costs, short pot life, and difficulties in cleaning equipment and tools.

In order for the sealant to perform its primary function in pavement joints, it must remain reliable and resilient at all temperatures it encounters. The material should not become excessively soft during hot weather, nor excessively hard and/or brittle during cold weather (Ray, 1969).

2.1.3 **Sealant Types**

Sealants are usually used to prevent intrusion of water and incompressible materials into pavement joints which can cause many problems in rigid pavements. The five sealants discussed below are among the most widely used (Collins *et al.*, 1986).

2.1.3.1 **Polysulfide Sealants**

Polysulfide sealant was the first type of cold-poured elastomeric sealant to be used in pavement joints. Cost is competitive and it possesses good-to-intermediate range properties of elongation and stiffness. Like most sealants, polysulfides are composed of a base polymer, curing agent, fillers added to strengthen the mixture, and in some cases, a plasticizing agent.

Polysulfide sealant consists of 100 parts liquid polymer, 100 parts reinforcing filler, 50 parts plasticizer, and 15 parts curing agent.

Polysulfide sealant is available in either one component or two-component system. The two-component system consists of a component that contains lead dioxide paste, which acts as the curing agent, and a plasticizer component. The two components are mixed immediately before application, and its pot life is generally three hours. Polysulfide sealant may not be applied at temperatures below 40 °F. The one-component polysulfide sealant cures through breaking water into atmosphere. It is more difficult to manufacture and more expensive than the two-component system.

The odor that polysulfide emits in its uncured state is very disagreeable, but after curing, the sealant is virtually odor free. Polysulfides have good water-immersion resistance and have high resistance to a number of organic solvents, oils, and a wide range of chemicals. It is nontoxic, non allergenic, and exhibits good resistance to aging and weathering; most polysulfides function well in pavement joints for over five years. Polysulfide hardness varies according to the type and the amount of filler being used.

The elongation range of polysulfides varies and depends on the chemical composition of the polymer, the amount of filler loading, and the plasticizer agent. Polysulfide laboratory specimens demonstrated elongation up to 1000 percent (Collins *et al.*, 1986). However, these materials have virtually no sharp recovery from such excessive deformations, and thus it is recommended that their elongation be limited to 50 percent or less.

2.1.3.2 **Silicone Sealants**

Silicone is considered to be a high-quality sealant and is therefore more expensive than other sealants commonly used in the construction industry. Silicone may withstand many years of exposure to a constantly changing environment while maintaining its initial physical properties.

Silicone sealant has three basic ingredients: long chain silicone polymer, curing agents, and fillers. The silicone polymers are formed by silica sand reduction, while fillers include calcium carbonate, clay, and ground silica. Silicone sealant cures to an elastomeric rubber when exposed to atmospheric moisture. During the curing process, the curing agent, also called the cross linker, reacts with the silicone polymer, forming a continuous Si-O-Si network. The acidic byproduct of the silicone sealants has a strong vinegar odor, while the neutral byproducts emit a musty odor.

The hardness of silicone is stable over a wide range of temperatures. It is relatively stable over a temperature range of 40 °F to 180 °F even after extended period of exposure. Due partly to its high recovery, and relatively high modulus, silicone sealant is characterized by a low tear resistance. Silicone sealants have a typical tear resistance value of 40 psi compared to a value of 70 and 80 psi for polysulfide and polyurethane sealants, respectively. However, low modulus silicone has tear resistance higher than those of polysulfides and polyurethanes.

Ultimate elongation of low modulus silicone is 1200 percent. It is recommended, however, that joint seals be designed for a maximum elongation of 50 percent due to seal shape and other field factors. Silicone sealant has a high elongation recovery between 90 and 100 percent after compression. Because of its high recovery, silicone performs well in cyclic tension and compression tests.

Silicone also exhibits excellent weathering resistance. It can withstand thousands of hours in a weatherometer without a significant change in its physical properties. This is partially due to its excellent ultraviolet resistance.

2.1.3.3 **Polyurethane Sealants**

Polyurethane is considered to be a high-quality sealant and competitively priced. It has high recovery, good workability, and good adhesion. The properties of the polyurethanes are, in general, between those of polysulfides and of silicones.

Polyurethane sealants have not been known to cause any significant odor problems. They are neither toxic nor allergenic. They have a good solvent resistance but only has fair resistance to water immersion, so they must be applied to dry substrates.

The hardness of polyurethane sealants is suitable for the requirements of traffic-bearing joints. The variation of hardness with temperature is between that of silicone and polysulfide sealants. Polyurethane's ultimate elongation has been shown to withstand 400 percent extension with portland cement concrete blocks before failing in adhesion. Also, polyurethane is considered to be a good weathering sealant and can survive well over 1000 hours in weatherometer chamber. It offers good resistance to abrasion and tearing, and displays insignificant creep or flow with high recovery value of 70 to 90 percent.

2.1.3.4 **Rubberized Asphalt Sealants**

Initially, asphalt cement was used as joint sealant and was found to be durable. Recycled rubber from used tires was added, and rubberized asphalt was developed. Medium-and low-quality rubberized asphalts are made from used rubber, asphalt, plasticizing agents, and fillers. However, higher-quality rubberized asphalt is made from virgin synthetic rubbers such as neoprene, rather than tires.

Rubberized asphalt is hot-poured sealant and requires strictly controlled heating practices. For example, if a rubberized asphalt should be heated to 400 °F at installation, heating to a temperature of 450 °F would render the sealant useless. Also, rubberized asphalt must not be exposed to more than one heating cycle.

Rubberized asphalt sealant is a nontoxic material and has no odor in the unheated state; however, it smells like any other bituminous compound in the heated state.

Most rubberized asphalt, at 77 °F, is not as hard as other joint sealant materials used in highway pavements. Rubberized asphalt becomes significantly harder at low temperatures and is very soft at temperatures approaching 150 °F. Rubberized asphalt has 80 to 90 percent deformation recovery at room temperature; at a high temperature, it tends to flow.

Other properties such as solvent resistance, aging and weathering, abrasion and tear resistance, and ultimate elongation vary depending on the rubberized asphalt's ingredients.

2.1.3.5 **Preformed Compression Seals**

Preformed seals arrive at the job site ready to install. Typically, the manufacturer needs to know the expected low and high temperatures at the site in order to provide the correct size seal. The seal must have a recovery of three psi pressure at the maximum joint width. A lubricant adhesive is used to ease installation and provide an adequate bond to the concrete.

The most widely used preformed highway joint sealants are neoprene rubber sealants. Other preformed sealants include silicone and butyl rubbers.

There is no appreciable odor to preformed sealants because they arrive fully cured. They are nontoxic and have a good resistance to aging and weathering. Preformed sealants' resistance to all types of solvents is very high. Preformed sealants are relatively hard and have high resistance to punctures and tears caused by stones and other incompressible materials.

2.1.4 **Joint Sealant Failures**

Some of the major factors which influence the performance and function of any sealant are the following:

1- Sealant depth.

2- Joint width.

3- Joint spacing.

4- Sealant properties (e.g., extensibility, strength, temperature susceptibility, and durability).

5- Properties and condition of the sealant-joint wall interface.

6- Joint characteristics and properties (e.g., maximum change in joint width, environmental effects, load transfer, and base support).

7- Proper joint cleaning.

8- Quality of workmanship.

If these factors are not considered in the design and construction of the joint, joint-sealant failure will most likely occur.

The major types of joint sealant failure are adhesive failure, cohesive failure, extrusion or intrusion failure, faulting, and impregnation of incompressible materials into the sealant. Adhesive failure occurs, due to tensile forces in the joint, when the sealant detaches from the joint wall. Cohesive failure occurs when the material is stressed beyond its tensile limit, causing tears in the sealant body which also are due to tensile forces in the joint, see Figure 2.2.

Incompressible intrusion failure occurs when extremely high compressive stress develops in concrete pavement due to

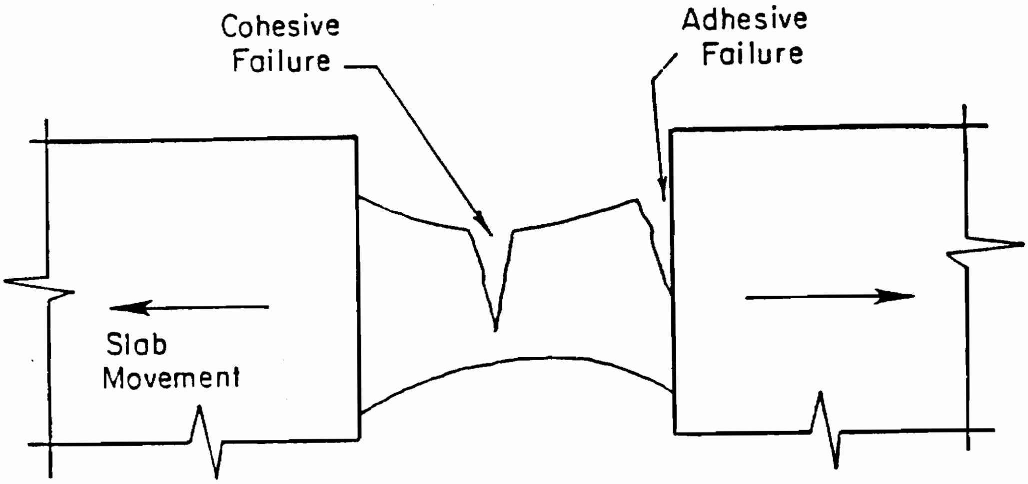


Fig. 2.2 Adhesive and Cohesive Failures

(Collins *et al.*, 1986)

the presence of incompressible materials which collect in the joints preventing joint closure. System failure will then occur when either compressive or buckling strength is exceeded. At high temperatures, pavement slabs expand and joints close; dirt may become trapped within the sealant during this process. The sealant then may fail during the following extension (Bugler, 1983).

Intrusion failure occurs when a sealant has relaxed during extension, and it does not possess adequate resilience to return to its original shape as the joint closes.

Extrusion failure occurs when a joint has been sealed to its full height when the joint is open. As the joint closes at high temperatures, the material is placed in compression, and the sealant either plugs or flows out of the joint. Once the sealant is higher than the pavement surface, it will be either flattened out onto the pavement or pulled out of the joint by passing vehicles. When the joint expands again, not enough sealant is left to properly seal the joint (Collins *et al.*, 1986).

2.1.5 **Effects of Joint Failures on Pavement Systems**

The most common pavement problems caused by joint failure are raveling, spalling, slab blow-up, slab crushing, and pumping, Figure 2.3 (Capas and Pennock, 1973).

Raveling may result from early sawing or untimely removal of grooving bars when grooves are formed in the plastic mix. An irregular tearing at the edges of the groove or saw cut occurs. Prevention methods include not sawing before the concrete has gained enough strength so that the saw cuts through the aggregate rather than pulling it out of the matrix. If forming bars are used, they should be taped or oiled to permit easy removal. Also repairs can be made with special bonding or epoxy mortar mixes.

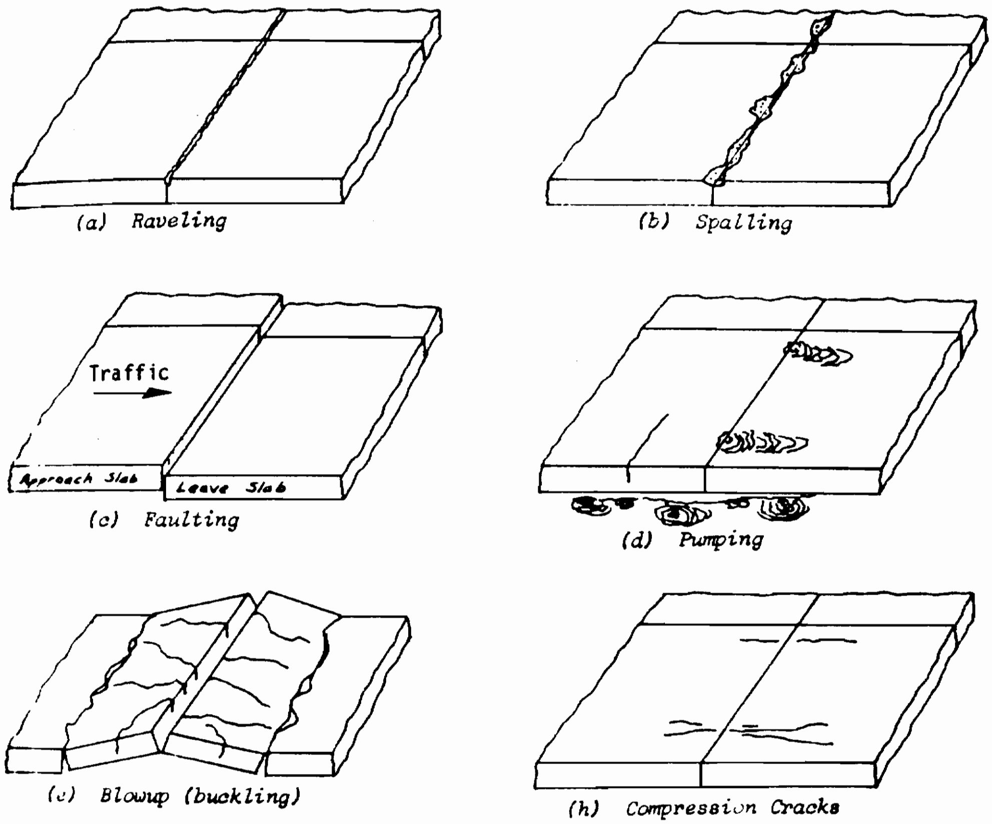


Fig. 2.3 Slabs Problems Due to Joints Failures

(Capas and Pennock, 1973)

Joint spalling occurs when portions of the pavement at the joint edges are dislodged by some stress. Joint spalls contribute to sealant failure and pavement roughness, and may forecast serious damage, such as blow-ups. Spalling usually occurs due to infiltration of incompressible particles in the joint. These particles resist joint closure during warmer weather and produce horizontal shear stress that can exceed the concrete shear strength. In long slab pavements, larger spalls may occur. When a large spall occurs on the upper corner of the joint, the seal becomes ineffective, and water may then enter the system. When spalls occur on the lower corner of the joint, the spalled concrete opens to pumping and faulting in the presence of water beneath the joint.

Resealing pavement with large spalls is nearly impossible; therefore, large spalls in concrete pavements should be repaired before the joints are resealed. Extrusive spalling may negate the use of preformed sealants, which need contact faces. Joint damage from spalling can be reduced by proper design and construction practice. Design must assure sufficient area of contraction joint faces to withstand compressive forces and must provide adequate load transfer.

Blowups occasionally occur at concrete pavement joints when high temperature and moisture in the concrete produce excessive expansion. The weakest joint usually offers stress relief to the compression built up in the pavement by shattering or by buckling upward. This may occur gradually or suddenly, and the failed areas may vary greatly in size and severity. Compressive thrust builds up in the pavement due to incompressible materials infiltrated in the joint. This thrust becomes eccentric because of some inadequacy in the joint face (such as soft or nondurable aggregate) or soft deterioration due to the application of deicers. Once the pavement blowup occurs and relieves the pressure, the adjacent joints open wider, thus funnelling more material into the joints, subsequently causing more blowups.

Design and construction techniques to reduce the frequency of buckled joints include a consideration of climate and environment, good base and shoulder design, proper spacing to minimize movement, good joint design with adequate and properly installed load transfer units, proper sealant reservoir design and selection, proper application of sealant, sufficient joint face area to withstand high compressive stresses, selection of sound aggregates for the concrete, and care in obtaining quality concrete at the joints.

In addition to retentive-maintenance techniques for the joint maintenance mentioned earlier, temporary relief of high compressive stresses can be provided by sawing a gap in the concrete and filling it with bituminous concrete or preformed compressible material. Blowup repair is a necessary reconstruction operation because the pavement at the joint must be replaced.

Pumping is a phenomenon that may lead to faulting. Pumping occurs when the fine particles of a pavement foundation or shoulder are carried by infiltrated water. Traffic produces a large number of deflections sufficient to cause the material to eject into the pavement or shoulder surfaces. Pumping becomes a serious problem when a large volume of material is displaced so that large areas of slabs are left unsupported. To assure good pavement life without pumping, subgrade conditions must be analyzed, slab thickness should be sufficient, and joints must be well constructed and sealed. Maintenance to reduce pumping on pavement consists of removing the source of water infiltration, restoring the support by slab jacking, and cleaning and resealing the joints.

Faulting is a type of joint deterioration produced by traffic. It is identified by "step off" development from the approach slab to leave slab. Methods of ensuring good pavement life without faulting are very similar to the methods used to prevent pumping.

Slab crushing and cracking occur due to the presence of incompressible materials in a joint. When incompressible materials enter an open joint, they do not allow the joint to close. If enough joints become immobilized, the pavement will have localized crushing at the joint. Other problems and failures, such as slab separation, may occur in some longitudinal joints.

A series of investigations were performed to evaluate the performance of many types of sealants; most of them were concentrated on inspecting preinstalled sealant joints. However, some studies investigated sealants installed in certain ways for evaluation purposes. Also, some studies investigated the performance of sealants in the laboratory under controlled conditions. Some of these investigations are discussed in the next section.

2.2 LABORATORY EVALUATION OF SEALANT PERFORMANCE

The laboratory tests performed on sealants have concentrated on tensile, compression, bond, penetration, flow, stress relaxation, heat cycling, and environmental cycling.

A series of tests including tensile, bond, flow, stress relaxation, compression, shear fatigue, penetration, and solubility have been performed on five types of sealants, two-part polysulfide, silicone, hot poured rubberized asphalt, polyurethane, and preformed sealant (Collins *et al.*, 1986).

The tensile test was performed on sealants installed between two-3 x 3 x 3 in. blocks and extended 0.5 in. per minute, under different temperatures (20 °F, 72 °F, and 130 °F). The effect of load on elongation is presented in Figures 2.4, 2.5, and 2.6 which show that the silicone performed the best at 20 °F with an elongation of 760 percent at approximately 50 lbs. while rubberized asphalt performed the

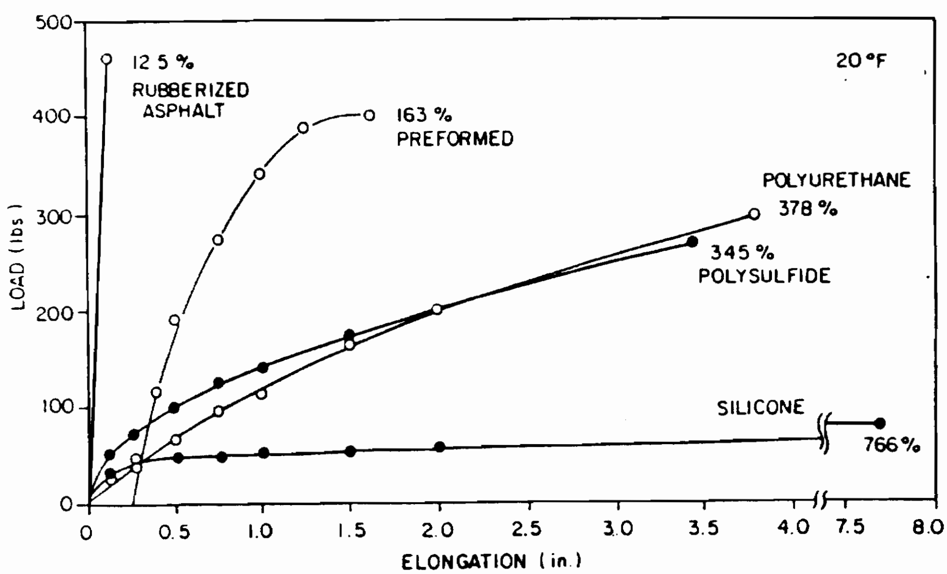


Fig. 2.4 Load Vs. Elongation for Different Sealants at 20 °F, Gage Length = 1 in. (Collins et al., 1986)

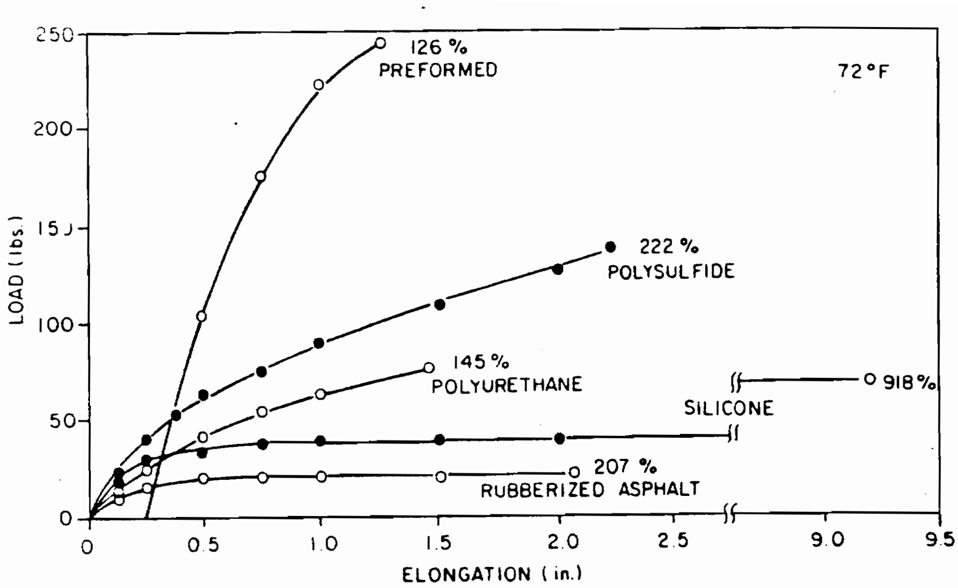


Fig. 2.5 Load Vs. Elongation for Different Sealants at 72 °F, Gage Length = 1 in. (Collins *et al.*, 1986)

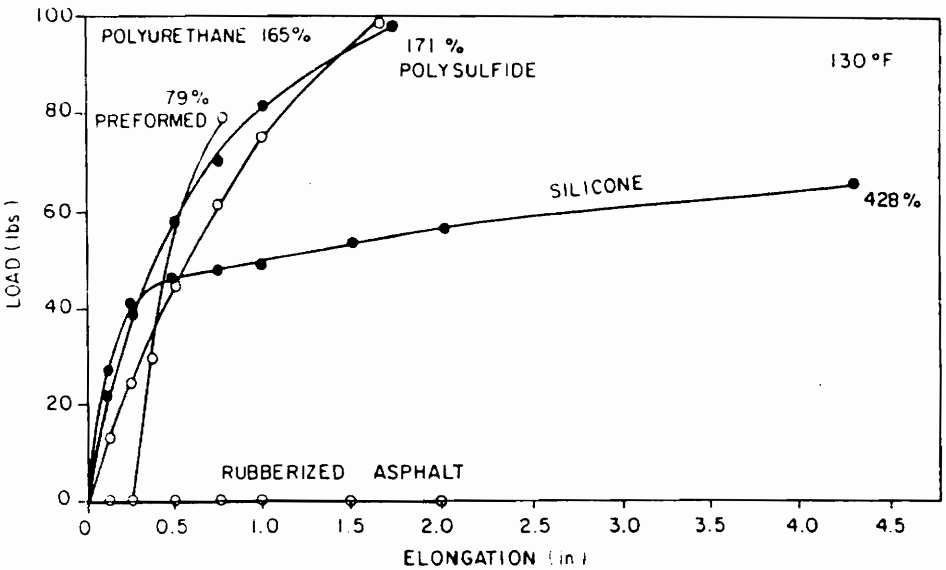


Fig. 2.6 Load Vs. Elongation for Different Sealants at 130 °F, Gage Length = 1 in. (Collins *et al.*, 1986)

worst with only 12.5 percent elongation at approximately 450 lbs. Also the load was almost constant throughout the elongation of silicone sealant. At 72 °F, based on percent elongation, rubberized asphalt performed better and the preformed sealant performed the worst. The silicone performance was again very good at 72 °F as well as 130 °F, while the rubberized asphalt performance was very poor at high temperature. Polyurethane and polysulfide performance was satisfactory at all three temperatures.

Bond between sealant and concrete was also tested, in accordance with ASTM D 3408-78 at different temperatures using 1 x 2 x 3 in. mortar blocks. The sealant was installed between the 2 x 3 in. block surfaces and maintained at 0 to 2 °F for four hours. The sealant was then extended 0.25 in. at a uniform rate for two hours. The load was then released, and the sealant returned to its original dimensions at room temperature. Two cycles were repeated within five days. After each extension, the specimen was examined for obvious separation within the sealant and/or between the sealant and the block. The results of the bond tests showed that no bonding was evident for any of the materials after five extensions of the cold applied sealant or three extensions of the hot-poured sealant.

Flow tests were conducted in accordance with ASTM D 3408. The specimen was prepared by pouring a portion of sealant in a mold (1.6 x 2.6 x 1/8 in.) and was allowed to cool for 30 minutes. The surface of the sample was then trimmed with a hot knife. An index line was inscribed on the panel of the specimen so that it was parallel and along an edge of molded sealant that was 1.6 in. wide. The specimen was placed in a forced draft oven at 158 °F for 72 hours, and then the flow was measured, while the longitudinal axis was at an angle of 75° with the horizontal. As Figure 2.7 indicates, the rubberized asphalt showed about 1 in. flow, while the other tested sealants showed less than 0.05 in. flow. This is due to the low viscosity of rubberized asphalt at the test temperature.

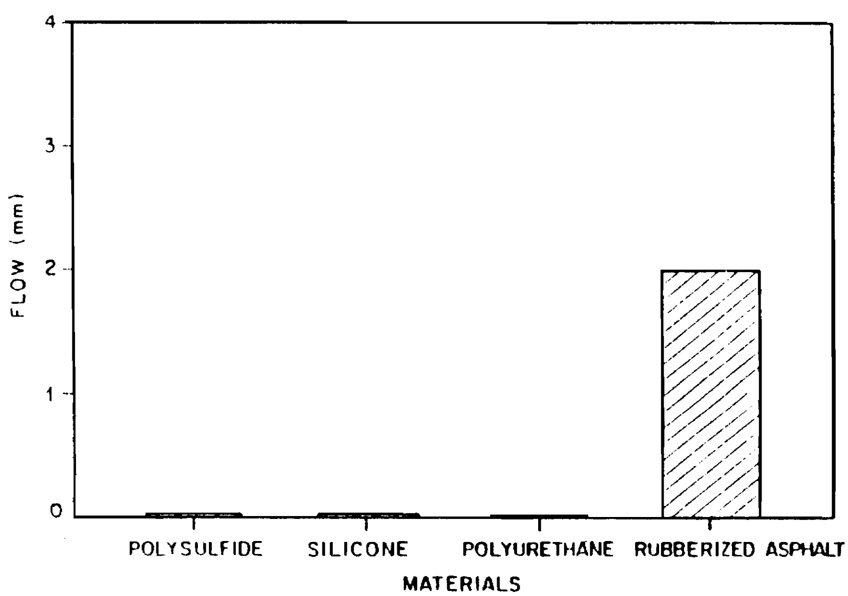


Fig. 2.7 Flow Test Results (Collins et al., 1986)

The stress relaxation test was performed using specimens prepared as in the tensile test and extended at 10 in. per minute until 50 percent elongation at 72 °F. The load on the sample was then recorded at specific times up to 60 minutes to measure the stress relief on the sample due to the flow of the sealant. The results of a typical test presented in Figure 2.8 show that rubberized asphalt has the highest flow value while the preformed sealant has the lowest flow value due to the same reasoning given earlier.

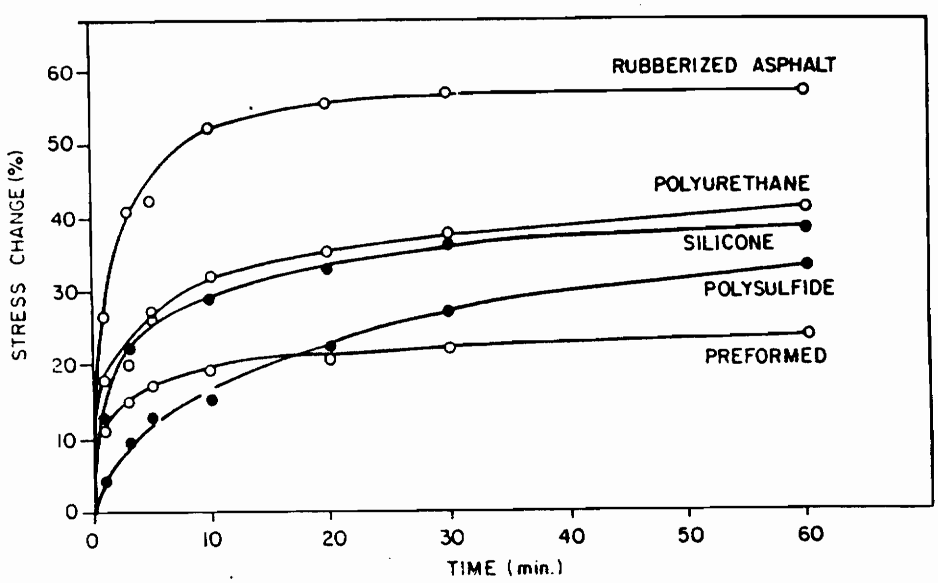


Fig. 2.8 Stress Relaxation Test Results (Collins et al., 1986)

For a shear fatigue test, a model of two pavement slabs joined by a dowelled contraction joint was considered. The model was loaded using a loading plate connected to an electronically controlled fatigue loading actuator. Electronic deflection measuring devices were used to measure deflection. All tested sealant materials (silicone, polyurethane, polysulfide, rubberized asphalt, and preformed sealant) performed excellently in the shear fatigue test. No visible failures among the evaluated specimens were noticed.

The penetration test was performed by allowing a 150 gram-weight moving cone to penetrate through the sealant at different temperatures. Penetration value is usually obtained at five seconds and expressed in 10 times the measured penetration in millimeters. Some results are presented in Figure 2.9 and show that rubberized asphalt has the highest penetration, followed by silicone. Polyurethane and polysulfide penetrations are approximately equal, and the lowest.

A two year-aging study was conducted by Sandberg (1991) on four sealants: a low modulus silicone, a medium-modulus silicone, a one-part polyurethane, and a two-part polyurethane. Specimens were prepared in accordance with ASTM C 719-86, by installing 0.5 x 0.5 x 2 in. of sealant between two-1 x 1 x 3 in. granite cubes. Gunning of the sealant was done using especially constructed jigs. Specimens were

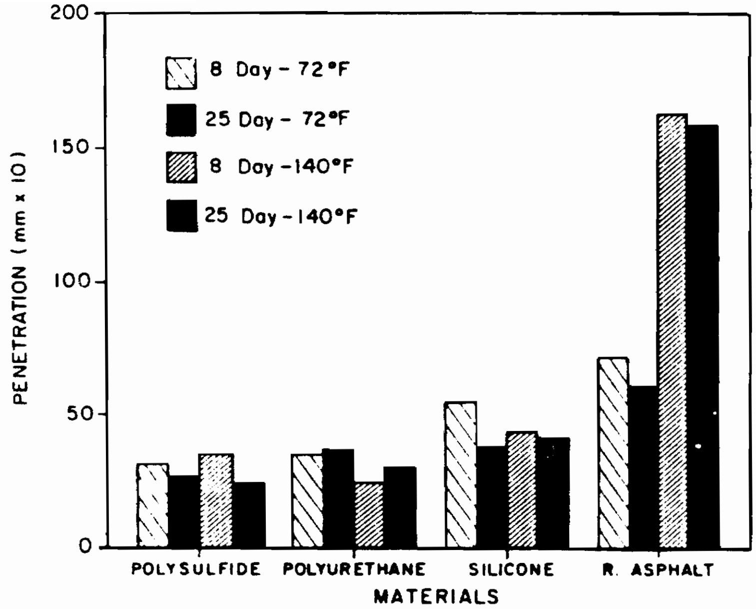


Fig. 2.9 Penetration Test Results (Collins *et al.*, 1986)

allowed to cure for approximately six weeks prior to any testing or weathering aging exposure. Six different aging exposures were evaluated.

The five aging exposures were ordinary room conditions; outdoors in Texas, Michigan, and Hawaii; and aging in a QUV accelerated weathering unit. Room and outdoor-aged specimens were tested at inception, 6, 12, and 24 month intervals. The QUV-aged specimens were tested at inception, 500, 1000, and 5,000 hours. In the post-aging tests, specimens were tested for 20 displacement cycles at the sealant's rated movement capacity and elongated to failure. Reported data include nominal stresses at 25 percent, 50 percent and 100 percent elongation, ultimate tensile strength, and corresponding elongation. Additionally, observations were made of surface cracking and dirt pickup. The final basis for evaluation was the change in appearance due to surface degradation, dirt pickup, and mildew. The results of the investigation showed a general drop in ultimate displacement with time for the four types of sealants under different exposure conditions.

The overall evaluation of low modulus silicone showed the highest qualification factor of safety (or QFS which is equal to lower bound of ultimate elongation divided by allowable elongation), twice the rated movement capacity, no visible aging indications, and stable mechanical properties. Silicone sealant was clearly the best of the four sealants. Medium-modulus silicone sealant had the third best QFS, 100 percent ultimate elongation, and was quite stable with respect to time and aging. It showed no visible evidence of degradation other than dirt pickup during outdoor exposure. Two-part urethane had the second highest QFS. However, in outdoor and QUV exposure, this sealant showed obvious evidence of rapid degradation in the form of deep surface cracking prior to any displacement cycling. One- part urethane sealant did not appear to be capable of performing at ±25 percent elongation for any length of time; it was too stiff. A number of specimens cracked cohesively near the substrate without any joint movement.

Laboratory studies were performed by Jones, *et al.* (1973) involving environmental cycling, heat-aging, ozone resistance, oil resistance, tension, hardness, and water tightness. A number of thermal cycles on 6 x 1.4 x 1.4 in. sealant specimens were used to simulate field conditions, with force deflection tests performed on the seal before and after the cycling to determine permanent set and loss in strength. A significant reduction in sealant strength after exposure to environmental cycling, heat aging, or field exposure was observed. The heat-aged test, where specimens aged in an oven for 70 hours at 212 °F, followed by a 24-hour recovery period, produced the greatest experimental effect on the sealants. The results appeared to correlate with the loss of strength of sealant taken from the pilot field test.

Laboratory evaluation of the sealants used in sawed joints was conducted by the Portland Cement Association (PCA) laboratories (Kuenning, 1962). The testing apparatus consisted of two beds: one was fixed and the other was movable. Three 2.5 x 4 x 16 in. concrete blocks were tested at a time. The blocks had sawed joints, which were in most cases 0.125-in. wide and 2-in. deep. The casted blocks contained tapered openings in the top connected with slots in the bottom. The blocks were fitted over cross-bars of the testing machine. The joint at the center of the block was sawed and sealed with asphaltic and coal tar base materials which were wire brushed before assembling, in accordance with a common recommended practice for field applications.

The machine may be operated either in laboratory air at 73 °F or in a walk-in freezer at 0 °F. An elongation rate of 0.003 in. per hour was used because it represents a travel rate per hour of 25 percent of the initial joint width.

Different types of sealants were opened to 100 percent of initial width at 0 °F, as an initial test. Joints were opened and closed at 73 °F in cycles and increased successively in magnitude by 20 percent increments. The cycles sometimes ranged from 60 to 100 percent increase in joint opening, and sometimes from 60 to 160 percent. Sealants which survived these tests at 73 °F were subjected to additional cycling at 0 °F. Asphalt asbestos-filled, silicone rubber, asphalt rubber, polyurethane foam (red two-component sealant), and polysulfide rubber (gray two-component sealant) showed adhesion failure, while polyurethane, and polysulfide rubber (black two-component sealant) showed cohesion failure. The best sealant performance was the asphalt rubber which resisted opening up to 140 percent of its initial width, while the worst was epoxy and urethane sealant performance which failed at 60 percent opening of initial widths.

The relationship between deformability of sealants and initial joint width was also investigated. Joints of 0.125, 0.25, 0.38, and 0.5 in. wide were sealed to the full depth with a rubber-asphalt, and to a depth of only 0.5 in. The specimens were then tested to failure in a single cycle, opening the joint at a rate of 0.125 in. per hour at 0 °F. The test results showed that an increase in the joint widths at failure with increasing initial joint width is more significant for polysulfide than for rubber asphalt sealant.

Thronton (1978) investigated the silicone by weatherometer, bond, and incorporating of debris into incurred material. A Dow 790 silicone was tested in weatherometer over 5300 hours, and the hardness did not change appreciably. No visible deterioration other than superficial staining from the metal was evident. In bond testing, Thronton noticed that greater extension was required for failure, which was usually cohesive when cured insufficiently. However, cured specimens were stronger, showed less extension, and the failure was usually adhesive.

The incorporating of debris into uncured material was tested by preparing specimens cured for different duration and temperatures in eight-oz. ointment cups having a diameter of 3 in. The silicone was covered with 1 in. of moist concrete sand and the amount of sand sticking to the 3 in. diameter surface was weighed. It was found that if the material was properly recessed, contamination before cure would not be a problem and traffic could be allowed on a resealed road after about an hour.

2.3 PRESEALED JOINT INSPECTION

Studies have been conducted to evaluate the performance of presealed joints in different climates and locations. Collins *et al.* (1986) conducted field studies on joint sealants. Their studies included 12 joints sealed with Dow Corning's silicone 888 which was observed eight years after sealing. The results indicated excellent bonding, with a total failure of only five percent. No extraction, intrusion, or incompressible embedment was noticed. However, bond failure was observed in the portion of the sealant used to fill spalled areas. In general, sealant performance was reported as excellent.

Another 12 test joints, located in Dallas, Texas, sealed with General Electric's primerless SCS 4400 and low modulus silicone, were evaluated. Observations were made eight months and 14 months after sealing. During the first evaluation, adhesive failure was observed along the length of one joint sealed by SCS 4400. A cohesive failure in another joint was noted during the second inspection sealed by SCS 4400 also.

Another inspection was conducted in Oklahoma City, Oklahoma. All joints, sealed with Dow Corning's silicone 888, were found to be in excellent condition with no visible failures of any type after six months. Electric primed 2342 silicone performed well over a period of two years except for some bubbling in the joint. Emulsified latex showed a small amount of sealant remained in the joints after 13 years.

Seven joints sealed with rubberized asphalt were inspected at one and two years after sealing (Collins, *et al.*, 1986). The first year observations showed that 40 percent of the sealant had experienced adhesive failures. Incompressible materials were embedded in up to 10 percent of the joint lengths. Continuing deterioration was observed during the second year inspection. Adhesive failure had increased only slightly, but the sealant had experienced serious intrusion failures. In addition sealant had been extruded and flattened onto the pavement in several places. Incompressible embedment had increased, and up to 60 percent of some joint lengths contained embedded incompressible material. The performance of that sealant was rated as very poor.

Another study of joints sealed with rubberized asphalt was conducted in Lavedo, Texas six years after joint sealing. The sealant had extruded onto the pavement surface along the entire length of most of the joints. The sealant that remained in the joint had experienced adhesion or cohesion failure in many places. Also, embedment was present in all joints. Overall, the joint sealant was observed to be in poor condition.

2.4 FIELD EVALUATION OF NEWLY SEALED JOINTS

Studies have been performed on several types of sealant installed in different highway sections and monitored at various time intervals.

Collins *et al.* (1986) studied the performance of polysulfide and silicone sealant installed in newly constructed pavement joints near Dallas, Texas. The joints were water blasted, dried, and backer rods were installed at the proper depth. A mixture of two-component polysulfide was poured into the joint. The joints were filled up to 0.25 in.

from the surface (0.38-in. depth). The silicone sealant was placed in the joints using a pump and leveled with the pavement surface. Both sealants performed satisfactorily with no observed failures after four months.

Wolters (1974) evaluated five liquid sealants and seven preformed sealants used in transverse joints. Each sealant-type was installed in at least 10 transverse joints. Periodic observations were made through the service life of each sealant. After one winter, none of the liquid sealants had shown any evidence of failure, but one out of seven preformed compression sealants exhibited 42 percent failure. After two winters, the liquid sealants where still performing satisfactorily with no significant failures, while four of the preformed sealant types showed failure. The failure of the preformed sealant, which began to fail during the first winter, had increased from 42 to 50 percent and the other three preformed sealant types showed failure ranged from 1 to 20 percent. Failure in the 12 investigated sealants ranged from one to 56 percent by the third winter.

Jones *et al.* (1973) conducted field evaluations of sawed joints. The joints were constructed with different cross-section geometry, material properties, and seal width. None of the sealants performed entirely satisfactorily after two years service.

Anderson (1987) evaluated Dow Corning silicone 888, Crafco Roadsaver 231, and Crafco Roadsaver 221 installed in a specially rehabilitated section. Existing joints were sawed to a width of 1 in. and a depth of 2 in. for the Dow Corning Silicone 888, and a width of 1 in. and a depth of 1.125 in. for the two Crafco Sealants. All old sealants were removed, and the area was cleaned to provide a new face on each side of the joint; reservoir sizes were recommended by the sealant suppliers. Joints were monitored for three years to determine their survival life and cost-effectiveness. A rating factor from one to five was used with one as very poor and five as excellent. All sealants performed exceptionally well over two years.

The performance of low modulus Dow Corning silicone 888 sealants, used in highway joints under various climate and pavement conditions, was presented by Zimmer *et al.* (1984). Several tests were developed to identify and measure adhesive and cohesive failures. The end of a thin 0.75-in. wide metal ruler was pushed into the sealant at intervals of three to six in. along the joint. Cohesive failure was apparent when the ruler was pushed into the sealant. Twisting the ruler pulled the sealant away from the joint wall and severely tested the bond. Any adhesive failure was noted and measured. Inspection of 14 highway sealant installation projects demonstrated the importance of two factors: joint wall cleaning and installation techniques. The inspected joints included four cleaning techniques: air blasting only, wire brushing followed by air blasting, water blasting followed by air blasting, and sand blasting followed by air blasting. Sand blasting was more effective than the other methods. Also removing old sealant residue from joint walls was found to be very important in resealing projects.

Installation techniques are also very important. Sealants should never be applied to a wet or damp joint. After the sealant is pumped into the joint, it must be tooled to push it against the joint walls. The fewest failures were observed at joints where the width of the tooling foot matched the joint width or where the sealant was carefully tooled by hand.

Joint design and sealant shape factors (joint width to joint depth ratio) are also important, especially when joint cleaning and installation techniques are marginal. The correct shape factor reduces stresses in the sealant and increases its service life. Sealants with shape factors of less than 0.5 in. and greater than 2.0 in. were performing well after five years.

Climate and age tended to have insignificant effects on the sealant modulus of elasticity. The modulus of elasticity varied from 20-25 psi at 7 days to 29 psi at 7 years.

Joint sealant evaluation has been performed by the Louisiana Department of Transportation (Kinchen *et al.*, 1977) on 13 products installed on a total of 56 bridge joints and 33 products installed on a total of 148 joints. The results show that the average sealant life for different sealant varies from zero to 76 months, with most failures being adhesive failures.

The Michigan Department of Transportation surveyed over 100 miles of concrete pavement in representative construction projects (Oehler and Bashore, 1972). Those surveys were initiated in 1965 to evaluate and compare the performance of preformed neoprene, hot pour rubber-asphalt, and two component elastomeric joint sealants. Hot pour rubber-asphalt was used in expansion joints and preformed neoprene in contraction joints. After five to 10 years of service, observation of hot poured asphalt performance showed that joint spalling was prevalent on a number of construction projects. Also, after 10 to 15 years of service, joint blowups occurred; an average of 0.7 percent of the joints had blowups at the end of 10 years, and 4.2 percent at the end of 15 years. Apparently, joint spalling was reduced on pavement sealed with neoprene seals due to the reduction in foreign material infiltration. A comparison of a few hot pour rubber-asphalt and preformed neoprene sealed joints on a construction project showed serious deterioration of the concrete under the hot pour rubber-asphalt sealant as contrasted with sound concrete under neoprene seal.

2.5 EXPERT OPINION ON SEALANT JOINT PERFORMANCE

Some researchers evaluated the joint performance by collecting data from different sources, sending questionnaires to different highway departments, and conducting interviews with engineers working in this area.

Data about the performance of various types of joint sealants like silicone, rubberized asphalt, and preformed sealant, were collected by Collins *et al.* (1986). Results of this collection showed that average silicone performance, as reported by seven states, was very good. Rubberized asphalt was reported as good. Also preformed sealant was reported as good, but it is expensive. The performance of polyurethane and polysulfide sealants was ranked as poor.

Cook and Lewis (1967) gathered opinions concerning joint practice and performance by sending questionnaires to state highway departments, turnpike authorities, and city and county highway authorities. Results of the opinions gathered showed that the most widely used sealants in rigid pavement highways are hot-poured bituminous, cold-poured bituminous, cold-poured elastomers, and preformed sealants. Also the most observed failures in joint sealants are extrusion of sealant on the surface, surface cracking, intrusion of dirt, and adhesion failure. The study concluded that more pavement studies were needed, a complete review of current specifications was necessary, and specifications on performance type and not material requirements were needed.

CHAPTER THREE

LABORATORY TESTING

3.1 FIXTURE DESIGN

To simulate field deflections of joint sealants, normal deflections due to temperature variations and shear deflections due to wheel loads, a special fixture was designed. A schematic diagram is presented in Figure 3.1, and detailed drawings are included in Appendix B. The specimen, which consists of sealant sandwiched between two 2 x 2 x 2 in. portland cement mortar cubes, is held by the fixture at different angles. By holding the specimen at a specific angle, the in-line deflection applied by the testing machine is transferred to applied normal and shear deflections on the sealant.

The two cubes of the specimen are held inside steel boxes by adjustable plates which secure the cubes and prevent specimen rotation. The fixture can be adjusted to different ratios of shear to normal deflections by changing the angle at which the specimen is held.

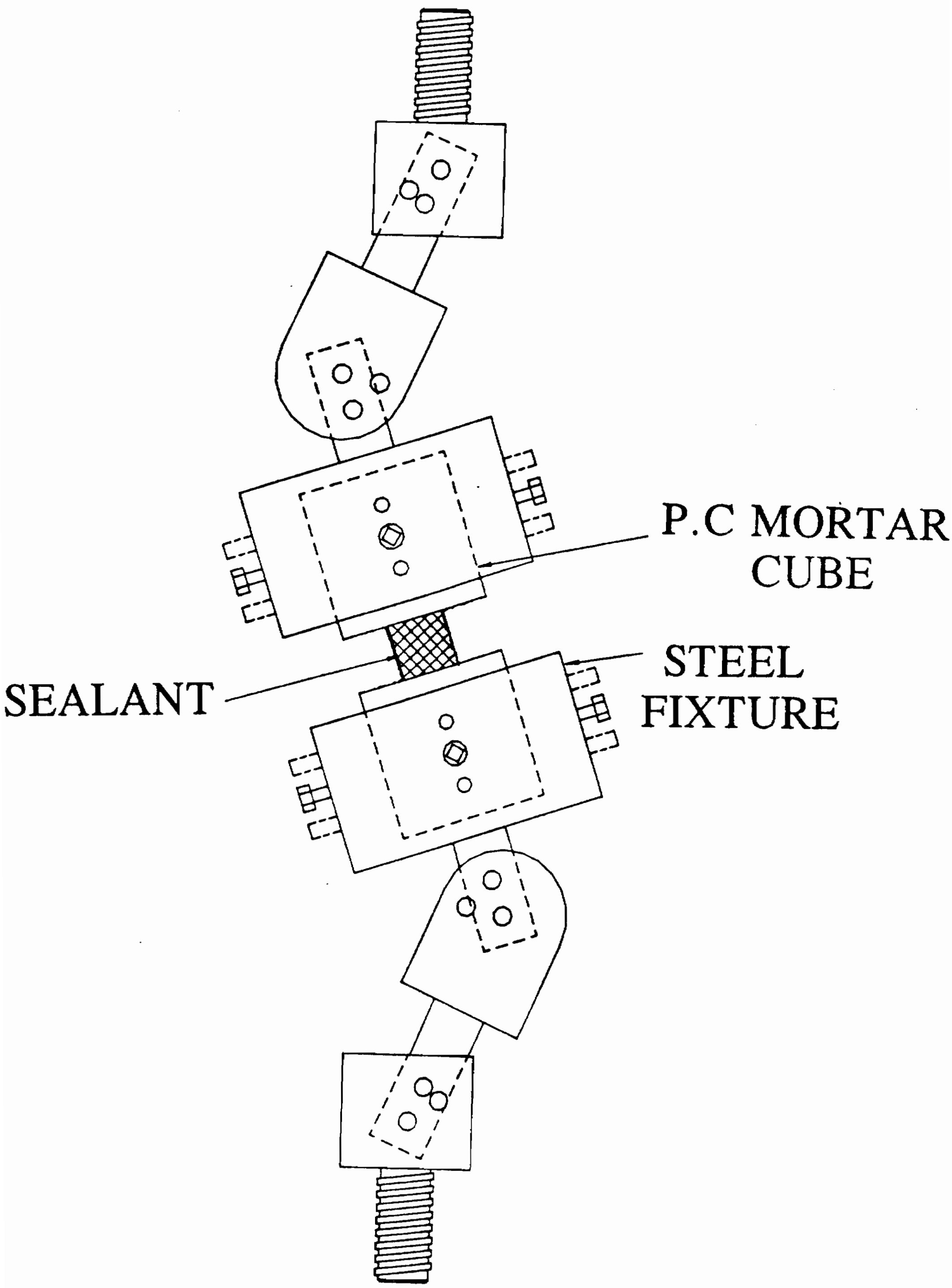


Fig 3.1 Schematic Diagram of Developed Fixture

3.2 TESTED SEALANTS

Three types of rigid pavement sealants were evaluated in this study: sealants A, B and C. Sealant A is a one part, cold applied material that readily extrudes over a wide temperature range. When it cures it is thought to produce a durable, flexible, low-modulus sealant. Because of its low-modulus characteristics and good extension/compression recovery (+100/-50 percent of original joint width), this sealant is easy to use with gunability at all temperatures. It also bonds to concrete without using a primer and is thought to have good weather resistance characteristics.

Sealant B is a one-component, cold-applied, self-leveling sealant that is thought to be readily extruded over a wide temperature range. The main expected features of this sealant are ease of application, good weatherability, and bondability to concrete without using a primer.

Sealant C is a one-part sealant, cold applied, that bonds to concrete by means of primer which is to be applied to the joint concrete surface one hour before joint sealing.

3.3 EXPERIMENTAL PROGRAM

3.3.1 Specimen Preparation

The test specimen consists of a sealant (0.75 x 0.75 x 2.0 in. or 0.25 x 0.25 x 2.0 in.) sandwiched between two 2 x 2 x 2 in. portland cement mortar cubes prepared in accordance with ASTM C109; mixture properties and compressive strength of the mortar cubes are given in Table 3.1.

The sealant shape was formed by placing a removable styrofoam forming section fixed between the mortar cubes and held in place with wrappings of duct tape. The sealant was then gunned between the styrofoam pieces and the mortar cubes. The duct tape and styrofoam was removed after five days, and the specimen was allowed to cure for an additional 25 days.

3.3.2 Research Approach

A testing program was developed to validate the testing fixture design. To accomplish this task, three types of sealant were evaluated, each at two different joint widths: 0.75 in. and 0.25 in. The specimens with 0.75-in. joint widths simulated, in the field, expansion and contraction

Table 3.1 Mortar Cubes Mixture Design and Properties

Ingredient	Wt/mix (g)
Weight of water	242.9
Weight of Ottawa sand	1375
Weight of Type I portland cement	500
Properties	
W/C ratio	0.49
28-day strength (Avg.)	4350 psi
28-day strength (STD)	71.48

joints between 60-ft. reinforced concrete slabs. The specimen with 0.25-in. joint width simulated joints in plain (unreinforced) concrete pavements. The normal slab length for plain concrete pavements is 15 ft. In addition, the influence of temperature and freezing and thawing cycles was evaluated, see Figure 3.2.

To simulate field condition, the specimens were tested under cyclic loading (deflection controlled). An Instron machine model 1331 was used to apply the deflection on the specimen through the designed fixture. The test fixture transfers the in-line deflection applied by the Instron machine into normal and shear deflections on the joint sealant. For the 0.75 joint width, a normal deflection used was 0.166 in., which corresponds to the maximum expansion and contraction of a 60-ft slab length due to a 50 °F temperature change. The shear deflection was 0.056 in., which simulates the maximum deflection caused by truck traffic. The normal to shear deflection ratio is controlled by the test fixture which can be adjusted to different normal to shear deflection ratios.

The cyclic deflection was applied at a rate of 25 Hz. For a specific test, the normal and shear deflections were held constant and the change in load was monitored. The joint sealant failure was considered as 20 percent cohesive and/or adhesive failure. If no failure was observed, deflection cycles were applied up to 500,000 cycles.

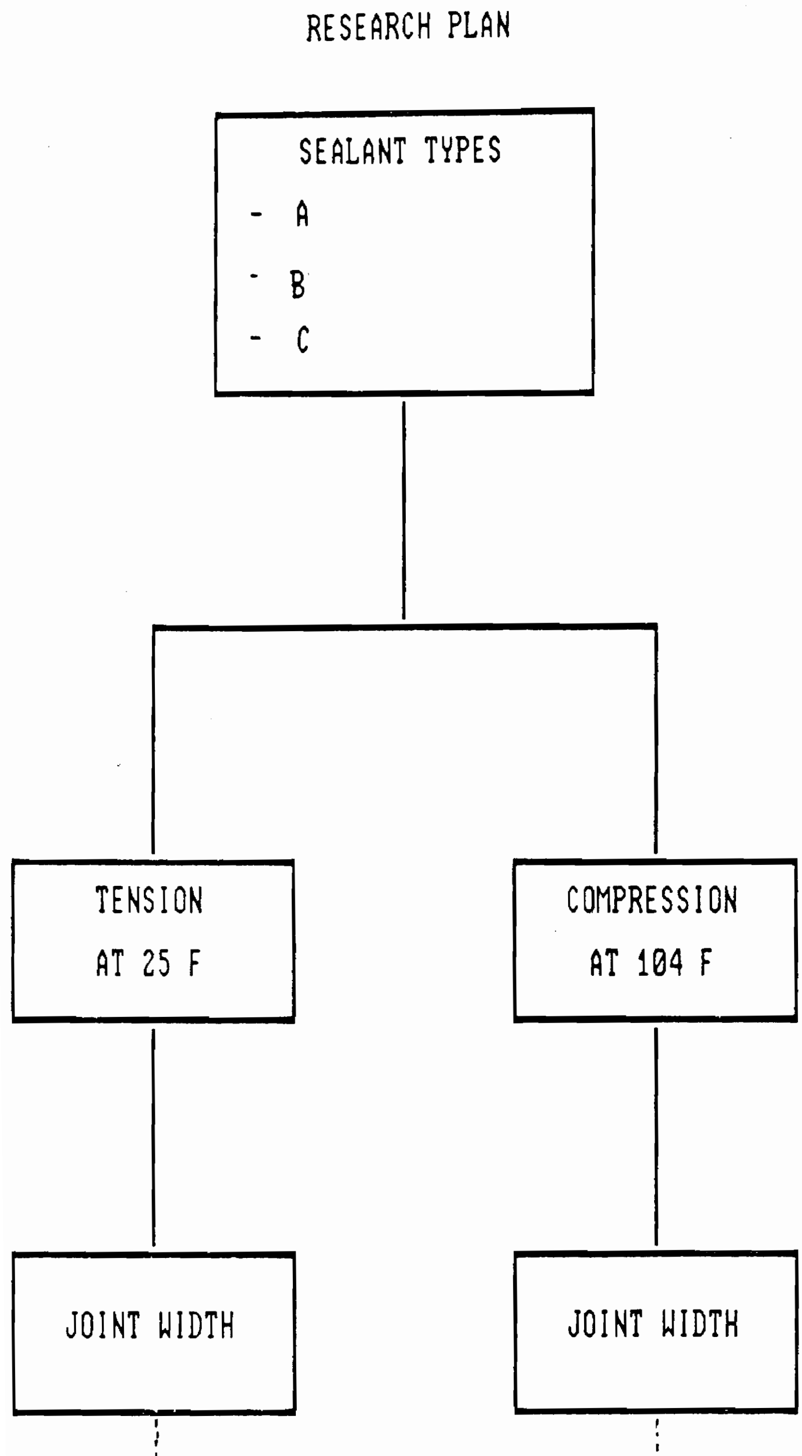


Fig 3.2 Research Approach

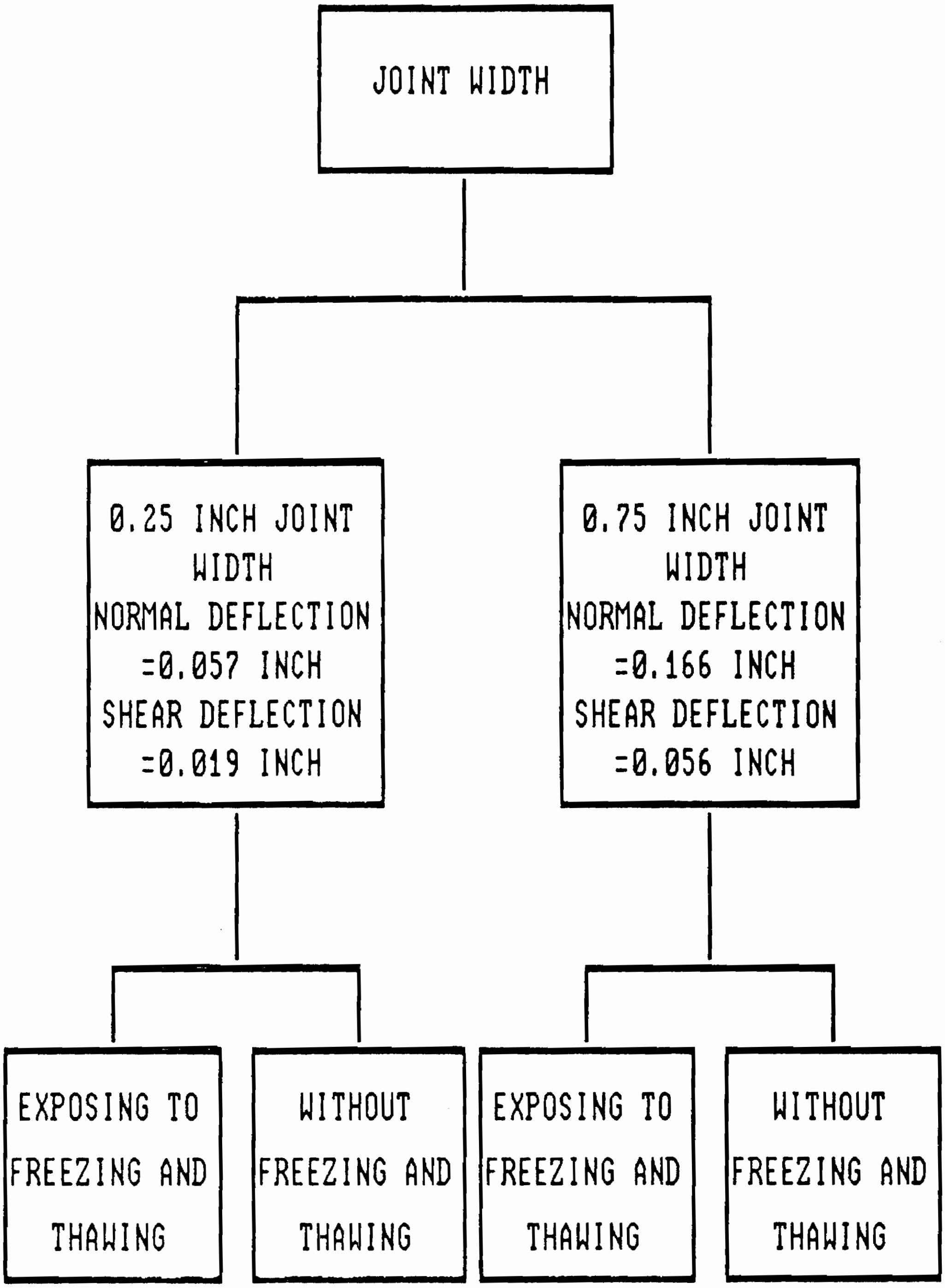


Fig 3.2 Research Approach (Continued)

Since the tension on joint sealant occurs during cold weather when the temperature is low and the slabs contract, the tension properties of joint sealant were evaluated at 25 °F. The compression of the joint sealant was evaluated at 104 °F. At that temperature, the slabs expand and compress the sealant in the joint.

An influence of weathering on joint sealant performance was evaluated by exposing the specimens to 50 cycles of freezing and thawing conditioning in accordance with ASTM standard C-666, rapid freezing and thawing, prior to being loaded. The test results of conditioned specimens were compared to those of unconditioned specimens.

3.3.3 **Testing Program**

A preliminary study was performed to choose a proper deflection frequency for use during testing. This preliminary study was performed on sealant A with a 0.75-in. joint width. Twelve specimens were tested either in compression or tension by using six different frequencies: 5, 10, 20, 25, 30, and 40 Hz at room temperature. The 25 Hz frequency was selected for use throughout the study due to the inaccuracy of load measurements at lower frequencies. This frequency is relatively high compared to traffic loading frequency.

After the deflection frequency had been chosen, sealant A with a 0.75-in. joint width was tested in compression; the specimen was heated in an oven at 104 °F for two hours. The specimen was placed in the fixture, and an in-line compression deflection equal to 0.175 in. was applied by the Instron machine at a frequency of 25 Hz producing a normal deflection of 0.166 in. and a shear deflection of 0.056 in. The force required to cause the deflection was monitored at the end of each 500 cycles, by means of an oscilloscope. Each test was run until failure or up to 500,000 cycles if failure did not occur. Sealant A with a 0.75-in. joint width was tested also under tension. The specimen was held at 25 °F for six hours prior to testing. An in-line deflection of 0.175 in. was applied at a frequency of 25 Hz in a tension mode and force was monitored at the end of each 500 cycles.

The same procedures were applied on sealant A with a joint width of 0.25 in. using an in-line deflection of 0.060 in. instead of 0.175 in.

After every 500 cycles, the sealant was visually inspected for any failure modes. The same testing sequence was repeated for both sealants B and C. All tests performed on the three sealants were repeated for conditioned specimens, exposed to freezing and thawing cycles. All tests were conducted in triplicates.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The main objective of this study was the development of a new method to evaluate pavement joint sealant which simulates field dimensional movements.

In order to achieve the other study objectives, assessment of sealant type and influence of joint width and environment, three types of joint sealant used in rigid pavement joints were evaluated in conditioned and unconditioned state. Cyclic loading (deflection controlled) was used to apply shear and normal deflections simultaneously, simulating field loading conditions, at 25 Hz.

Sealant test results, summarized in Table 4.1, were plotted as normal or shear stress versus number of cycles. The performances of the three types of sealant investigated under different loading and environmental conditions are presented in Figures 4.1 through 4.8, while the performance of the same sealants for different joint widths is presented in

Table 4.1 Sealant Test Results

Sealant Type	Type of Test	Joint width (in.)	Conditioned	Failed	Type of Failure	No of Cycles	Normal* Stress at Failure (psi)	Shear * Stress at Failure (psi)
A	Comp	0.75	No	Yes	Adhesive	15,000	28	9.33
			Yes	Yes	Adhesive	10,000	26.5	8.83
		0.25	No	No	-	500,000	36	12.00
			Yes	No	-	500,000	10.5	3.50
	Tension	0.75	No	Yes	Adhesive	7,500	26.5	8.83
			Yes	Yes	Adhesive	7,500	20	6.67
		0.25	No	No	-	500,000	24	8.00
			Yes	No	-	500,000	9	3.00
B	Comp	0.75	No	Yes	Cohesive	1,000	11	3.67
			Yes	Yes	Cohesive	1,000	10	3.33
		0.25	No	No	-	500,000	6	2.00
			Yes	No	-	500,000	6.5	2.17
	Tension	0.75	No	Yes	Cohesive	1,000	6	2.00
			Yes	Yes	Cohesive	1,000	6	2.00
		0.25	No	Yes	Cohesive	100,000	5	1.67
			Yes	No	-	500,000	5.5	1.83
C	Comp	0.75	No	No	-	500,000	28	9.33
			Yes	No	-	500,000	28	9.33
		0.25	No	No	-	500,000	50	16.67
			Yes	No	-	500,000	13	4.33
	Tension	0.75	No	No	-	500,000	32	10.67
			Yes	Yes	Adhesive	76,000	27	9.00
		0.25	No	No	-	500,000	61	20.33
			Yes	No	-	500,000	12	4.00

* If no failure was observed, stress is at 500,000 cycles, values are an average of three specimens.

Figures A.1 through A.12 (Appendix A) for both compression and tension tests. Figures A.12 through A.24 (Appendix A) present comparisons of sealant performance under compression and tension. Finally, the effect of freezing and thawing cycles on sealant performance is presented in Figures A.25 through A.36 (Appendix A).

4.2 SEALANT PERFORMANCE UNDER CONTROL CONDITIONS

The test results showed that sealant C at 0.75 in. joint width performed the best in tension and compression as compared to other sealants at their corresponding temperatures. Figure 4.1 illustrates that sealant C, when tested in compression was resisted 500,000 cycles of a normal deflection of 0.166 in. and a shear deflection of 0.056 in. without failure. Sealant A failed adhesively after 15,000 cycles, while sealant B failed cohesively after approximately 1,000 cycles.

The stress (both normal and shear) was the smallest for sealant B, while that for sealants A and C was approximately twice as great in the case of compression and almost five times in tension. In compression, the stress of sealant C was around 29 psi, which dropped to 28 psi at around 1,000 cycles and then remained constant to 500,000 cycles. Sealant A

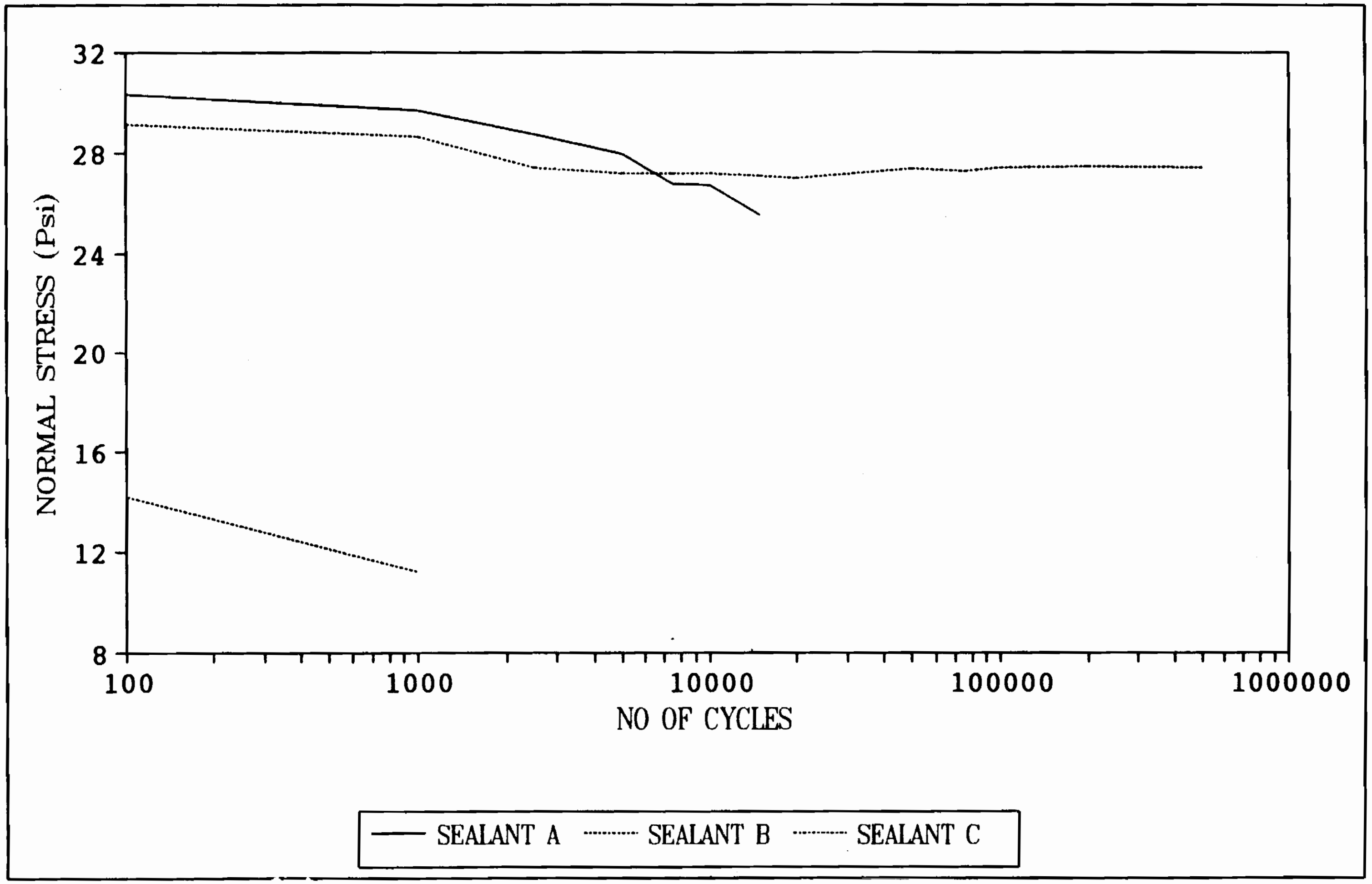


Fig. 4.1 Cyclic Loading Performance of Sealants in Compression at 0.75 in. Joint Width, Unconditioned

initial stress was about 30 psi which decreased to 29.5 psi at 1,000 cycles and then gradually decreased to 28 psi until it failed adhesively at 15,000 cycles. Sealant B initial stress was 14 psi and decreased to 11 psi in the first 1,000 cycles where it failed cohesively.

The superior performance of sealant C is due to its high stiffness, high recovery capability, and ultimate extension. Sealant A's adhesive failure after 15,000 cycles was due to the low bond between the sealant and the portland cement mortar cubes. Note that no primer was used with this sealant. Sealant B, on the other hand, failed cohesively after 1,000 cycles at a lower stress than the other two sealants. Failure was due to the low stiffness of sealant B and its low elongation capability related to insufficient curing. Although all specimens were cured for 30 days before testing, there is reason to believe that sealant B may have exceeded its shelf life.

The three sealants performed similarly in tension. As shown in Figure 4.2, sealant C performed as it did in compression; however, the stress was a little greater, 32 psi, and remained almost constant throughout the 500,000 cycles. Sealant A exhibited the same stress trend in tension as in compression except it failed at a lower number of cycles,

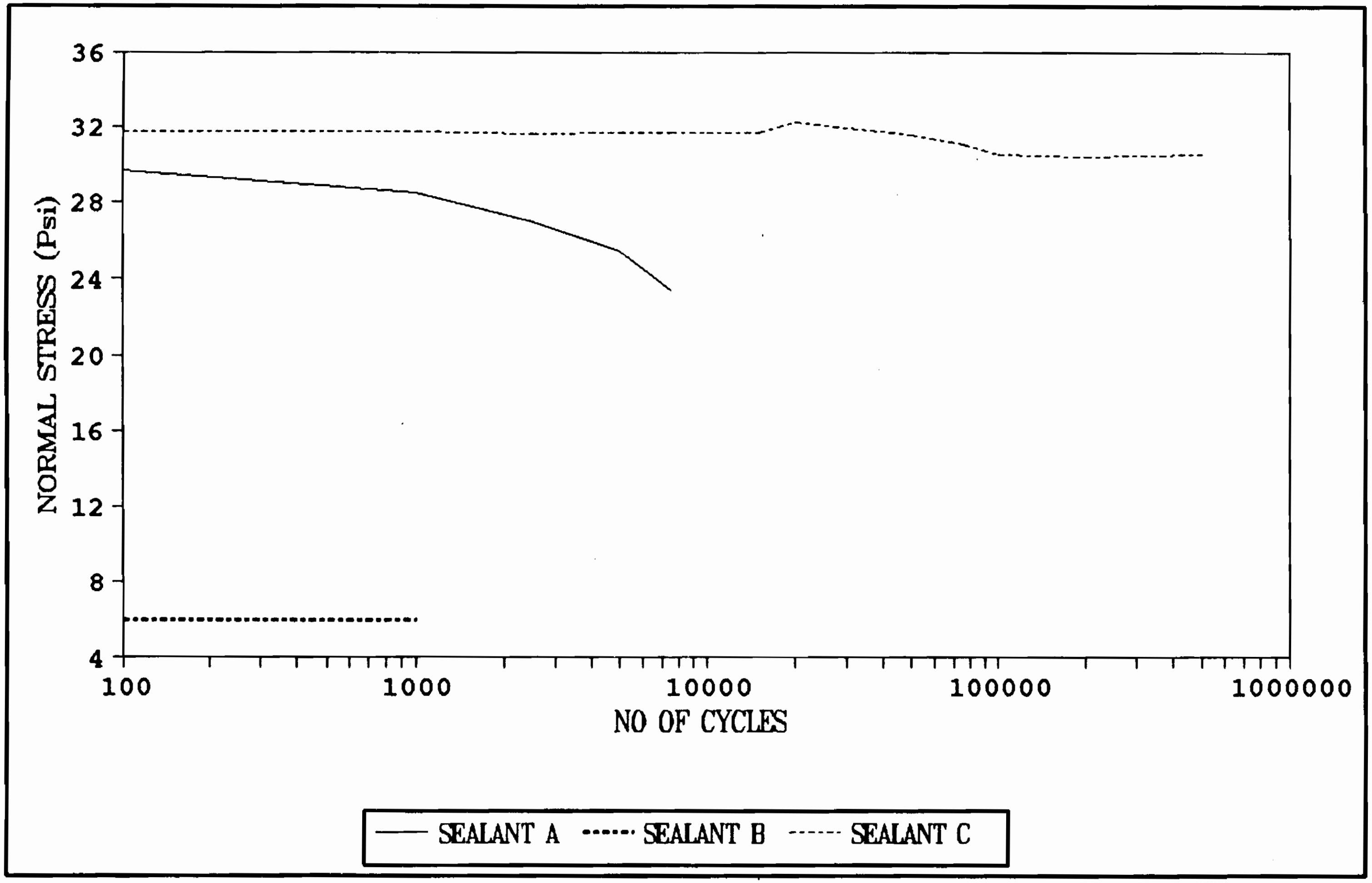


Fig. 4.2 Cyclic Loading Performance of Sealants in Tension at 0.75 in. Joint Width, Unconditioned

7,500 cycles, at a stress of 26.5 psi. The performance of sealant B was again poor. The sealant failed at about 1,000 cycles, and the stress remained constant throughout the 1,000 cycles at about 6 psi. The same types of failure noticed in compression occurred in tension. Sealant B failed cohesively, while sealant A failed adhesively.

At 0.25 joint width, the testing demonstrated that both sealants A and C performed very well in tension and compression, see Figures 4.3 and 4.4. Sealants A and C resisted 500,000 cycles of normal deflection of 0.057 in. and shear deflection of 0.019 in. without failure. In compression, sealant B resisted 500,000 cycles of deflection, while in tension it failed cohesively after 100,000 cycles. Sealant B, at 0.25 in. joint width, showed better curing than that at 0.75 in.; however it did not fully cure.

The normal stress was the highest for sealant C, approximately twice that of sealant A, and almost 10 times sealant B for both cases: compression and tension. In compression, the initial stress in sealant C was about 80 psi, which dropped gradually to 52 psi at 500,000 cycles. Sealant A's initial stress was about 36 psi and remained almost constant for the 500,000 cycles. Sealant B's initial stress was 10 psi and decreased gradually to 6 psi until 500,000

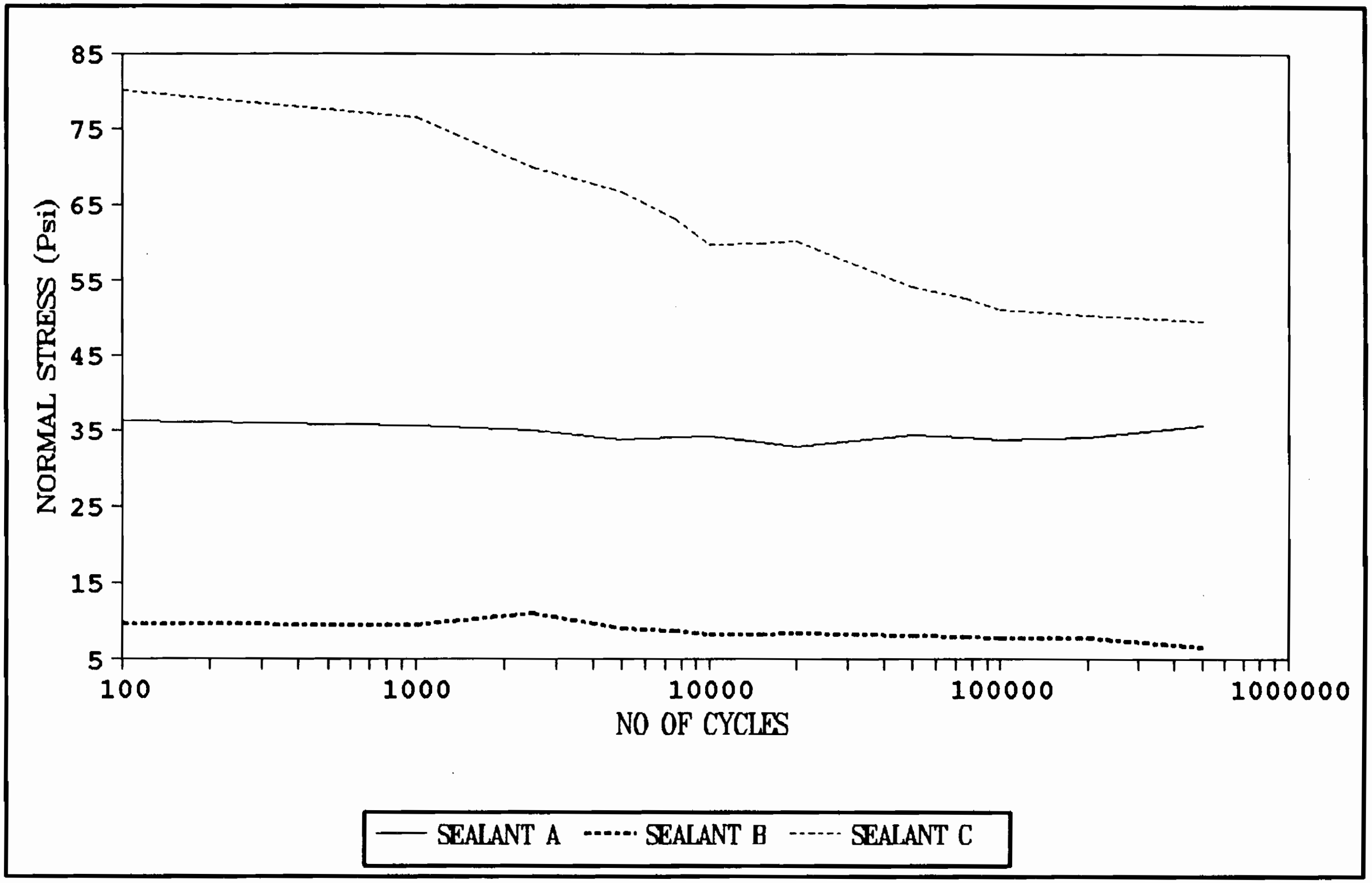


Fig. 4.3 Cyclic Loading Performance of Sealants in Compression at 0.25 in. Joint Width, Unconditioned

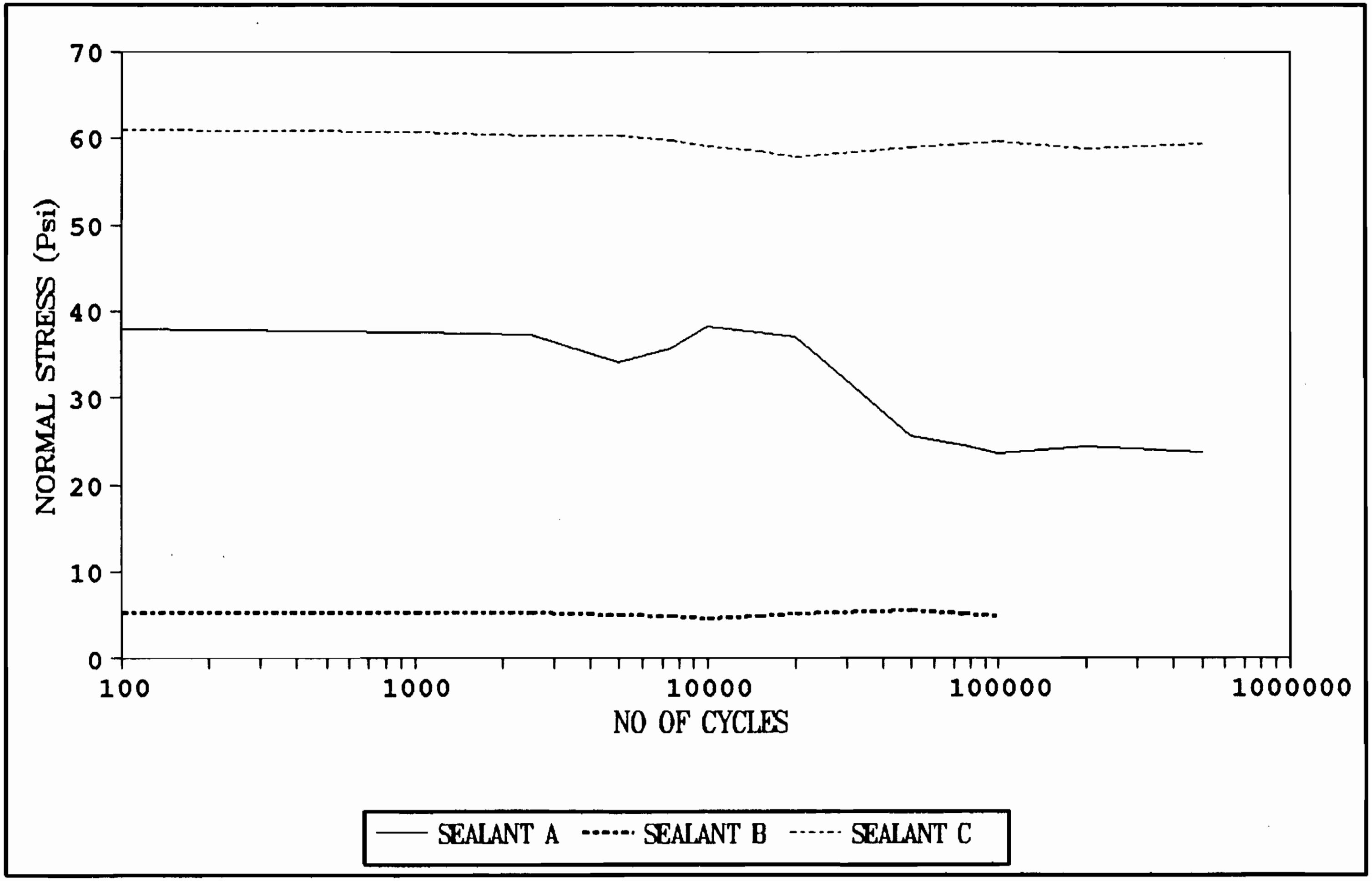


Fig. 4.4 Cyclic Loading Performance of Sealants in Tension at 0.25 in. Joint Width, Unconditioned

cycles. In tension, the initial stress in sealant C was 61 psi which remained almost constant for the 500,000 cycles. Sealant A's initial stress was 38 psi and remained constant for 25,000 cycles, then fluctuated between 24 and 40 psi to 500,000 cycles. On the other hand, sealant B had an initial stress of 5 psi and remained constant until 100,000 cycles when it failed cohesively. This performance may be explained by the fact that sealant C possesses higher stiffness, recovery capability, and extension compared to the other two sealants. Also, sealant A has a low bonding characteristic to the joint wall, while sealant B has a low stiffness.

After exposure to 50 cycles of freezing and thawing, sealant C's performance was also best compared to other sealants. For joint width 0.75 in. in compression, see Figure 4.5, sealant C was resisted 500,000 cycles without failure. Sealant A failed adhesively at about 10,000 cycles, while sealant B failed cohesively at about 1,000 cycles.

In tension at 0.75 in. joint width (Figure 4.6), conditioned sealant C also performed the best, but it failed adhesively after 76,000 cycles. Sealant A failed adhesively after 7,500 cycles, while sealant B failed cohesively at 1,000 cycles.

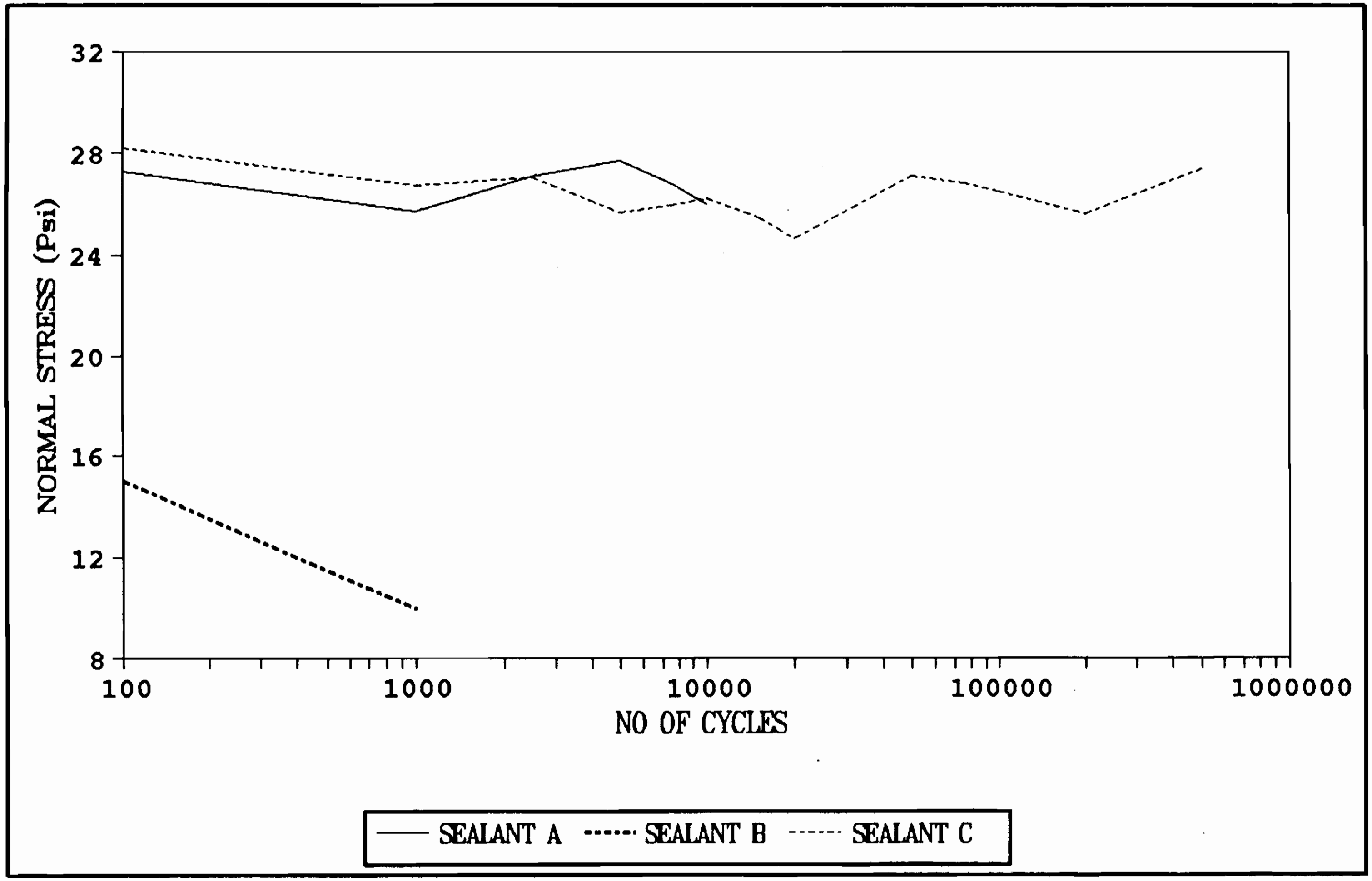


Fig. 4.5 Cyclic Loading Performance of Sealants in Compression at 0.75 in. Joint Width, Conditioned

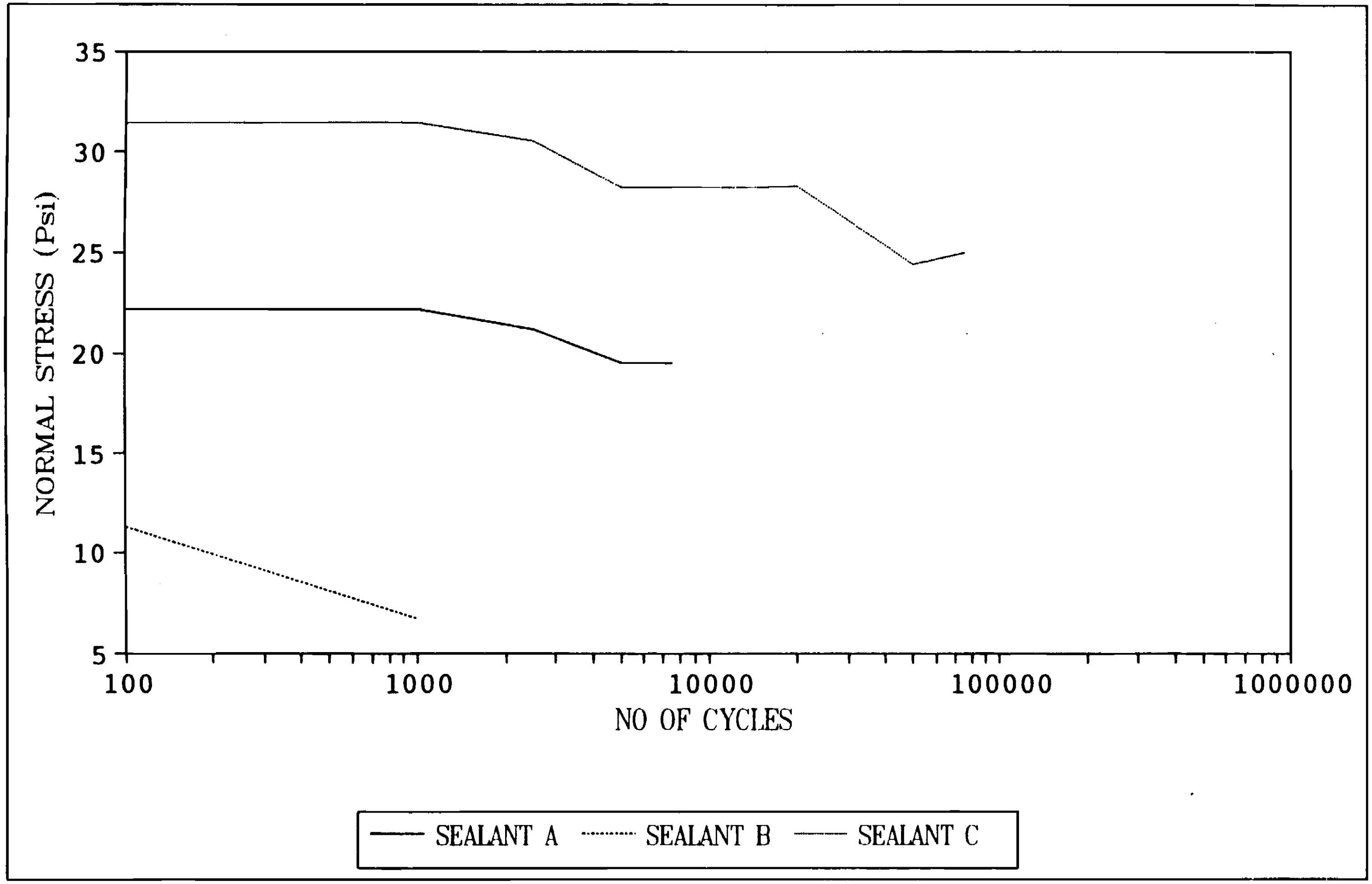


Fig. 4.6 Cyclic Loading Performance of Sealants in Tension at 0.75 in. Joint Width, Conditioned

The stress in compression was the least for sealant B, 10 psi, while that for sealant A and C was almost equal and approximately three times that for sealant B. While in tension sealant C's stress at failure, 27 psi, was five times greater than that of sealant B, 6 psi, and one and almost one half times greater than that of sealant A, 20 psi. Sealant B showed better curing after the exposure to freezing and thawing cycles.

In compression, the stress of sealant C fluctuated between 24.5 and 28 psi throughout the 500,000 cycles. Sealant A initial stress was 27 psi and gradually decreased to 25.5 psi at 1,000 cycles, then increased to 28 psi at 5,000 cycles, decreased to 26.5 psi at 10,000 when it failed adhesively. Sealant B's initial stress was 15 psi and decreased to 10 psi where it failed cohesively after 1,000 cycles.

In tension, sealant C's initial stress was 32 psi, and remained constant until 1,000 cycles and then decreased gradually to 27 psi before failing adhesively at 76,000 cycles. Sealant A initial stress of 22 psi decreased to 20 psi before it failed adhesively at 7,500 cycles. Sealant B initial stress of 12 psi decreased to about 6 psi when it failed cohesively at 1,000 cycles.

For the conditioned specimens at 0.25 in. joint width, all the sealants resisted 500,000 cycles, in compression and tension modes, as illustrated in Figures 4.7 and 4.8, respectively. These results tend to agree with the unconditioned specimen results. In both states, conditioned and unconditioned, sealants A and C possess high stiffness and ductility compared to sealant B.

4.3 DISCUSSION OF FACTORS AFFECTING SEALANT PERFORMANCE

4.3.1 Effect of Joint Width

The test results illustrate that the smaller the joint width, the more resistance to failure in both compression and tension. Sealant A resisted 500,000 cycles without failure at 0.25 in. joint width (see Figures A.1 and A.2 Appendix A), while at 0.75 in. joint width, the failure was observed at 15,000 cycles in compression and 7,500 cycles in tension. Sealant C also resisted 500,000 cycles without failure in both compression and tension at both joint widths, 0.25 in. and 0.75 in., as shown in Figures A.3 and A.4 (Appendix A). Sealant B failed at 1,000 cycles in both tension and compression at 0.75 in. joint width. At 0.25 in. joint width, it resisted 500,000 cycles in compression without failure but failed in tension at about 100,000 cycles.

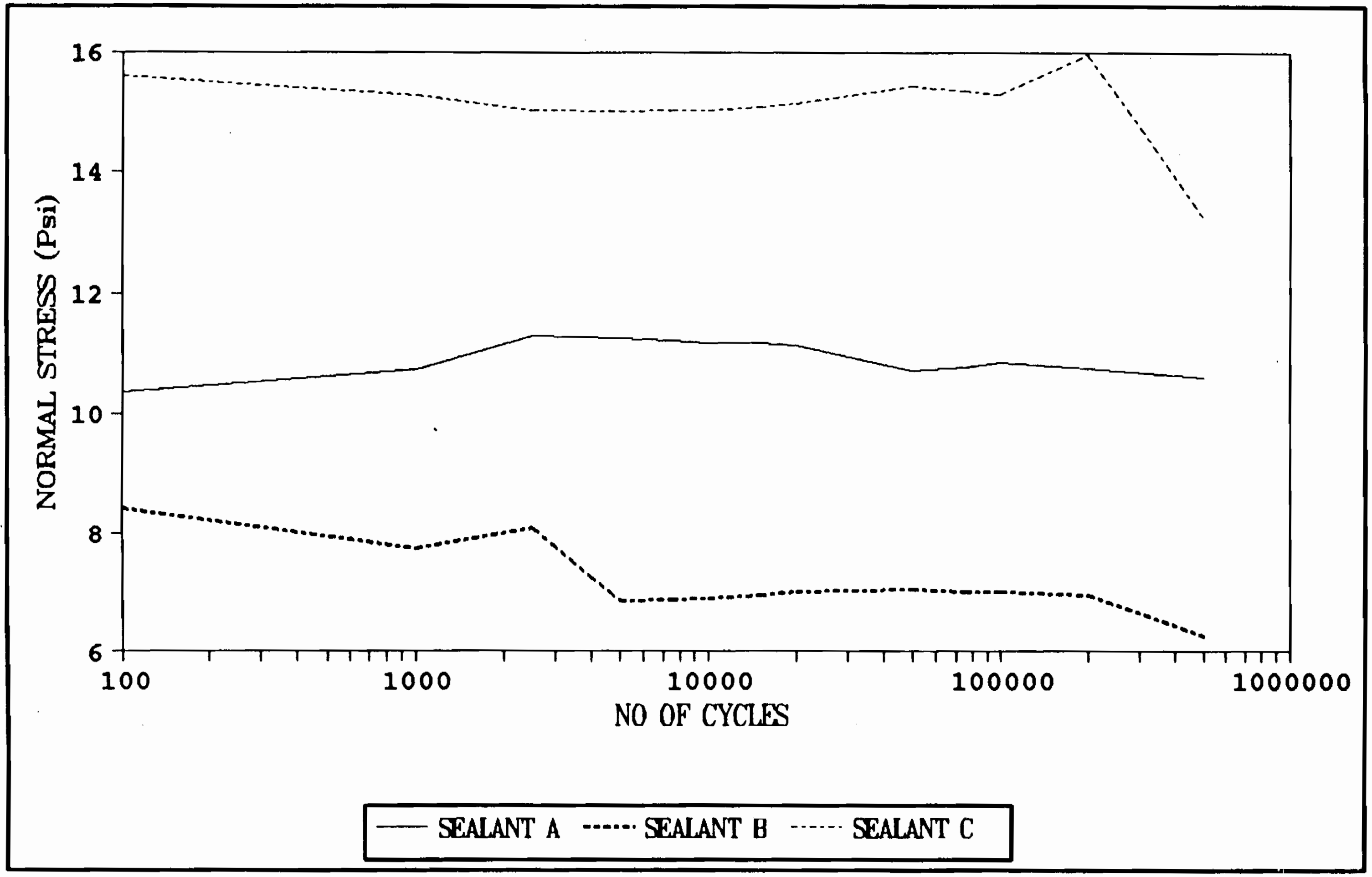


Fig. 4.7 Cyclic Loading Performance of Sealants in Compression at 0.25 in. Joint Width, Conditioned

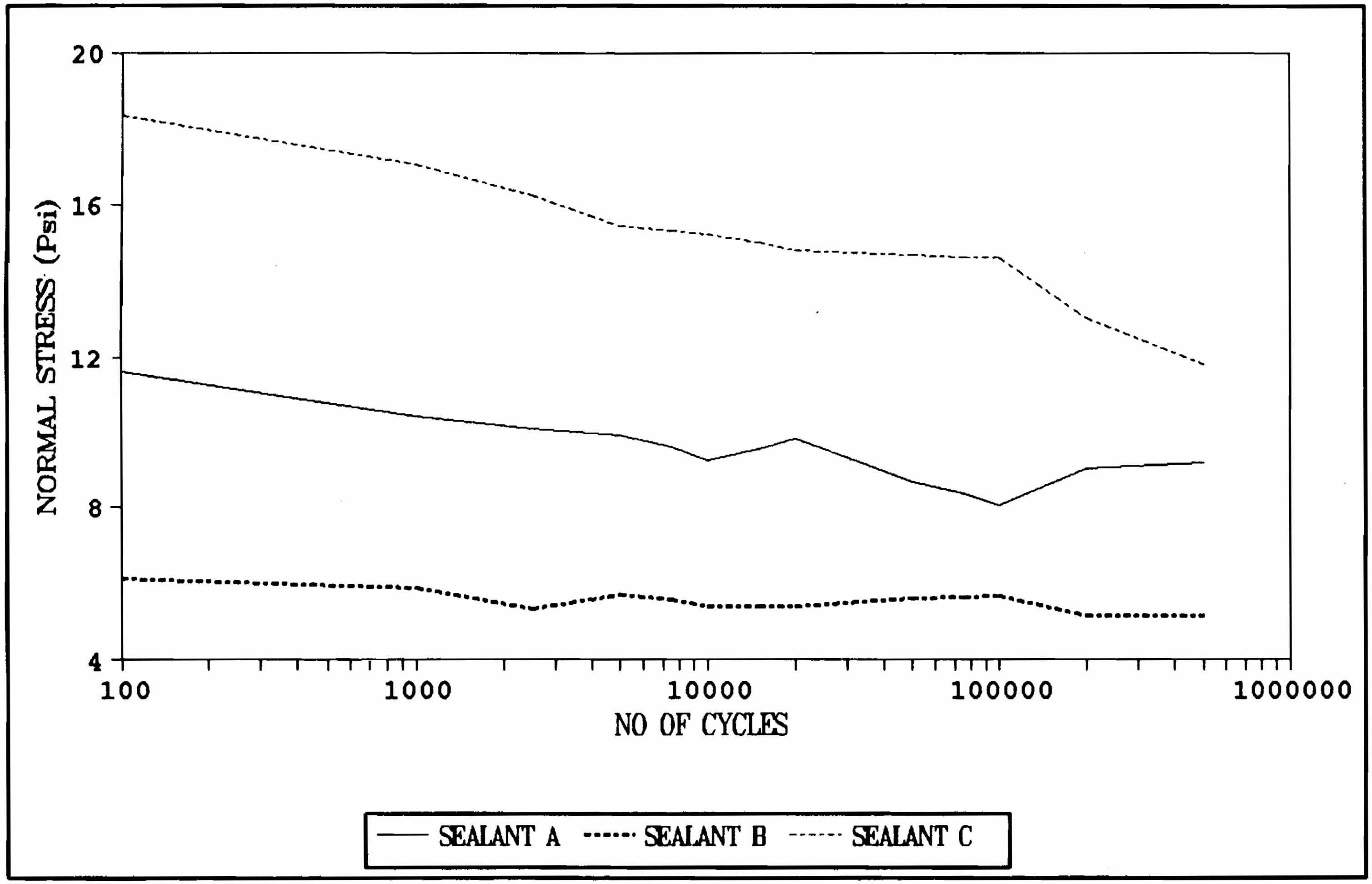


Fig. 4.8 Cyclic Loading Performance of Sealants in Tension at 0.25 in. Joint Width, Conditioned

The lower performance of the sealants at 0.75-in. joint width may be related to its large dimension which allowed less curing for the inner parts of the sealant as observed during the inspection of failed specimens. This resulted in less stiffness, dimensional recovery capability, and extension capability. Similar observations were noticed after the sealants were exposed to 50 cycles of freezing and thawing as presented below.

Similar failure resistance of sealants was observed after the specimens were exposed to freezing and thawing cycles. At 0.25-in. joint width, all the sealants in both compression and tension resisted 500,000 cycles without failure. At 0.75 in. joint width, sealant A failed in compression and tension at 15,000 and 7,500 cycles, respectively. Sealant C in compression, see Figure A.9 (Appendix A), resisted 500,000 cycles without failure, but in tension it failed after 76,000 cycles, Figure A.10 (Appendix A). Sealant B failed at 1,000 cycles in both compression and tension, Figures 11.A and 12.A (Appendix A).

4.3.2 SEALANT PERFORMANCE UNDER COMPRESSION/ TENSION

The test results reflect that, in general, the three evaluated sealants performed in compression better than in tension. Sealant A, at joint width 0.75 in., failed in compression at 15,000 cycles, while in tension it failed at 7,500 cycles, Figure A.13 (Appendix A). In compression and tension, at 0.25 in. joint width, sealant A was exposed to 500,000 cycles without failure, Figure A.14 (Appendix A). In compression and tension and at both joint widths, 0.25 in. and 0.75 in., sealant C was exposed to 500,000 cycles without failure, Figures A.15 and A.16 (Appendix A). Sealant B at 0.75-in. joint width showed failure at around 1,000 cycles in both compression and tension, Figure A.17 (Appendix A), while at 0.25-in. joint width it failed in tension at 100,000 cycles, and in compression it resisted 500,000 cycles without failure.

The greater resistance of the sealant in compression compared to that in tension for both conditioned and unconditioned states, is related to the sealant's properties; the sealant is stiffer and more viscous in compression when exposed to dynamic loading. Also, the increase in pressure on the contact surface, at compression, between the portland cement mortar and the sealant supports the chemical bonding at the sealant-joint wall interface.

4.3.3 EFFECT OF FREEZING AND THAWING CYCLES

The test results demonstrated that when sealant A and C were exposed to freezing and thawing cycles, the number of cycles needed to cause failure decreased as well as stress at failure. However the number of cycles and stress at failure for sealant B increased at 0.25-in. joint width, while it remained the same at 0.75-in. joint width.

Sealant A, unconditioned, at 0.75-in. joint width, see Figure A.25 (Appendix A), failed in compression at 15,000 cycles, while conditioned specimens failed at 10,000 cycles. In tension, see Figure A.26 (Appendix A), conditioned and unconditioned specimens failed at 7,500 cycles. At 0.25-in. joint width, sealant A in compression and tension, both conditioned and unconditioned specimens resisted 500,000 cycles without failure as shown in Figures A.27 and A.28 (Appendix A), respectively.

Sealant C at 0.75-in. joint width in compression, see Figure A.29 (Appendix A), both unconditioned and conditioned specimens resisted 500,000 cycles without failure. In tension, Figure A.30 (Appendix A), the unconditioned specimens resisted 500,000 cycles without failure, while the conditioned specimens failed at 76,000 cycles. At 0.25-in. joint width in compression, both conditioned and unconditioned specimens resisted 500,000 cycles without failure; similar results were observed in tension.

The reduction in the number of cycles for sealant A and C to cause failure is due to change in the sealants' properties (reduction in stiffness and ductility) and degradation of bonds within each sealant itself and between the sealants and portland cement mortar cubes caused by freezing and thawing cycles.

The behavior of conditioned sealant B is related to the increase in its stiffness and ductility after conditioning. The freezing and thawing cycles assisted the curing process of sealant B. Sealant B was not fully cured after 30 days but after conditioning, observations revealed a better curing state.

CHAPTER FIVE

SUMMARY, FINDINGS AND CONCLUSIONS

5.1 SUMMARY

A new method to evaluate the performance of sealants used in rigid pavement joints was developed. A specially designed fixture was used to apply cyclic normal and shear deflections on a sealant sandwiched between two-2 x 2 x 2 in. portland cement mortar cubes. The normal and shear deflections were applied simultaneously at a specific ratio controlled by the fixture setup. The new testing method simulates field conditions, where shear deflection on sealant is caused by vehicle loads, while the normal deformation (tension or compression) is caused by contraction or expansion due to temperature variation.

Three sealant types were evaluated using the newly developed setup. The effect of joint width was investigated using two joint widths (0.25 and 0.75 in.). The weathering effect on sealant performance was evaluated by exposing specimens to 50 cycles of rapid freezing and thawing prior to testing.

The sealant type used with a primer performed, in general, the best followed by a low modulus sealant. However, a self leveling sealant's performance was the least and showed uncompleted curing although it was cured for 30 days.

5.2 FINDINGS

The observed study findings are as follows:

1. In general, sealants performed better at 0.25 in. joint width.
2. Sealant C required special care in sealing joints due to its low initial viscosity, up to five days of curing. Those joints sealed with sealant C need to be covered for a period of five days after the sealant installation.
3. The test results demonstrate the ability of the tested sealants to resist simultaneously applied normal and shear deflections.

5.3 CONCLUSIONS

The main objective of this study was to develop a new testing technique to evaluate joint sealant performance under simultaneous cyclic shear and normal deflections. Other secondary objectives, involving the validation of the new testing technique, included the evaluation of three types of sealants, each evaluated at two different joint widths. The sealants were evaluated also for the effect of freezing and thawing cycles on joint sealant performance.

Based on the information presented, the following conclusions are made:

1. A new testing technique was developed to evaluate sealant performance under simultaneous cyclic shear and normal deflections.
2. Based on limited test results, sealant C's performance ranked highest, followed by sealant A and then sealant B. Sealant B poor performance is related to its incomplete cure, although it cured for 30 days.
3. Exposure to 50 cycles of freezing and thawing reduced the number of loading cycles to cause failure for sealant A and C. The three sealants experienced a higher rate of stress reduction over the number of loading cycles after conditioning. However, the number of loading cycles to cause failure for sealant B increased due to a better curing state after being exposed to freezing and thawing cycles.
4. Joint width greatly affects sealant performance. Small

joint widths, which means short pavement slabs, offer high sealant failure resistance.

5. Sealant performance in compression is better than in tension.

CHAPTER SIX

RECOMMENDATIONS FOR FURTHER STUDY

As indicated in the objective of this study the main objective was to develop a new testing technique to evaluate sealants. Thus, this study is considered the start of more comprehensive research project.

Based on the findings of this study, the following recommendations will be helpful to extend the research in the following areas:

1. Sealant performance should be evaluated using the developed fixture at different environmental conditions; using an environmental chamber with controlled temperature and humidity is recommended.
2. Sealant performance at different deflections and different normal to shear deflection ratios should be investigated.
3. Sealant should be evaluated at lower deflection frequencies. Using frequency simulating vehicular loading is recommended.
4. Incompressible material effects on sealant performance

should be evaluated.

5. Sealant exposed to cyclic deflection at the sealant-joint wall interface (shear) at a static normal deflection should be investigated.
6. More variability in the joint parameters (joint width and shape factor) should be studied.
7. A comprehensive investigation should be conducted to evaluate other sealants used in the field.
8. A comprehensive investigation of vertical and horizontal movements of pavement slabs should be conducted to better understand the factors influencing sealant performance.
9. A field performance study, long-term observation, of in-place sealant is recommended. Results from the field observations should be compared to laboratory results.
10. Further studies on the effect of hydraulic fluid, jet fuel, and deicing salts on joint sealant performance could lead to a better understanding of sealant durability.
11. Research on the above areas should lead to the development of a model that predicts the service life of joint sealants.

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APPENDIX A

STUDY RESULTS

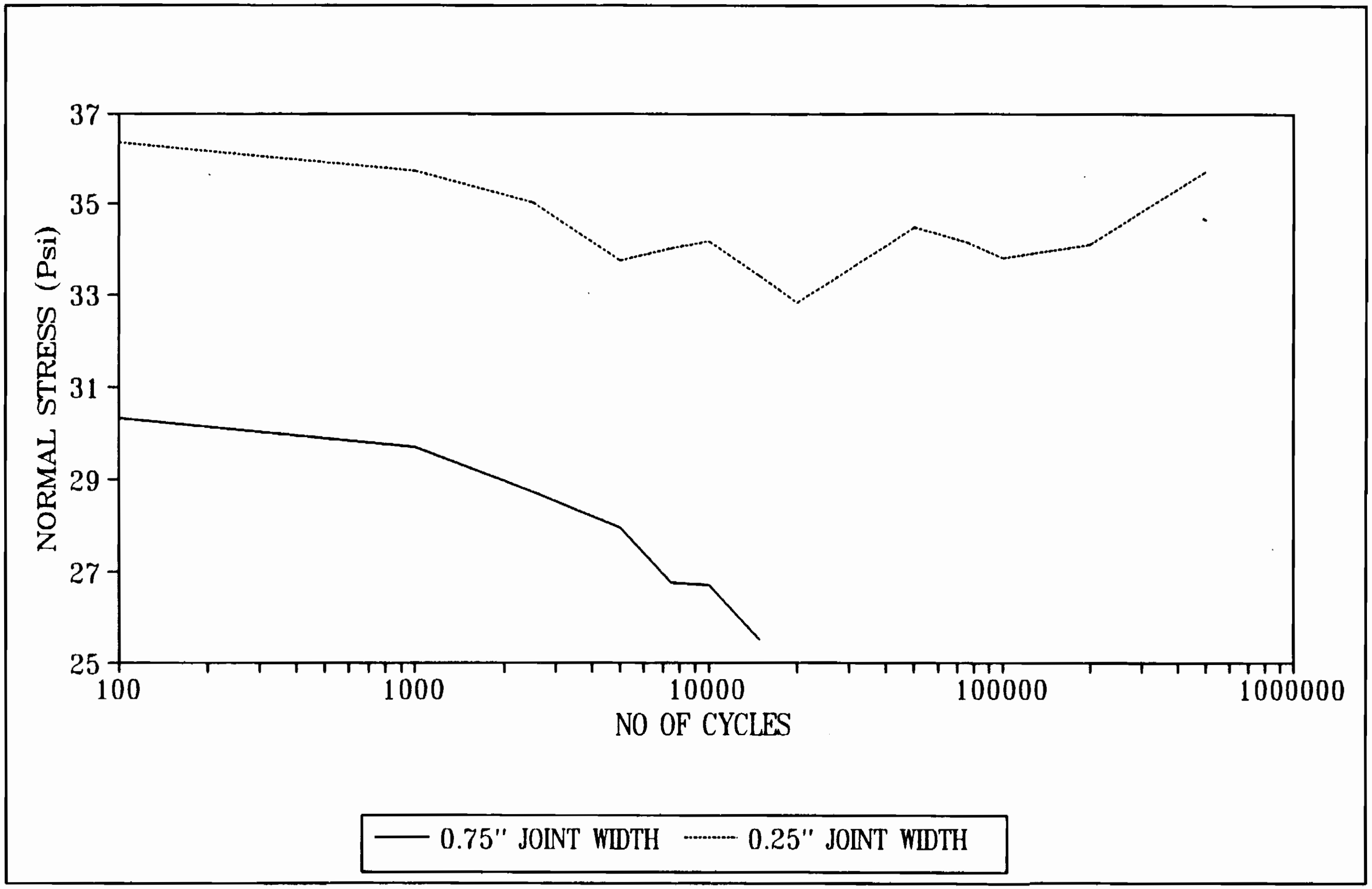


Fig. A.1 Effect of Joint Width on Sealant A Performance Under Compression, Unconditioned

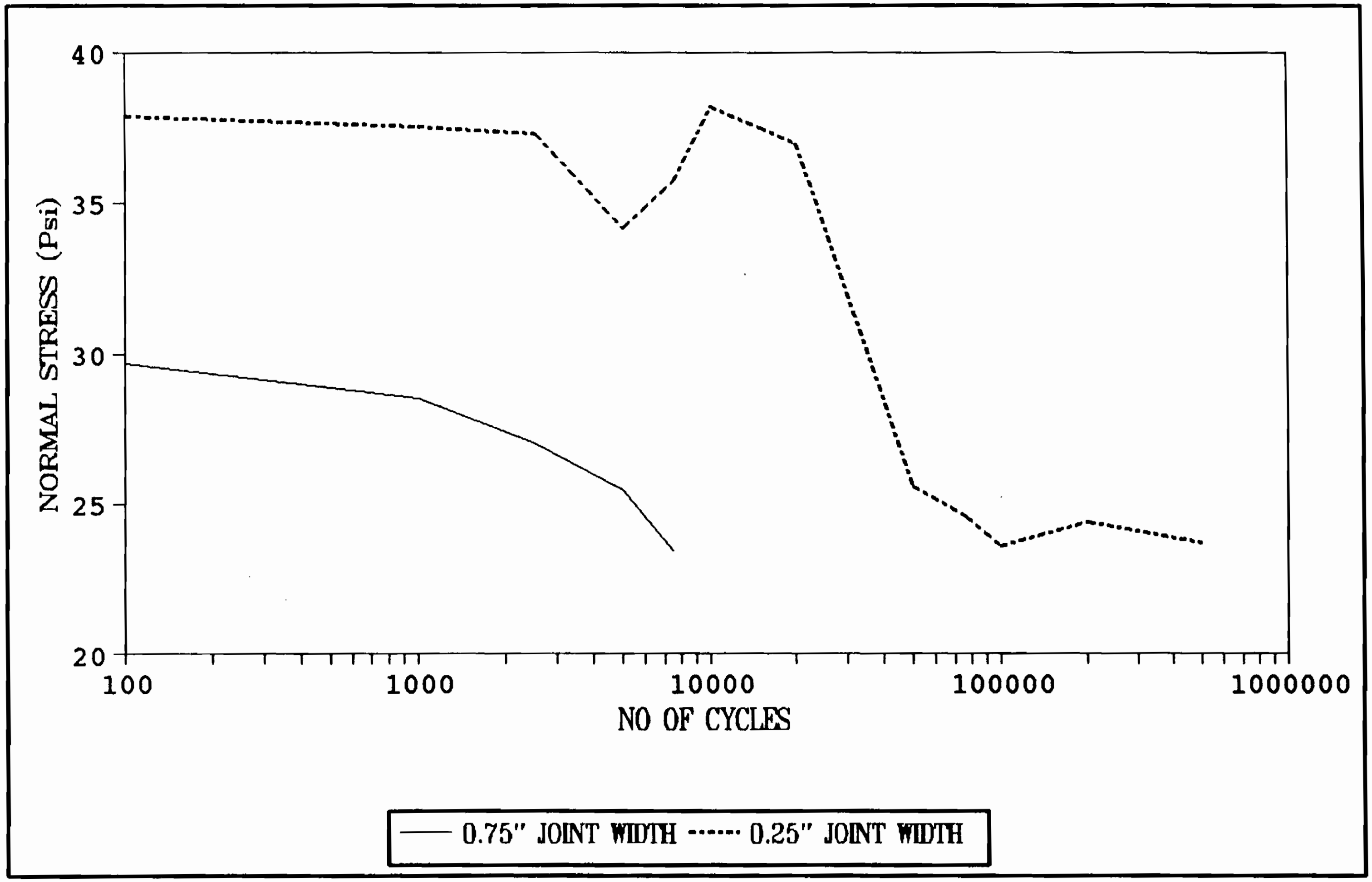


Fig. A.2 Effect of Joint Width on Sealant A Performance Under Tension, Unconditioned

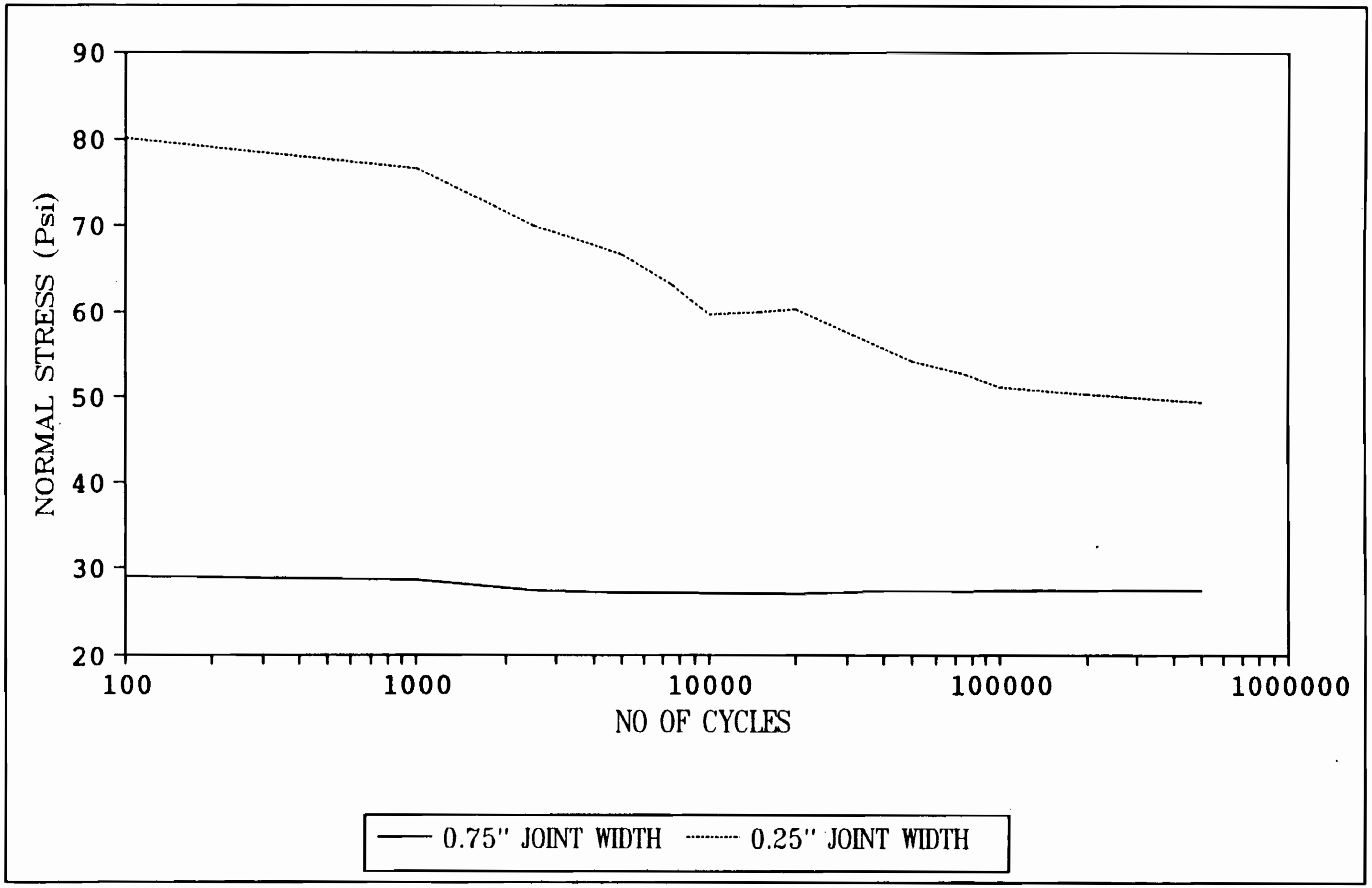


Fig. A.3 Effect of Joint Width on Sealant C Performance Under Compression, Unconditioned

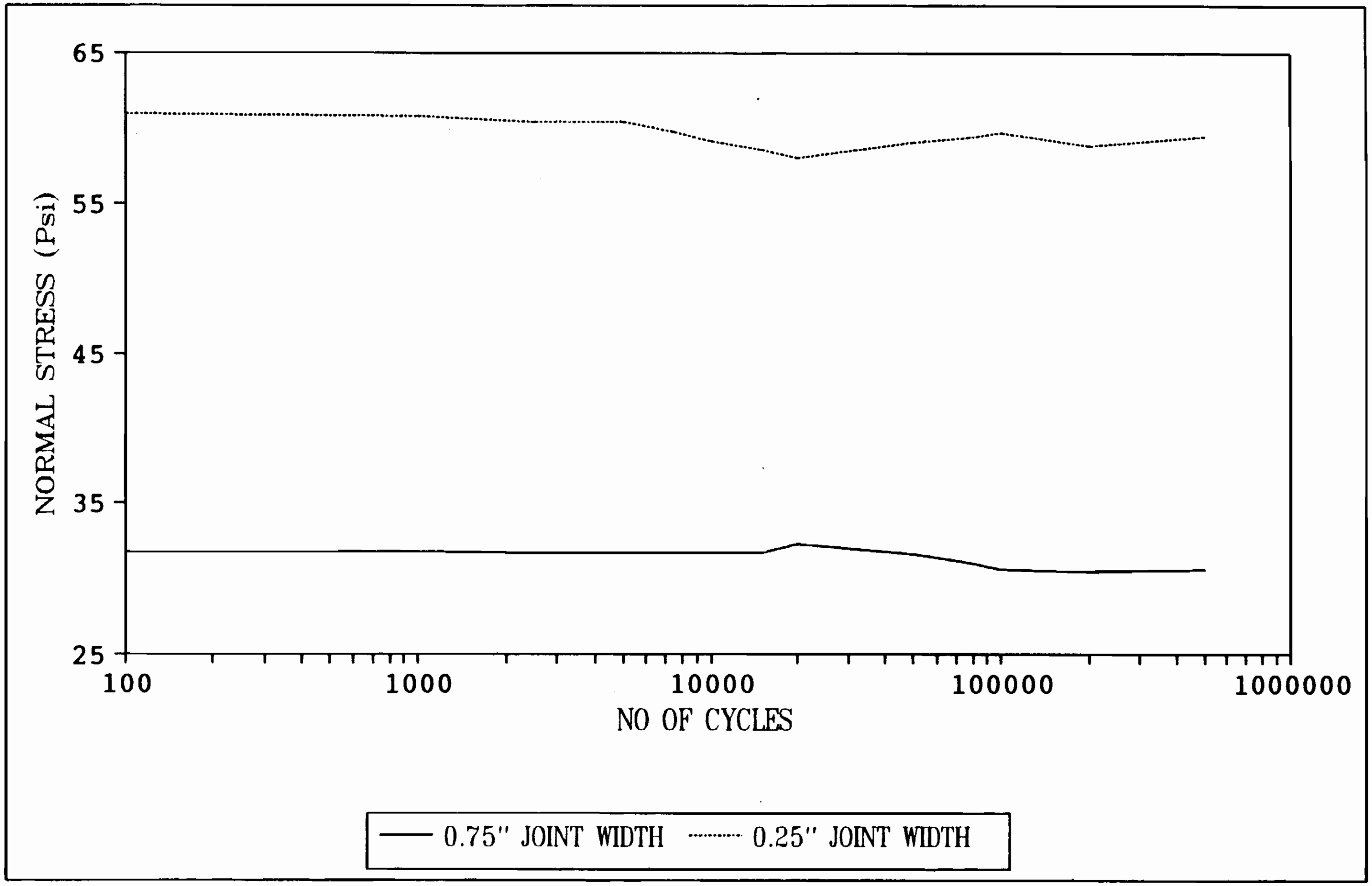


Fig. A.4 Effect of Joint Width on Sealant C Performance Under Tension, Unconditioned

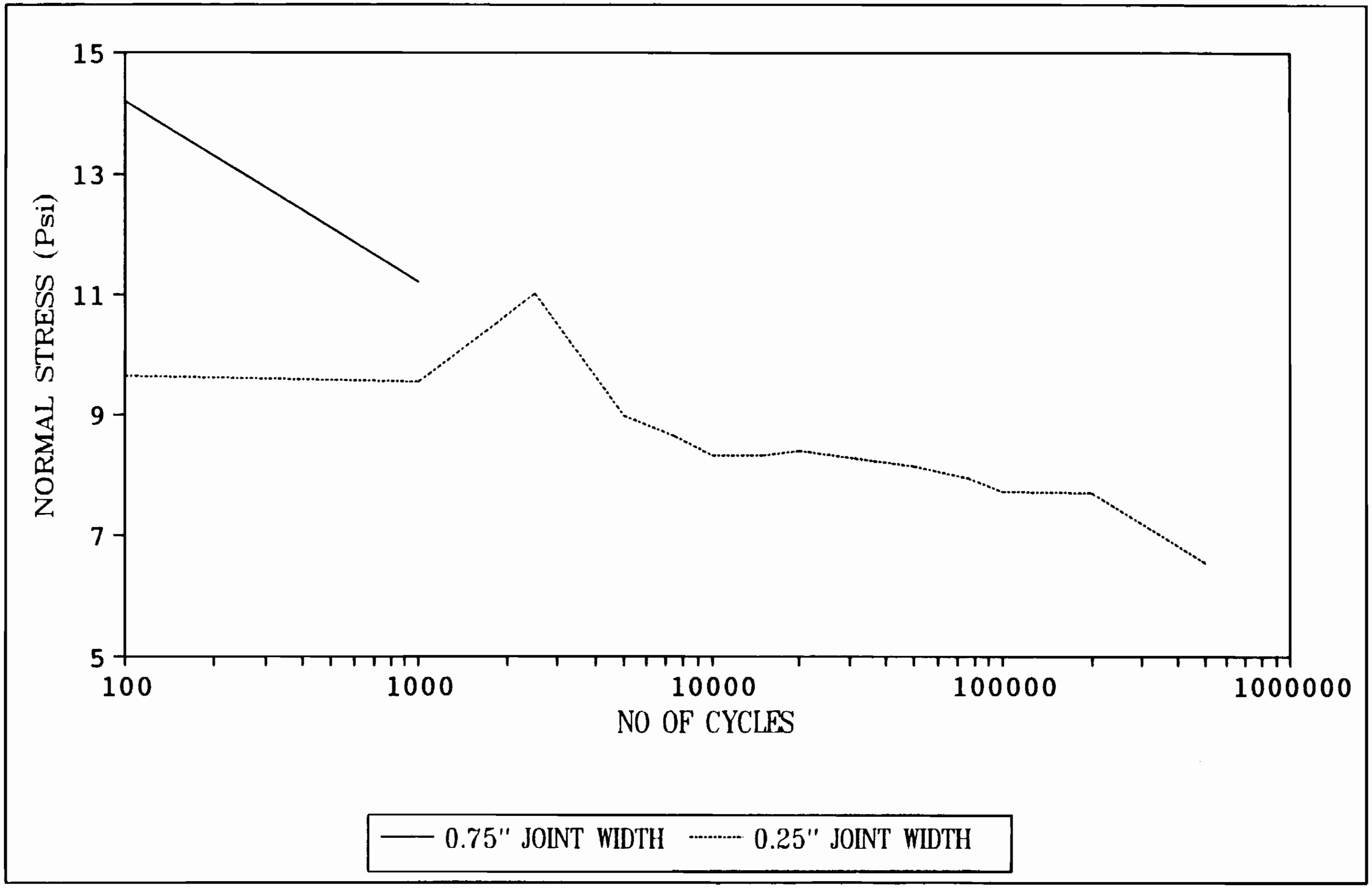


Fig. A.5 Effect of Joint Width on Sealant B Performance Under Compression, Unconditioned

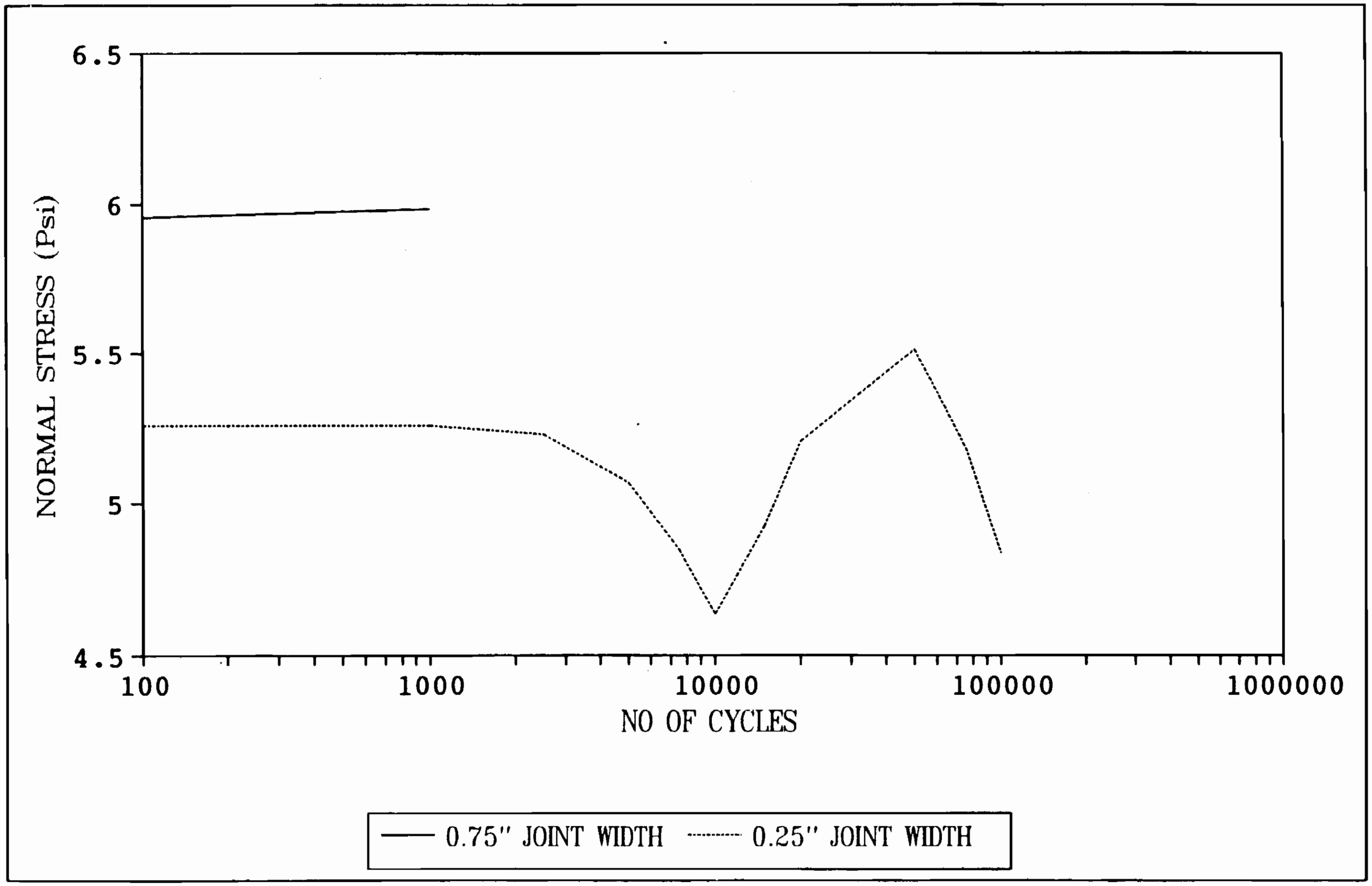


Fig. A.6 Effect of Joint Width on Sealant B Performance Under Tension, Unconditioned

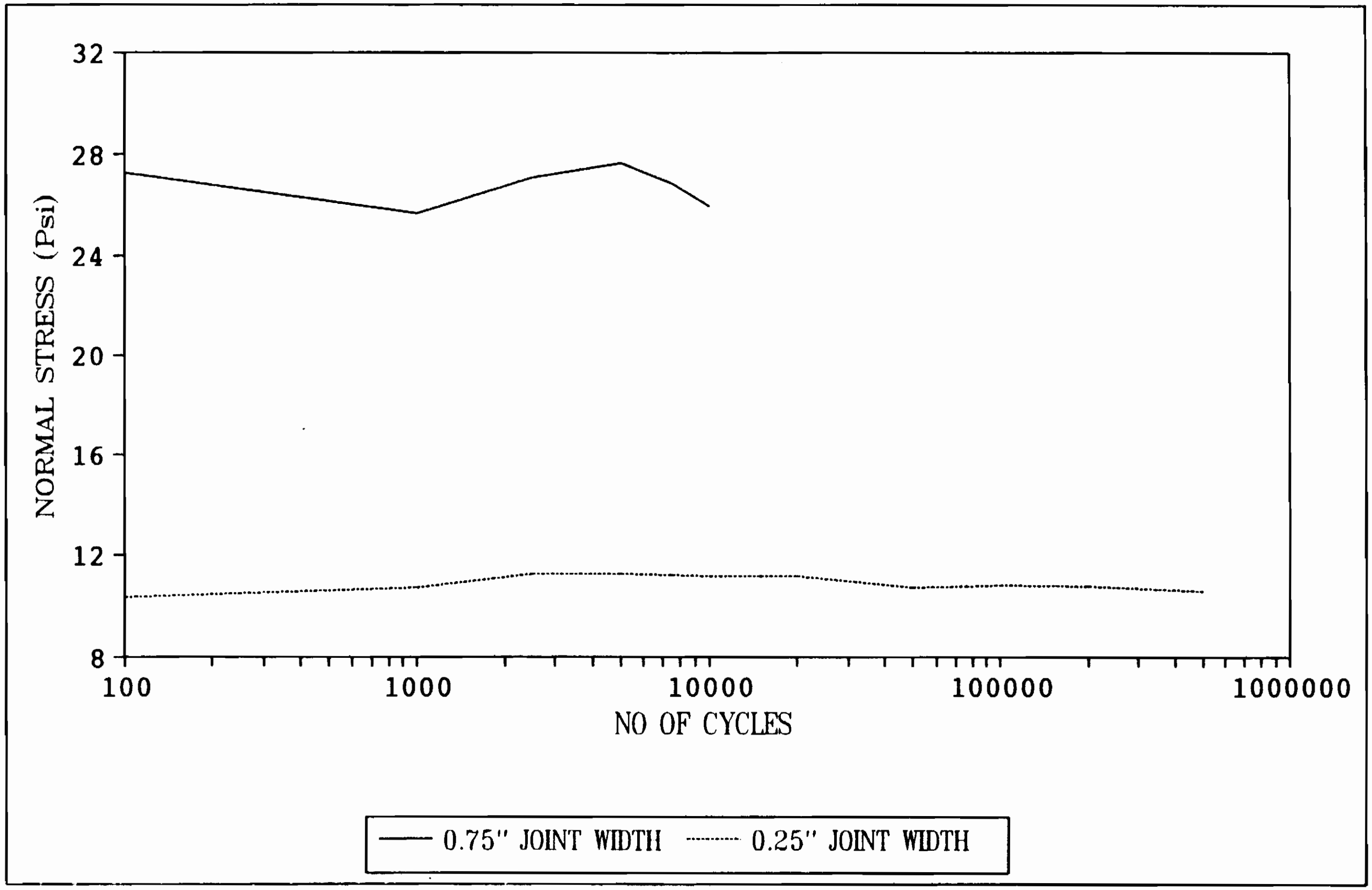


Fig. A.7 Effect of Joint Width on Sealant A Performance Under Compression, Conditioned

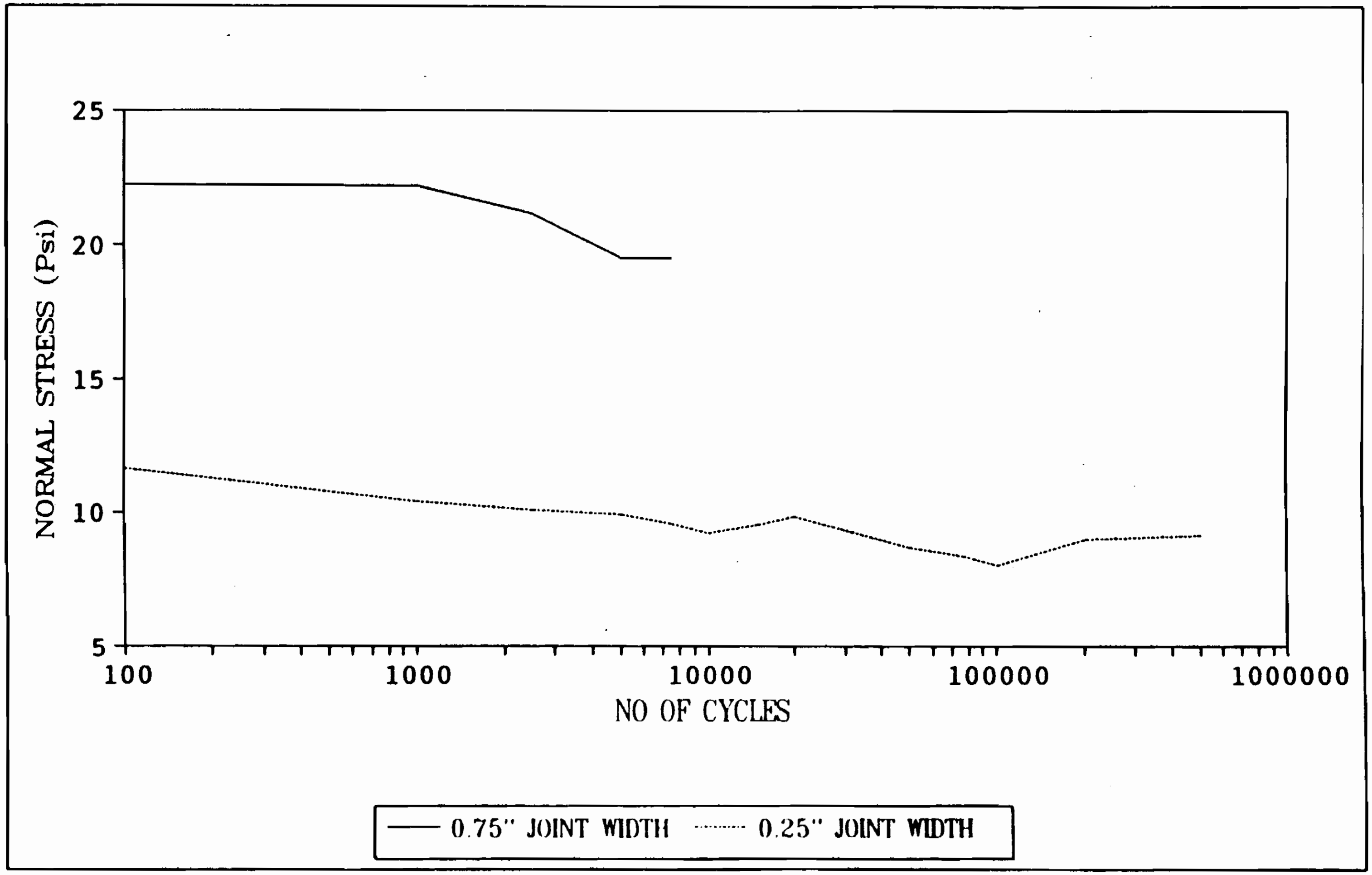


Fig. A.8 Effect of Joint Width on Sealant A Performance Under Tension, Conditioned

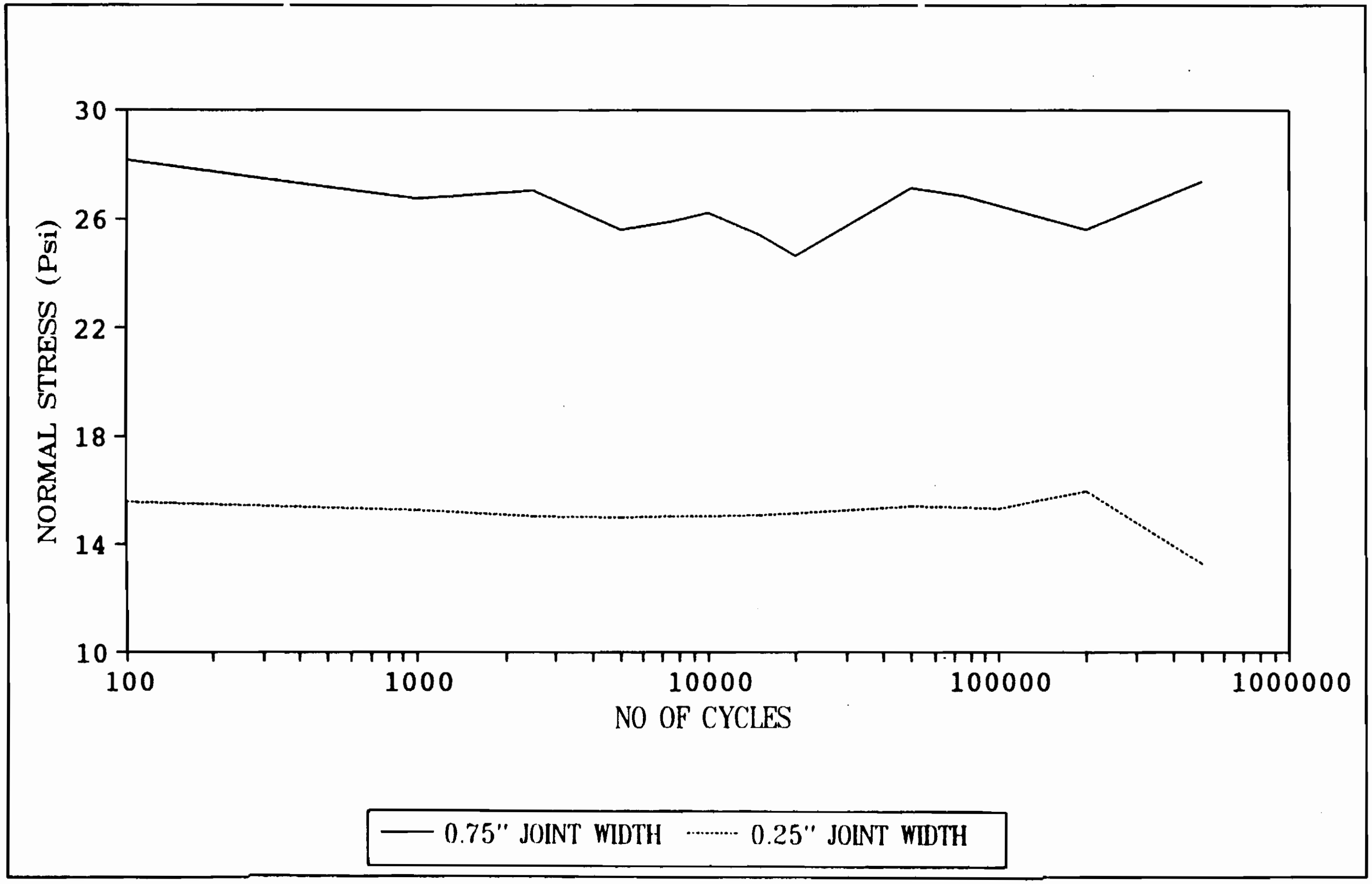


Fig. A.9 Effect of Joint Width on Sealant C Performance Under Compression, Conditioned

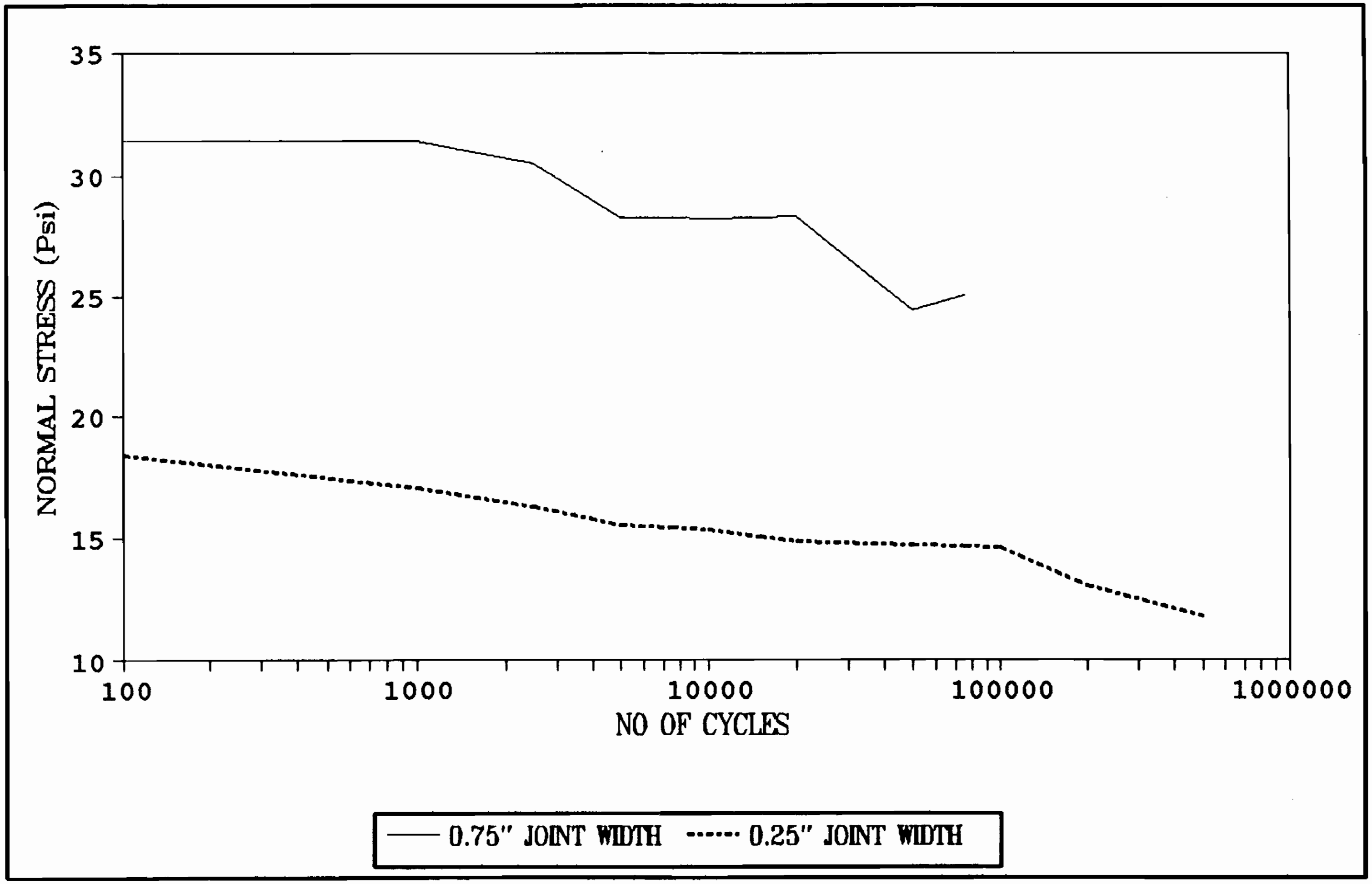


Fig. A.10 Effect of Joint Width on Sealant C Performance Under Tension, Conditioned

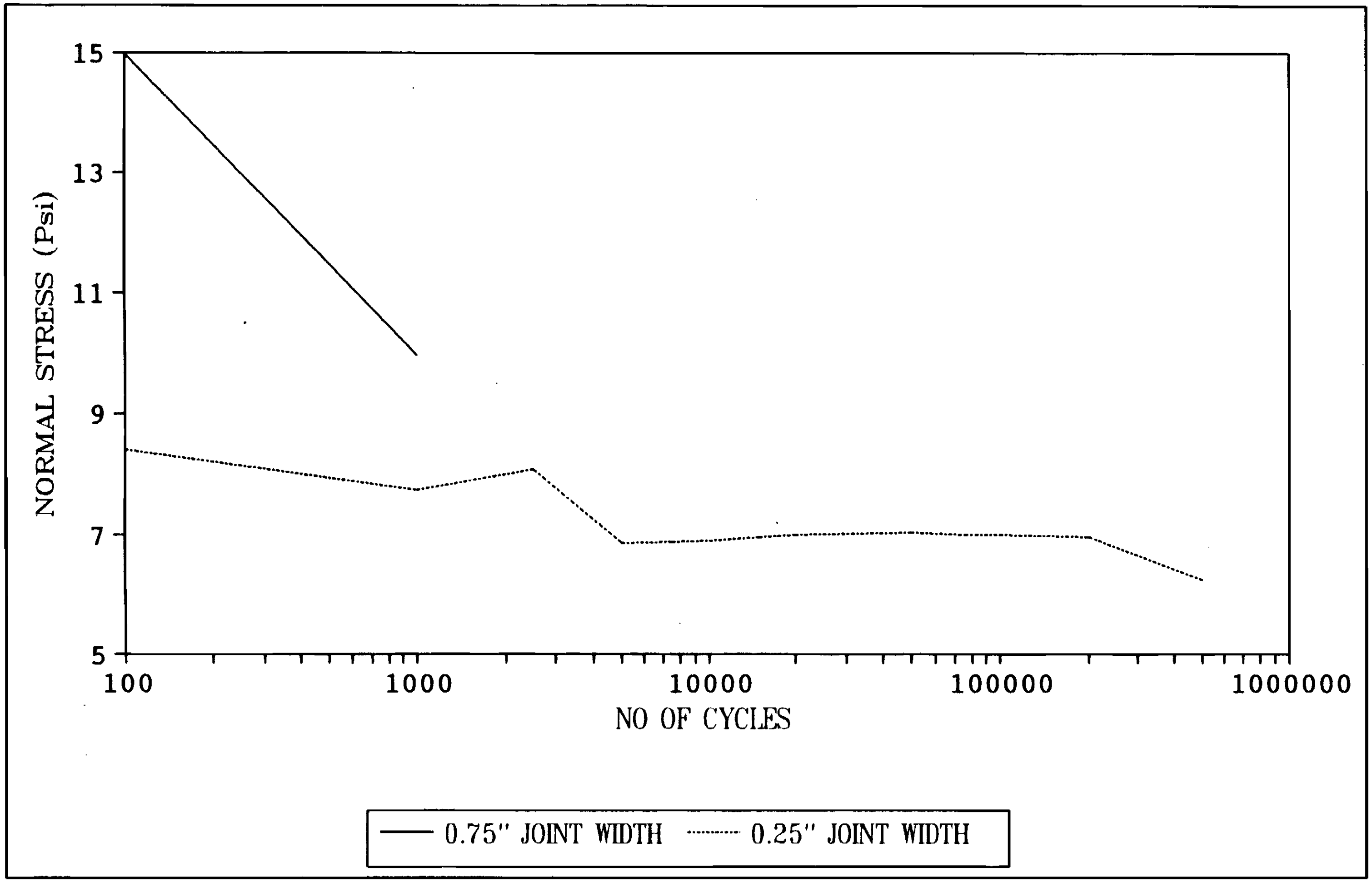


Fig. A.11 Effect of Joint Width on Sealant B Performance Under Compression, Conditioned

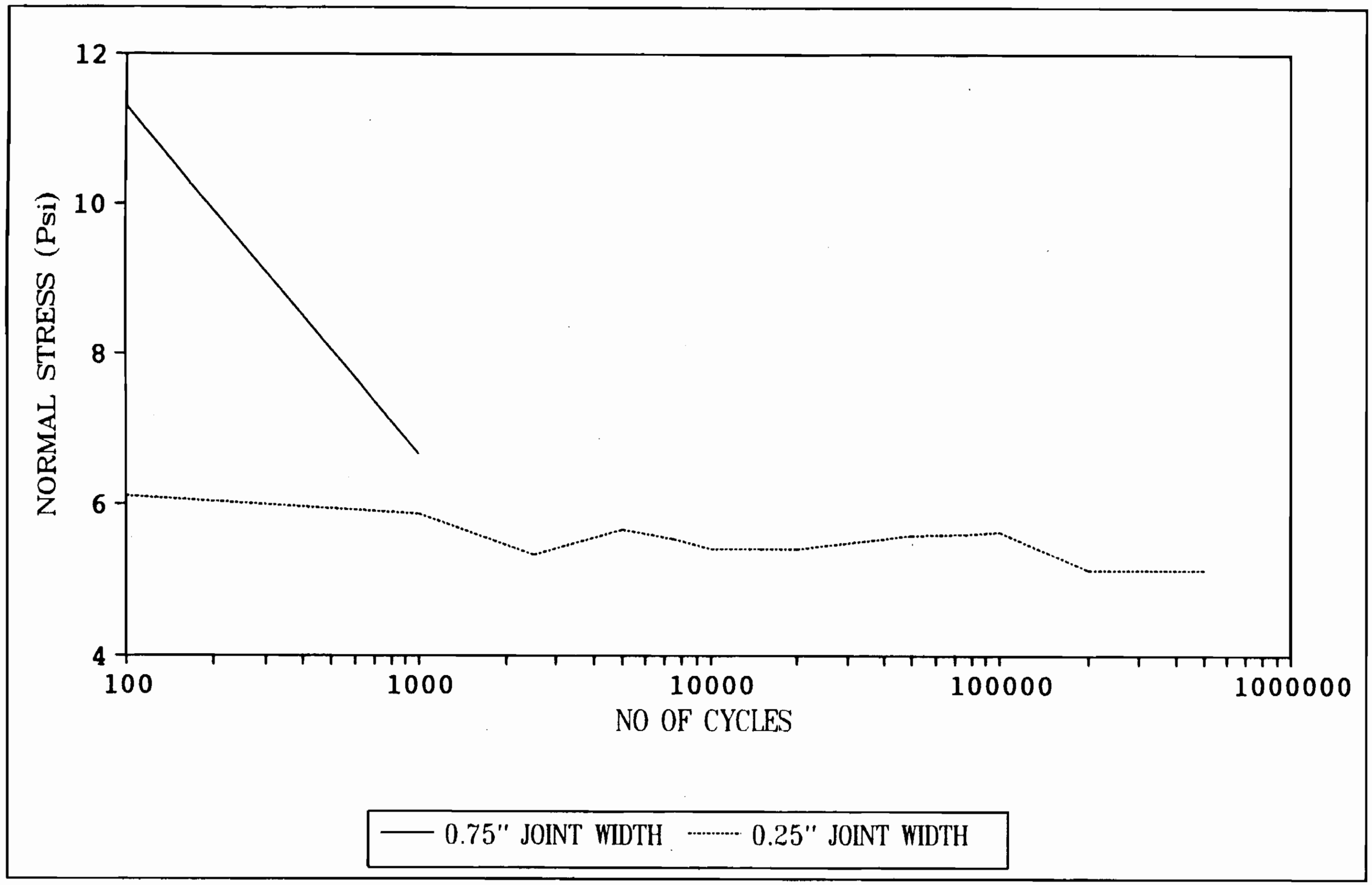


Fig. A.12 Effect of Joint Width on Sealant B Performance Under Tension, Conditioned

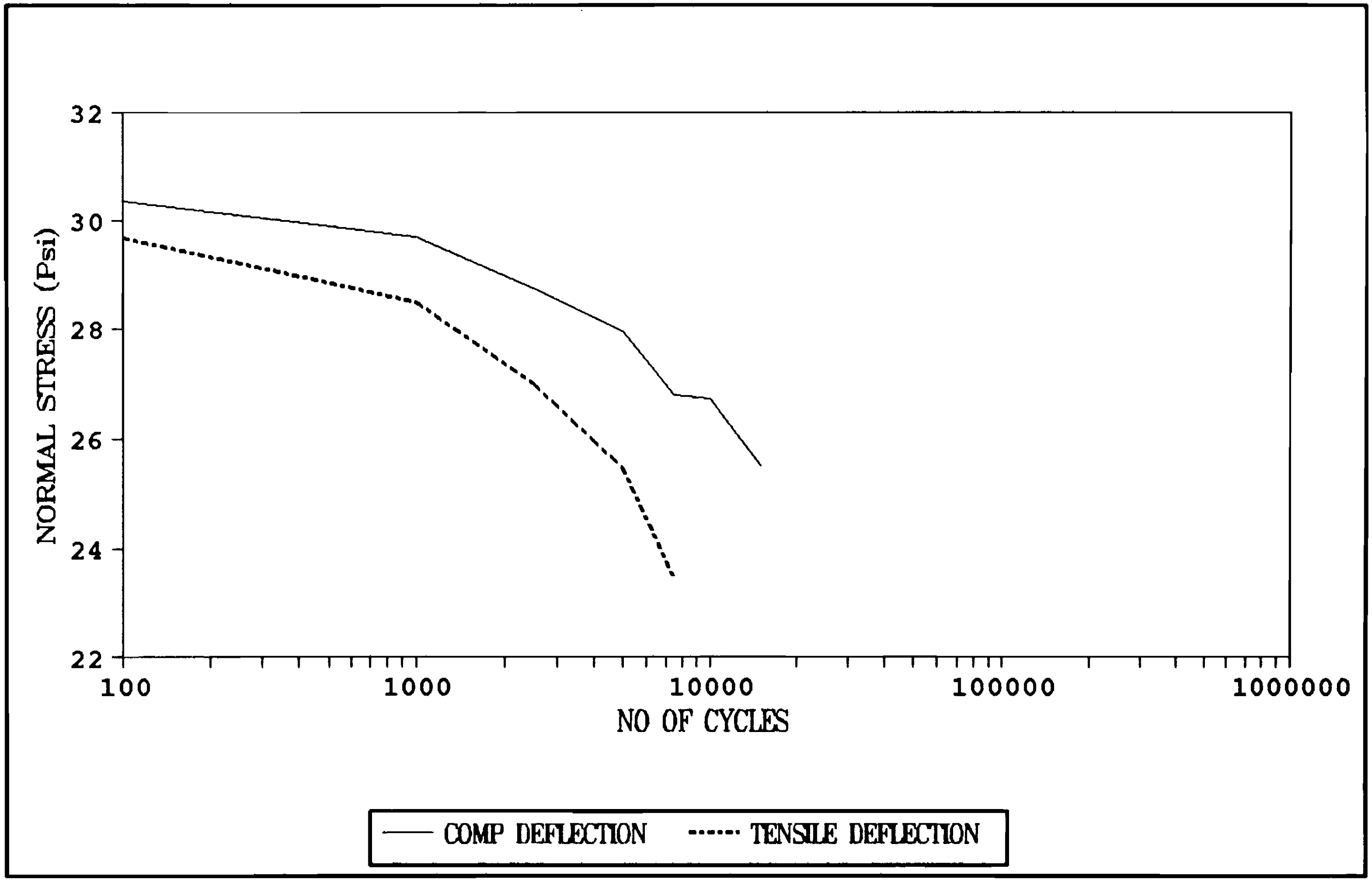


Fig. A.13 Sealant A Performance Under Compression/Tension at 0.75 in. Joint Width, Unconditioned

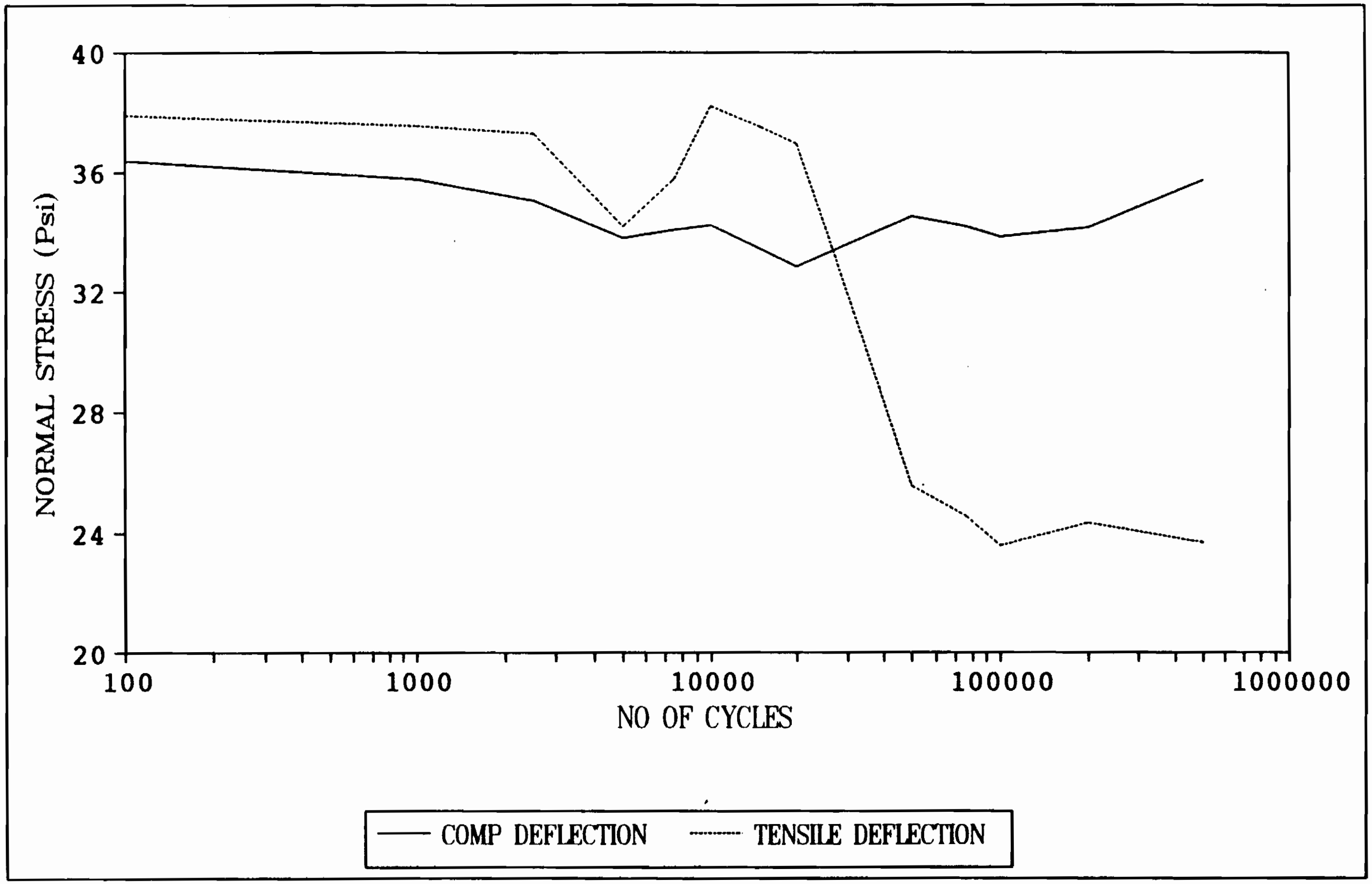


Fig. A.14 Sealant A Performance Under Compression/Tension at 0.25 in. Joint Width, Unconditioned

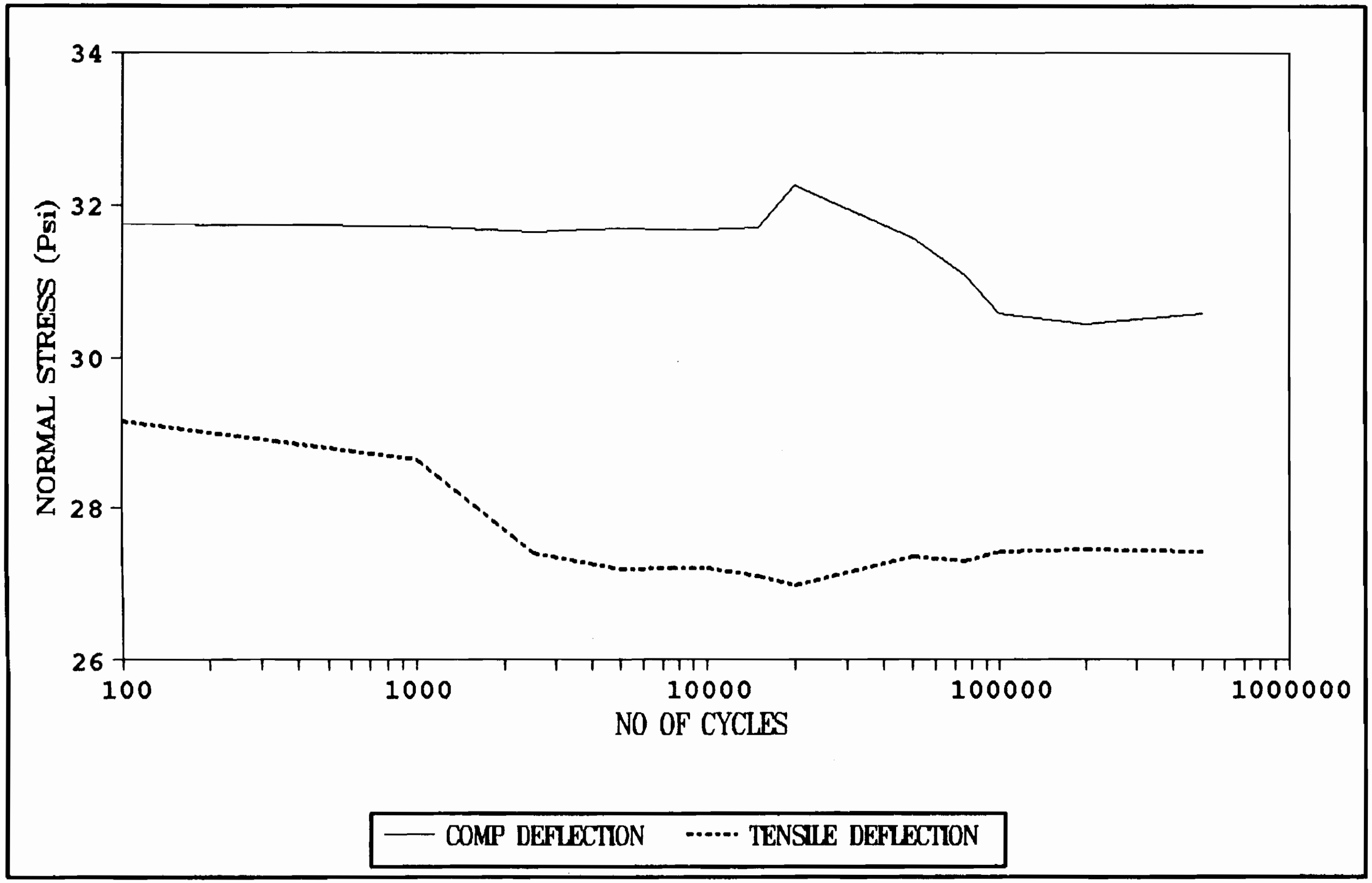


Fig. A.15 Sealant C Performance Under Compression/Tension at 0.75 in. Joint Width, Unconditioned

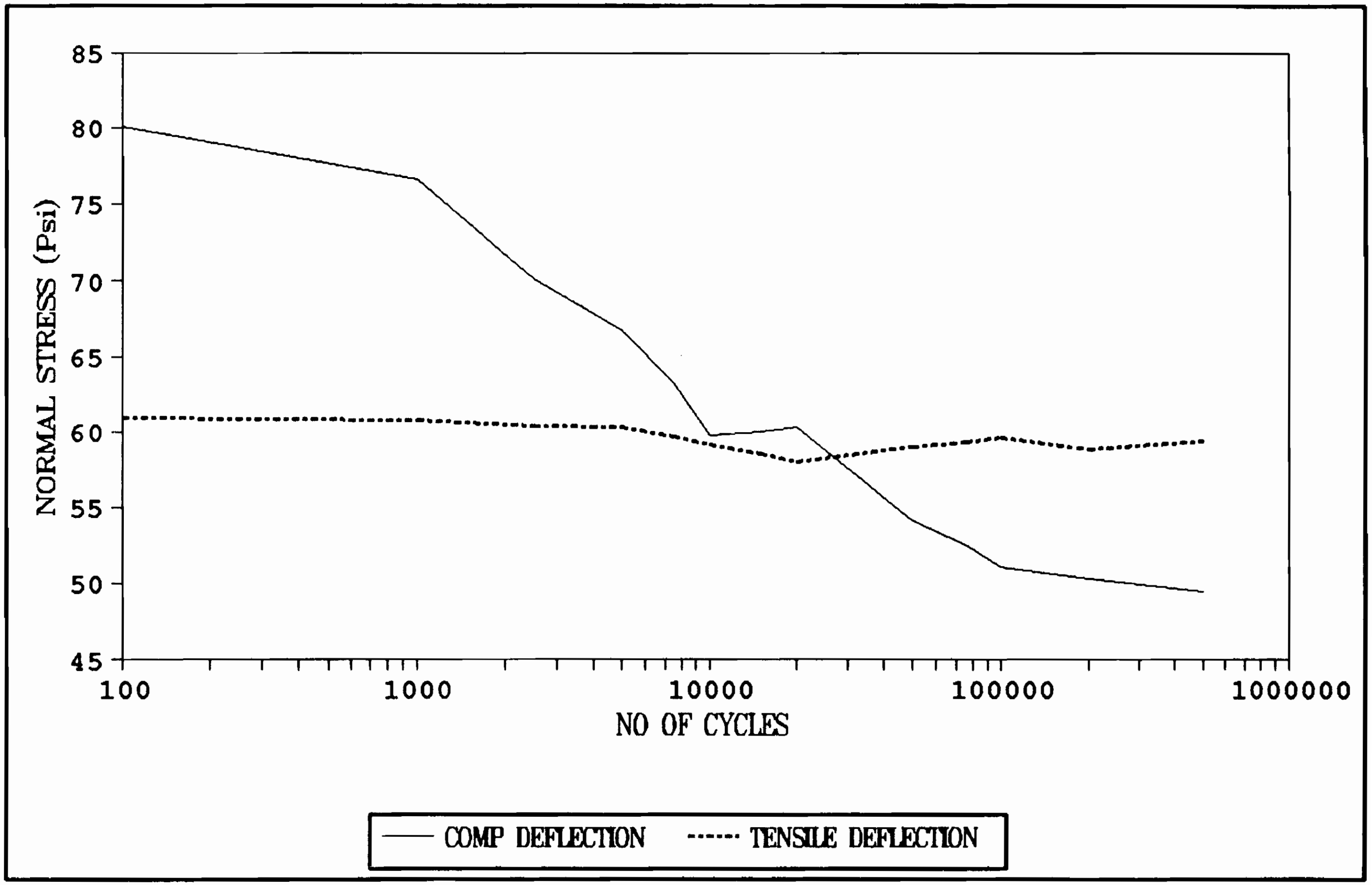


Fig. A.16 Sealant C Performance Under Compression/Tension at 0.25 in. Joint Width, Unconditioned

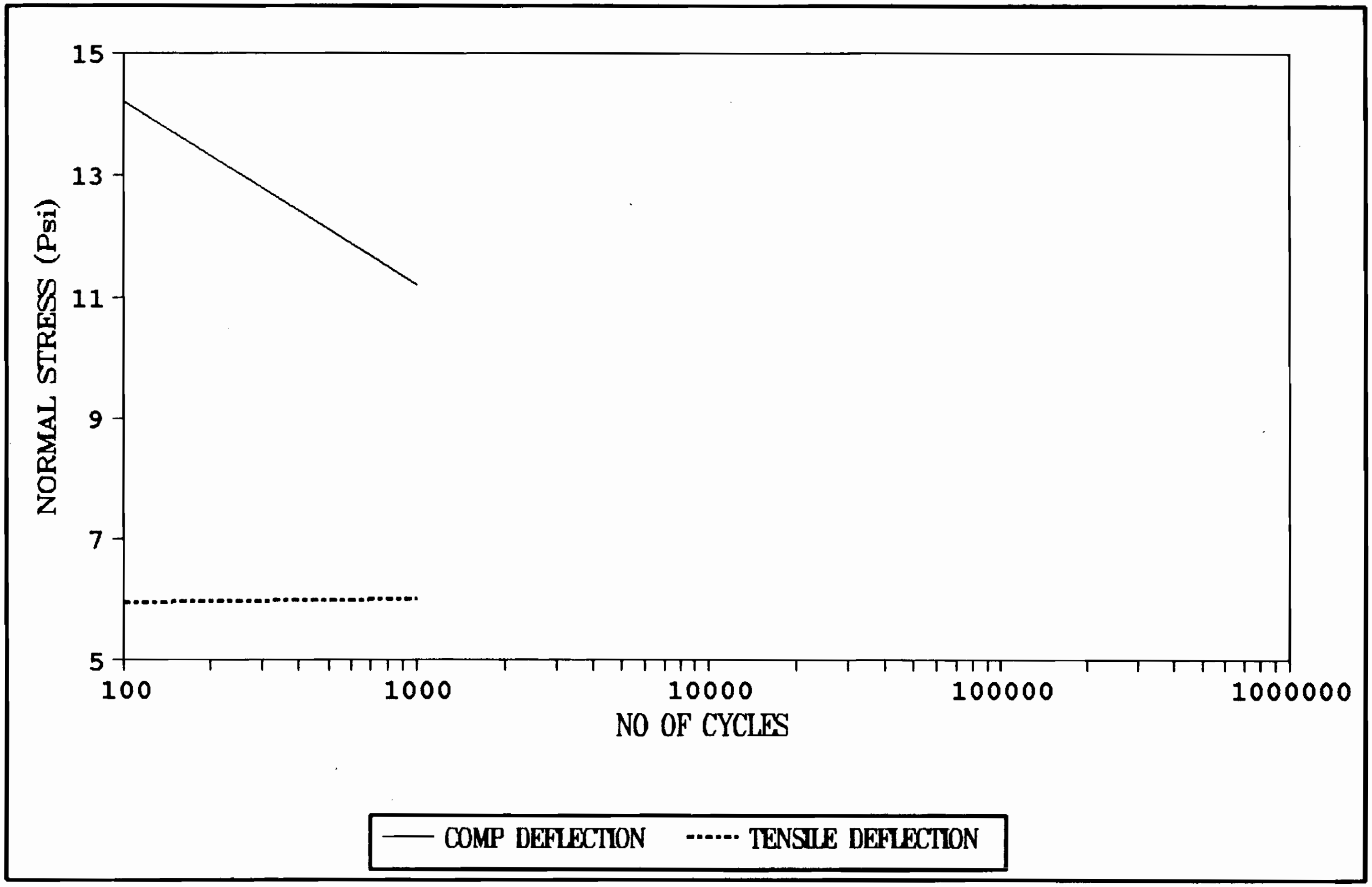


Fig. A.17 Sealant B Performance Under Compression/Tension at 0.75 in. Joint Width, Unconditioned

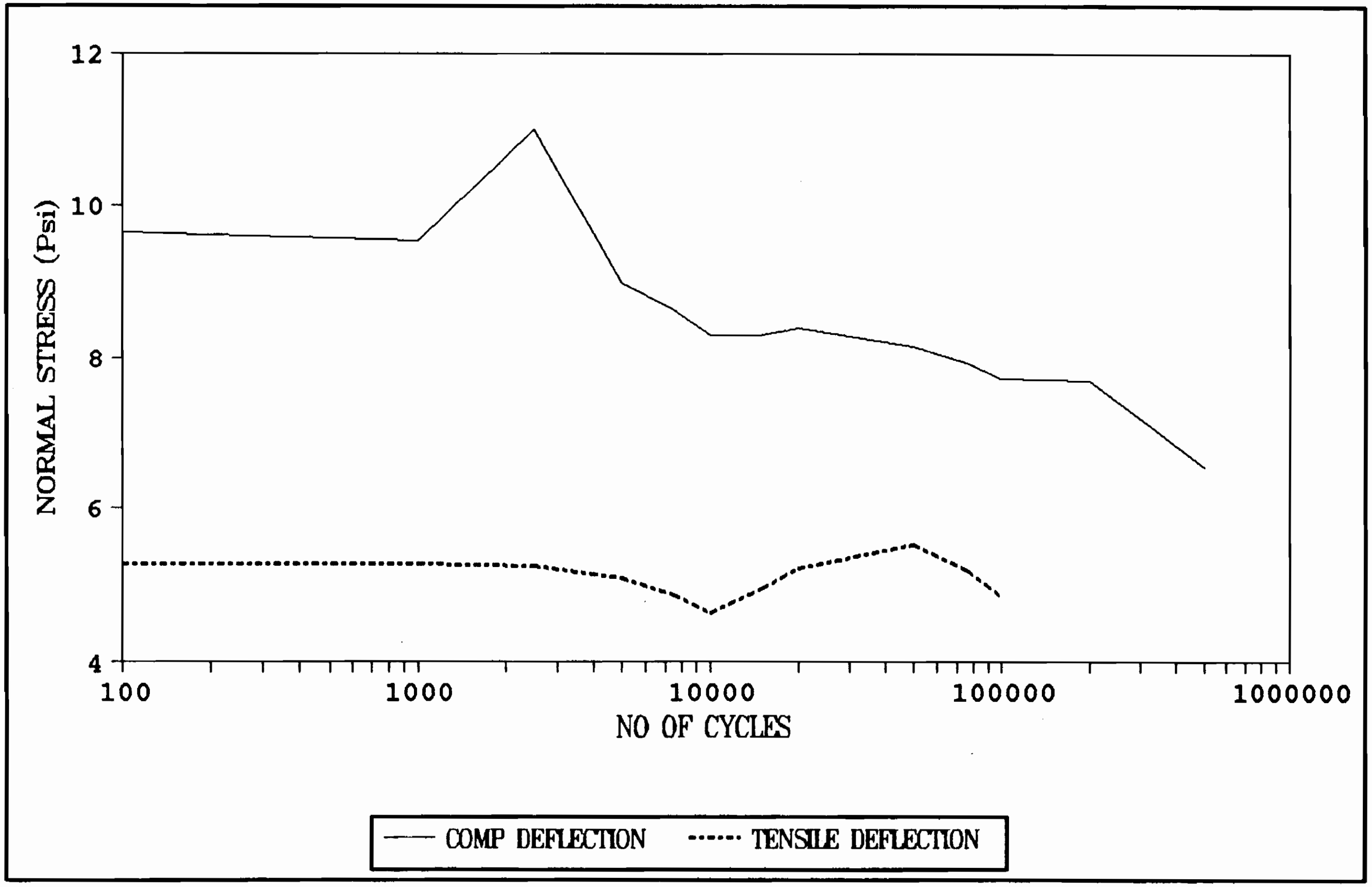


Fig. A.18 Sealant B Performance Under Compression/Tension at 0.25 in. Joint Width, Unconditioned

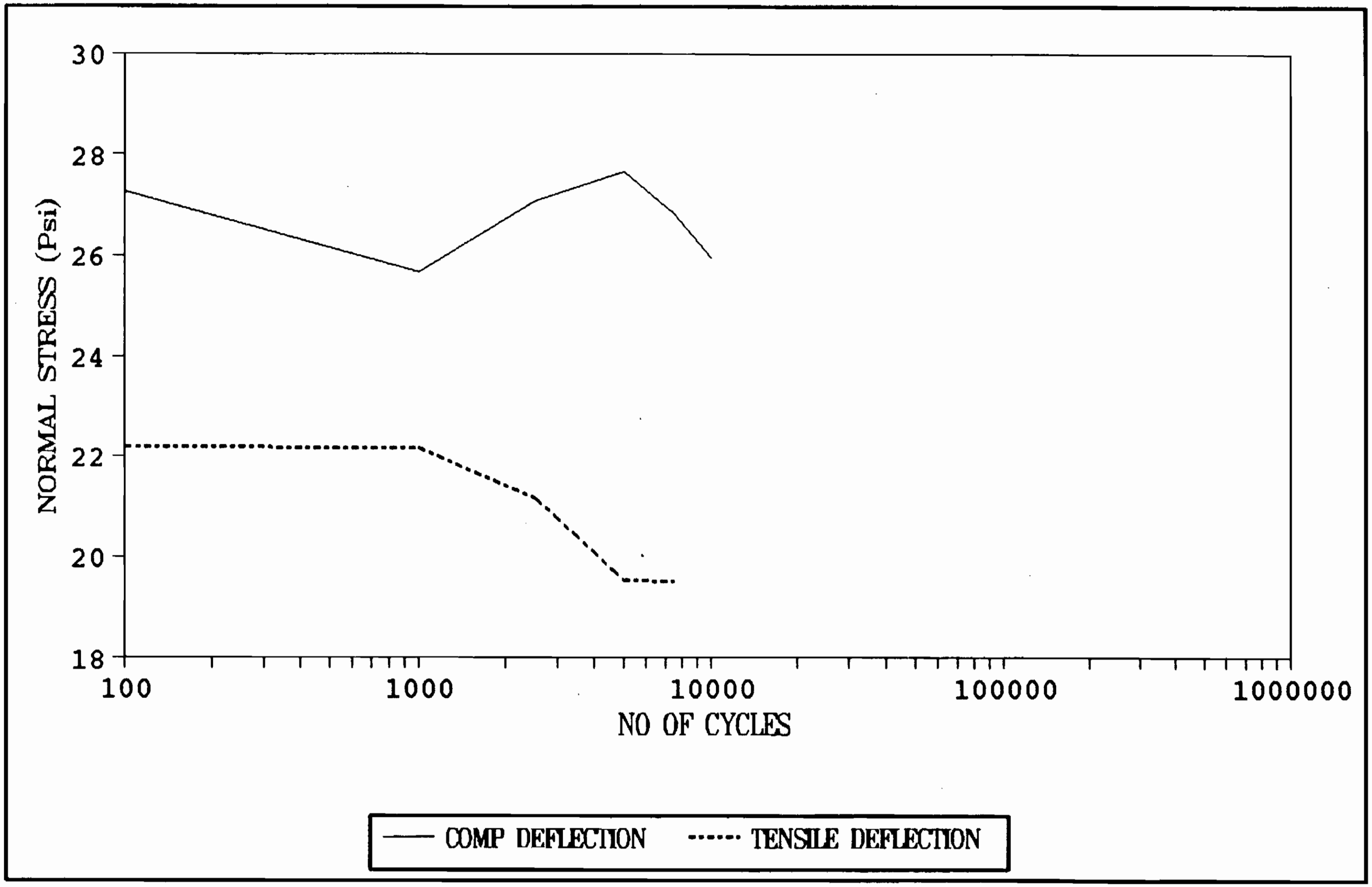


Fig. A.19 Sealant A Performance Under Compression/Tension at 0.75 in. Joint Width, Conditioned

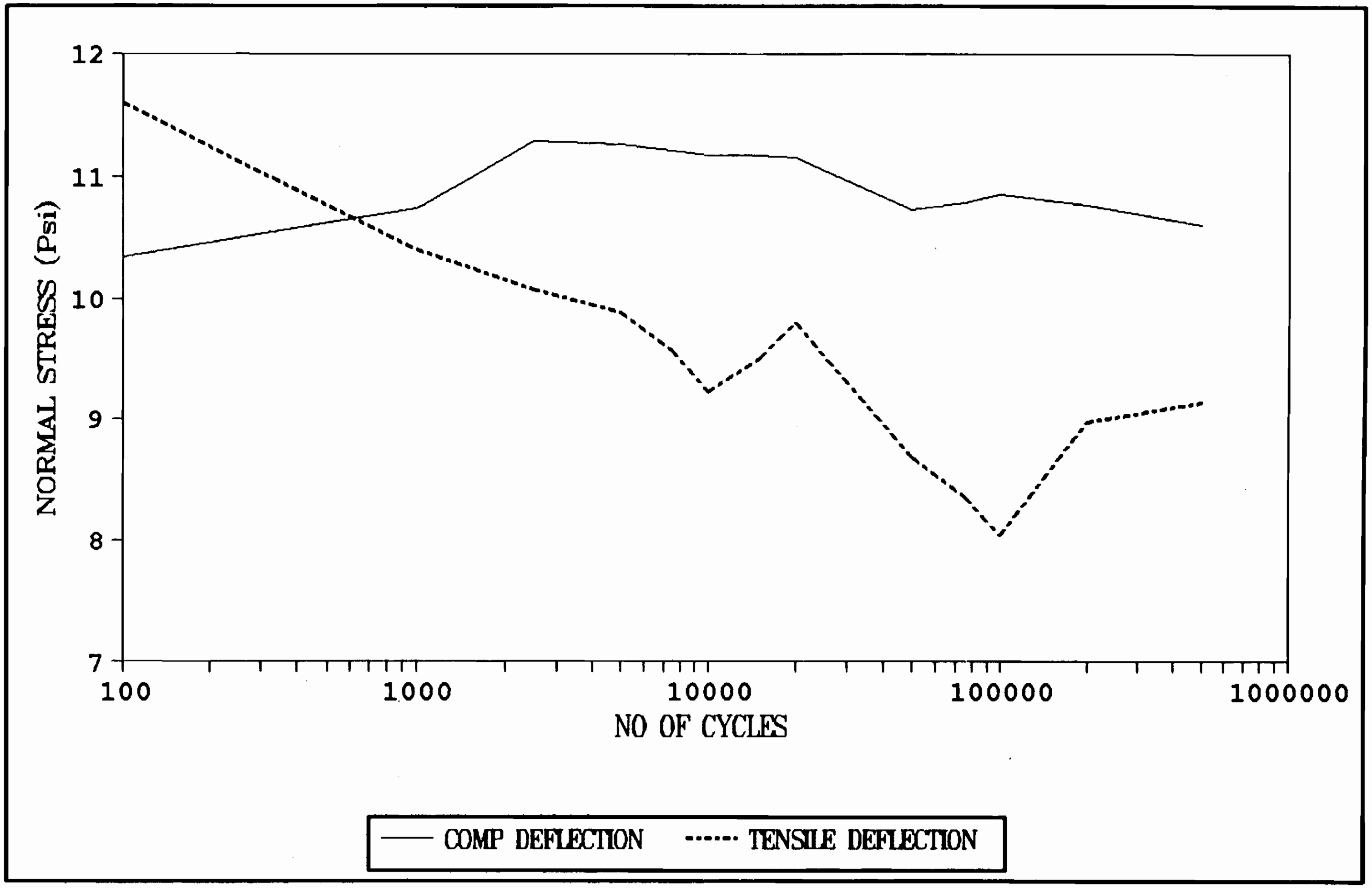


Fig. A.20 Sealant A Performance Under Compression/Tension at 0.25 in. Joint Width, Conditioned

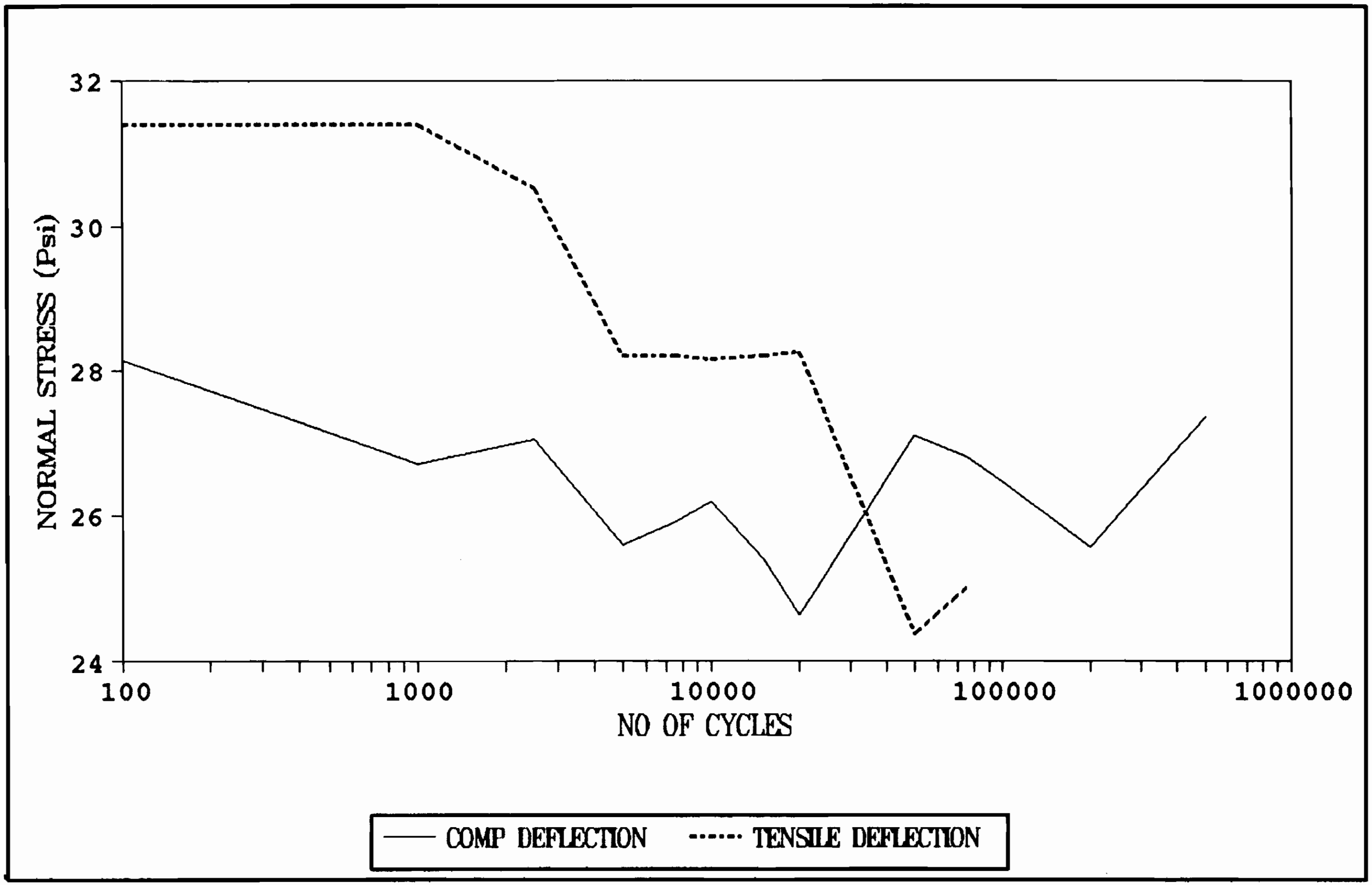


Fig. A.21 Sealant C Performance Under Compression/Tension at 0.75 in. Joint Width, Conditioned

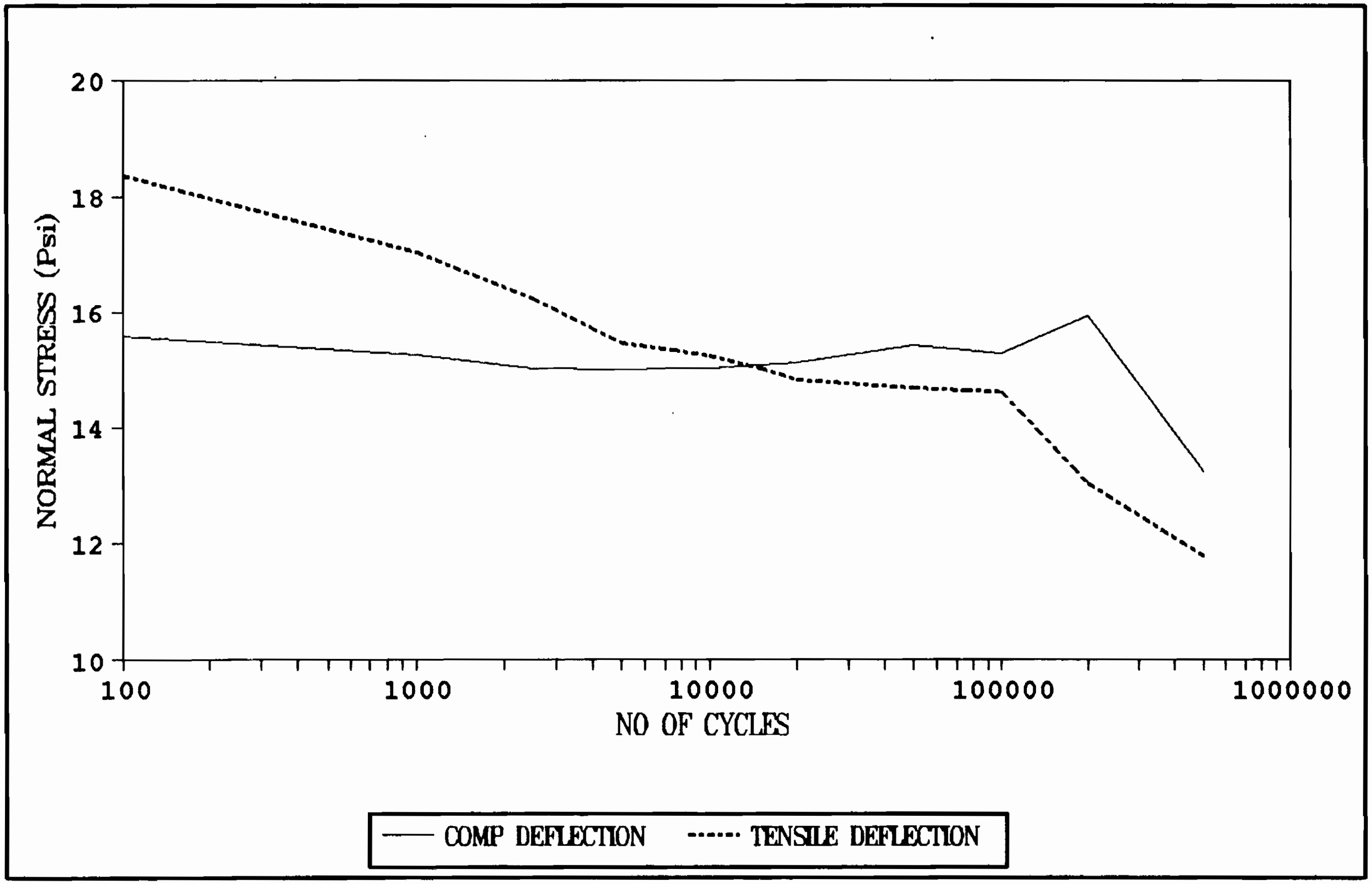


Fig. A.22 Sealant C Performance Under Compression/Tension at 0.25 in. Joint Width, Conditioned

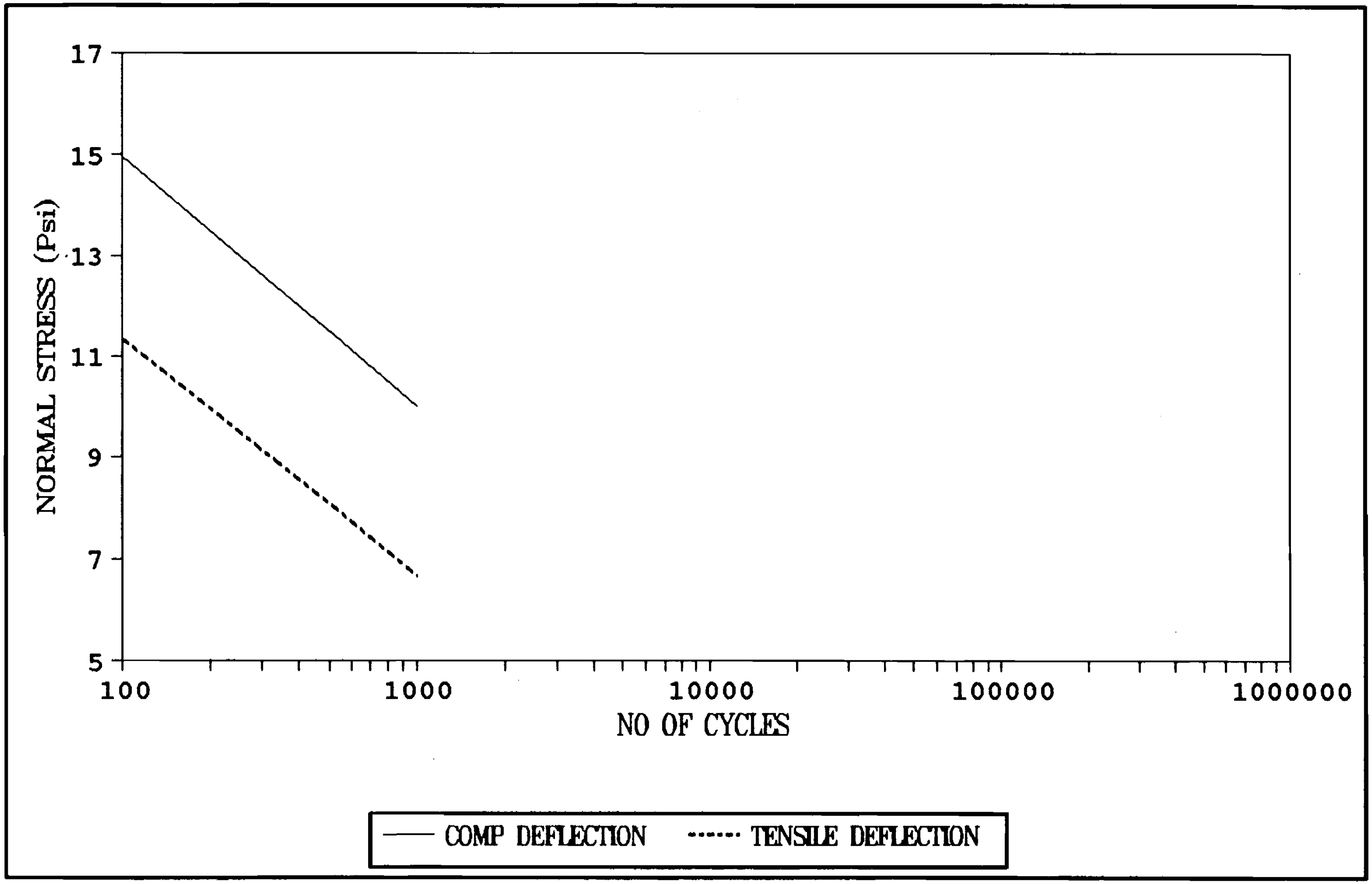


Fig. A.23 Sealant B Performance Under Compression/Tension at 0.75 in. Joint Width, Conditioned

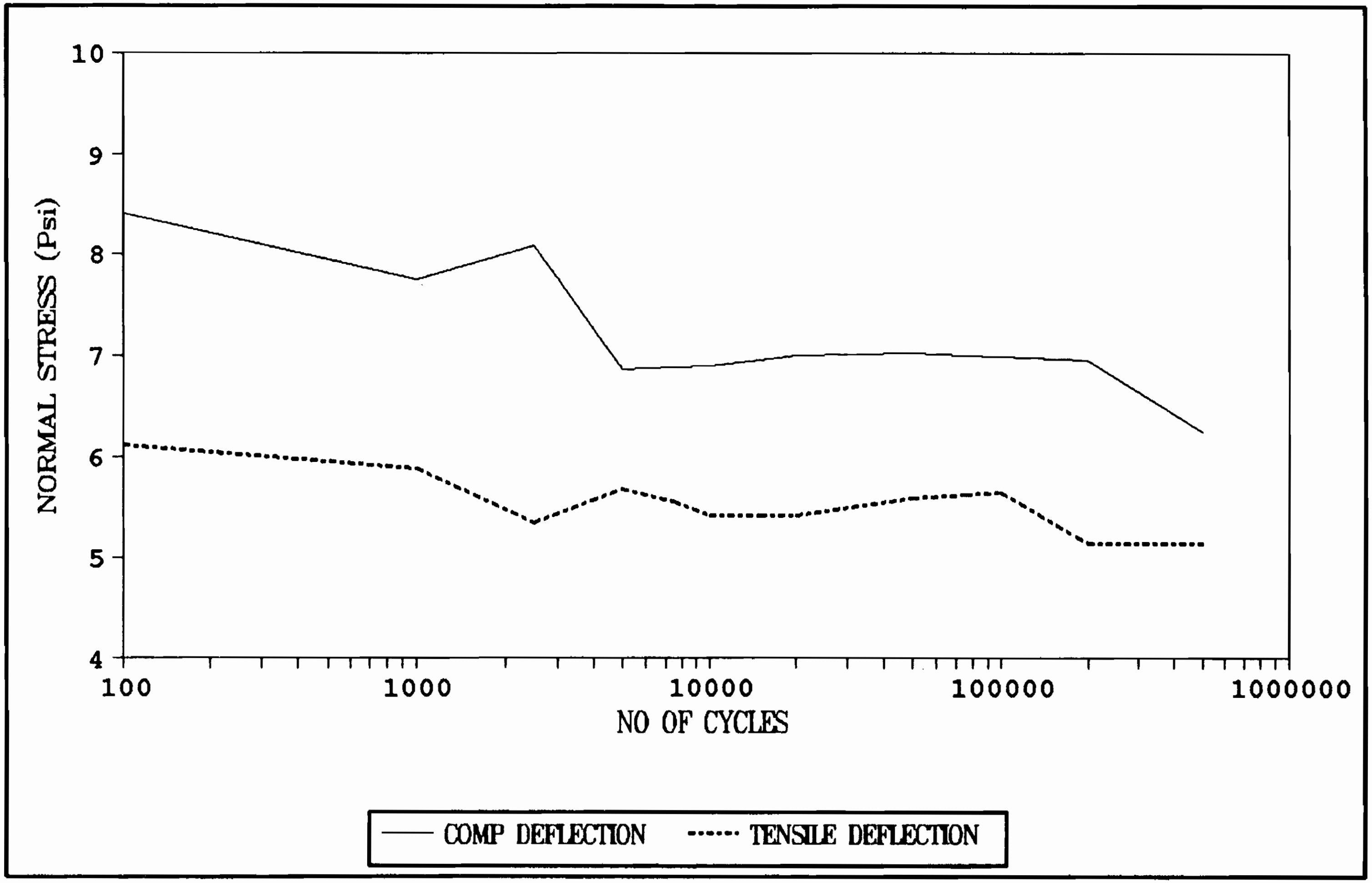


Fig. A.24 Sealant B Performance Under Compression/Tension at 0.25 in. Joint Width, Conditioned

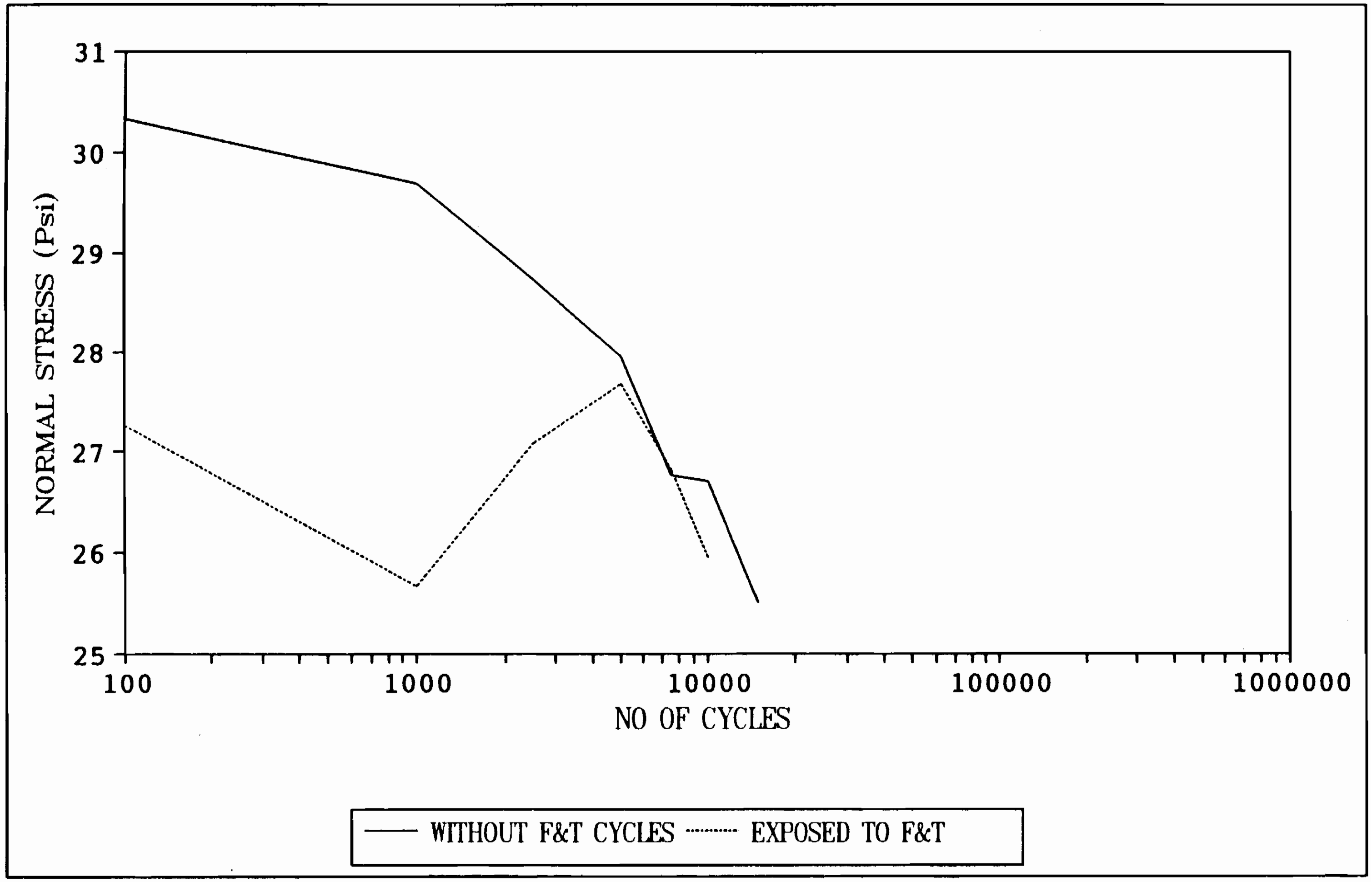


Fig. A.25 Effect of Freezing and Thawing Cycles on Sealant A Performance at 0.75 in. Joint Width Under Compression

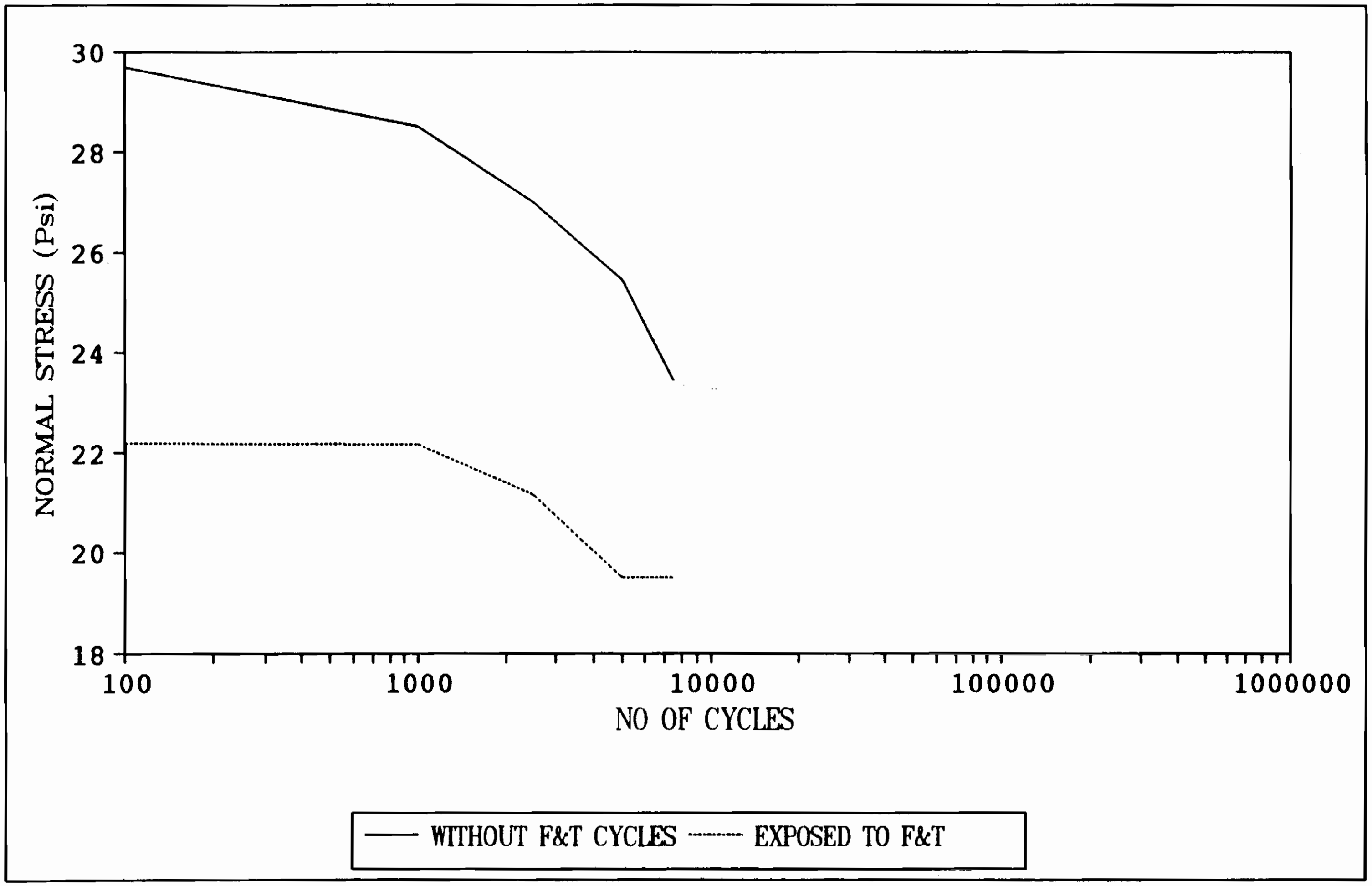


Fig. A.26 Effect of Freezing and Thawing Cycles on Sealant A Performance at 0.75 in. Joint Width Under Tension

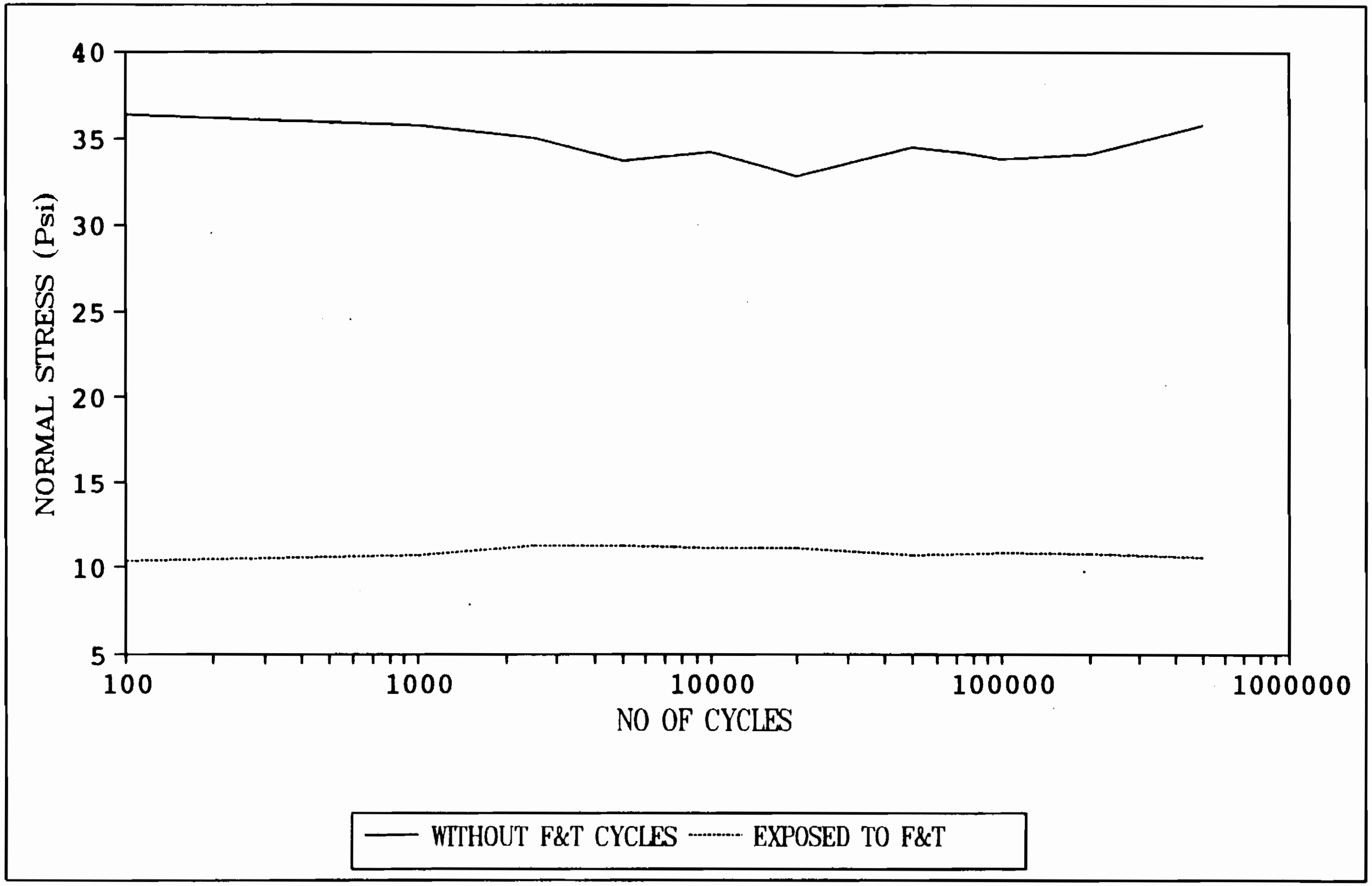


Fig. A.27 Effect of Freezing and Thawing Cycles on Sealant A Performance at 0.25 in. Joint Width Under Compression

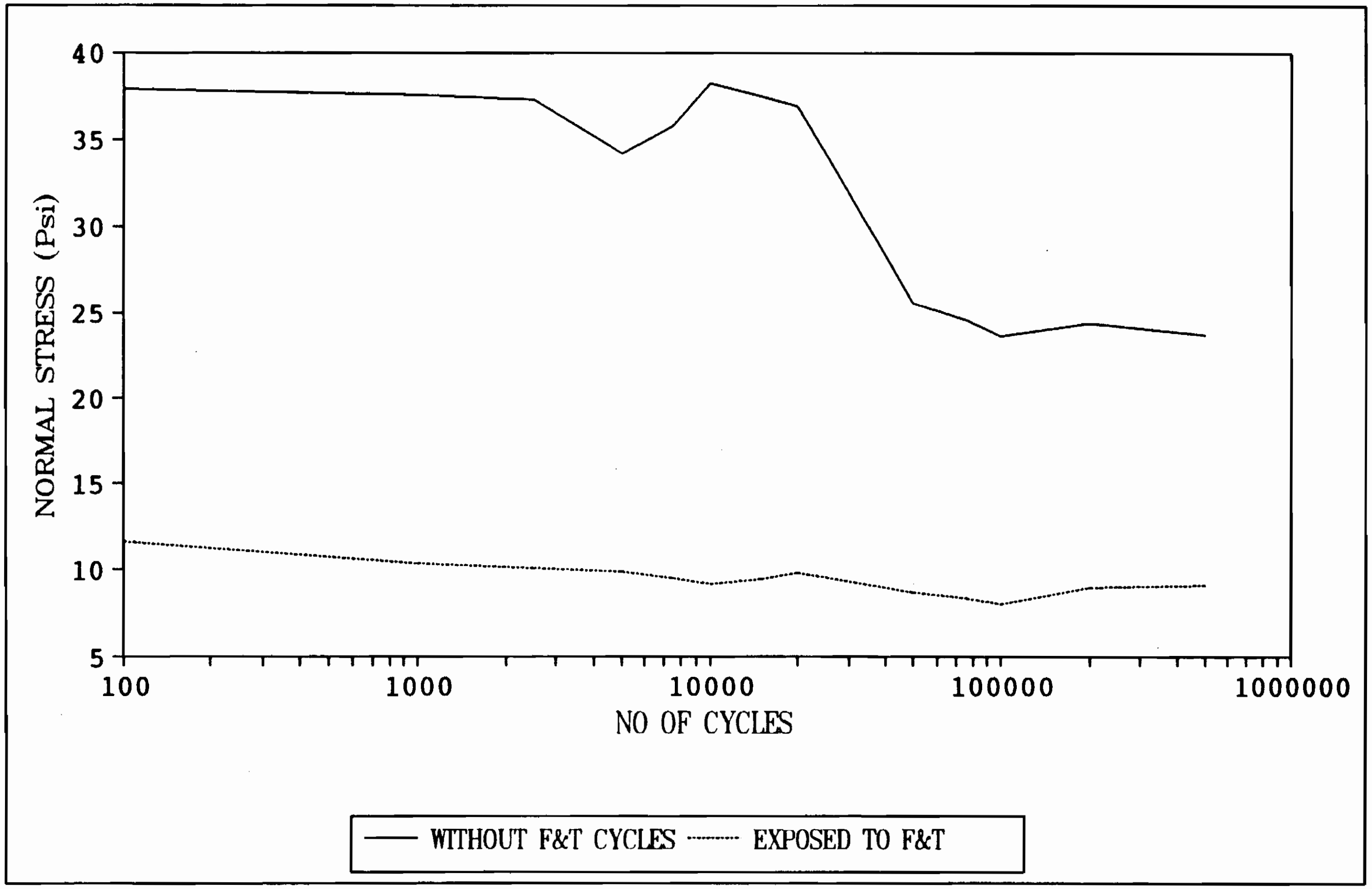


Fig. A.28 Effect of Freezing and Thawing Cycles on Sealant A Performance at 0.25 in. Joint Width Under Tension

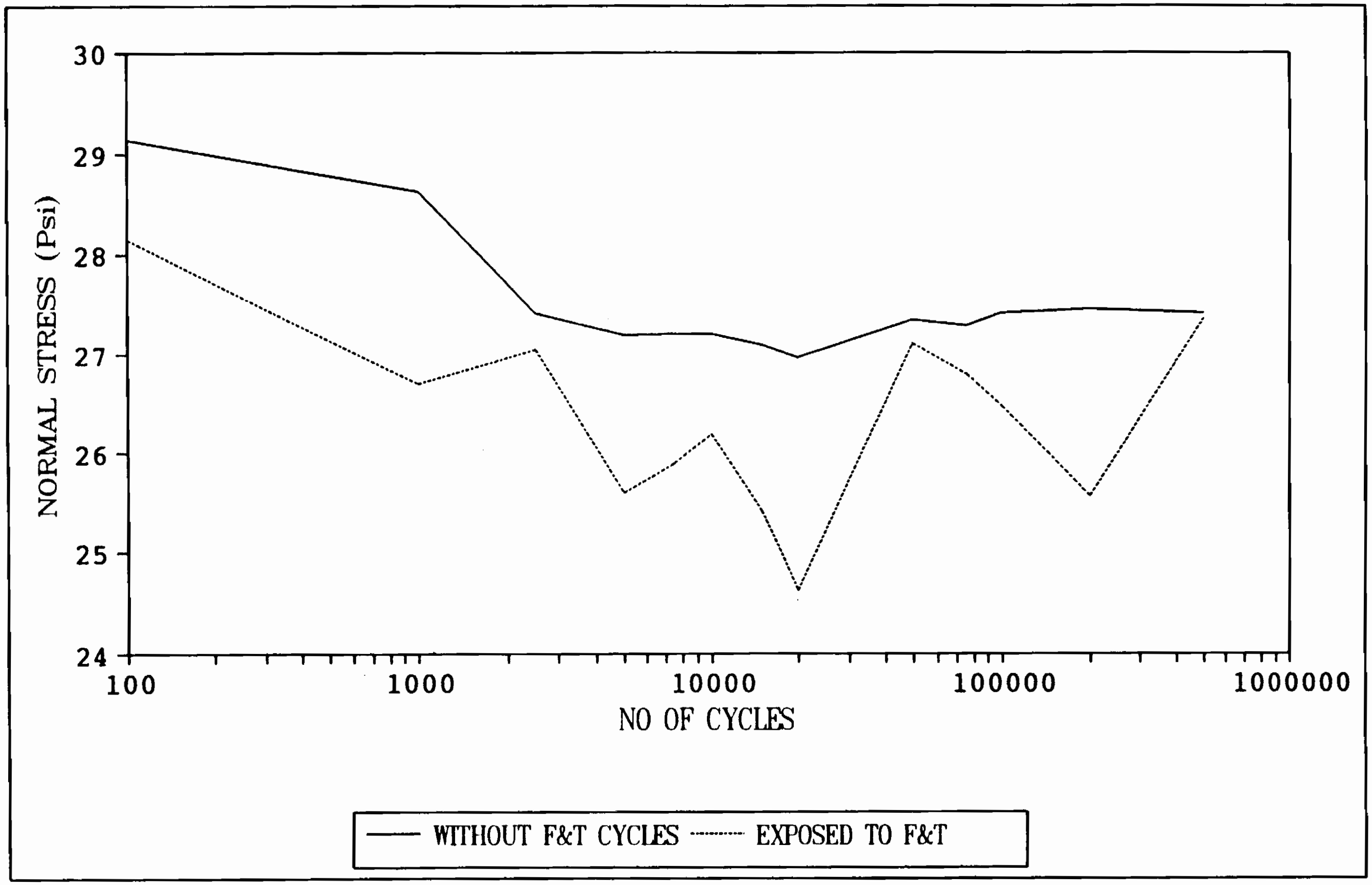


Fig. A.29 Effect of Freezing and Thawing Cycles on Sealant C Performance at 0.75 in. Joint Width Under Compression

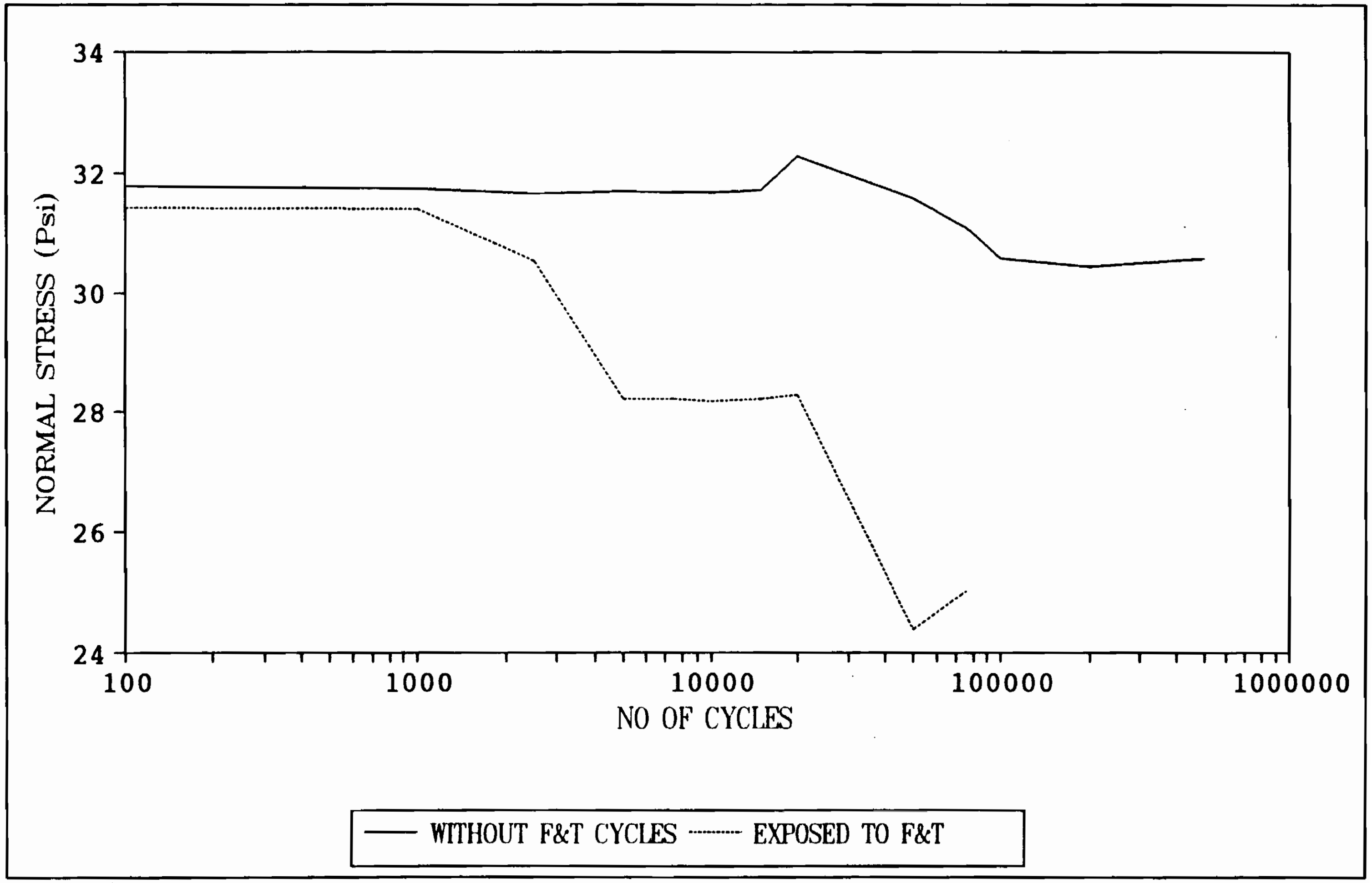


Fig. A.30 Effect of Freezing and Thawing Cycles on Sealant C Performance at 0.75 in. Joint Width Under Tension

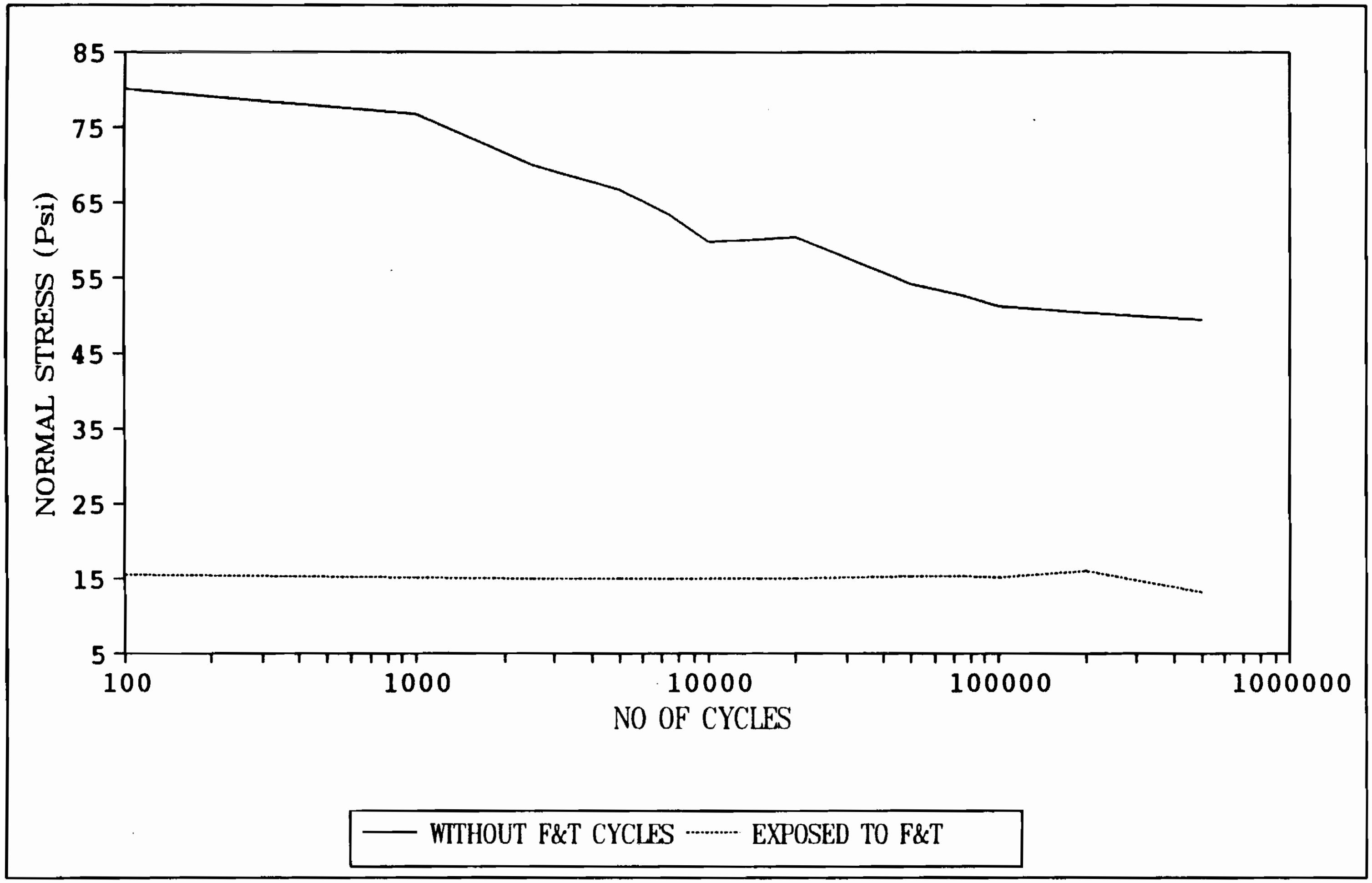


Fig. A.31 Effect of Freezing and Thawing Cycles on Sealant C Performance at 0.25 in. Joint Width Under Compression

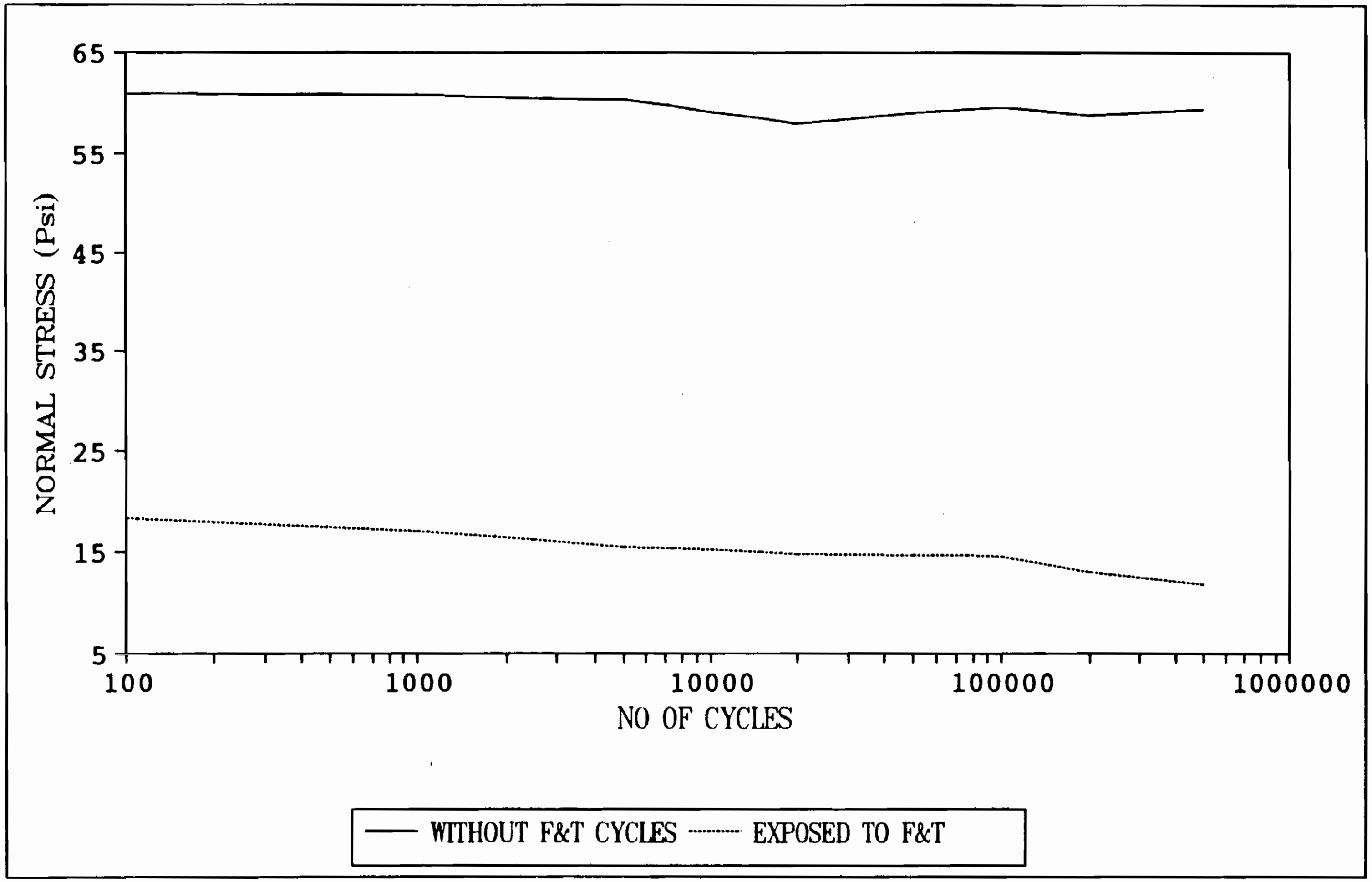


Fig. A.32 Effect of Freezing and Thawing Cycles on Sealant C Performance at 0.25 in. Joint Width Under Tension

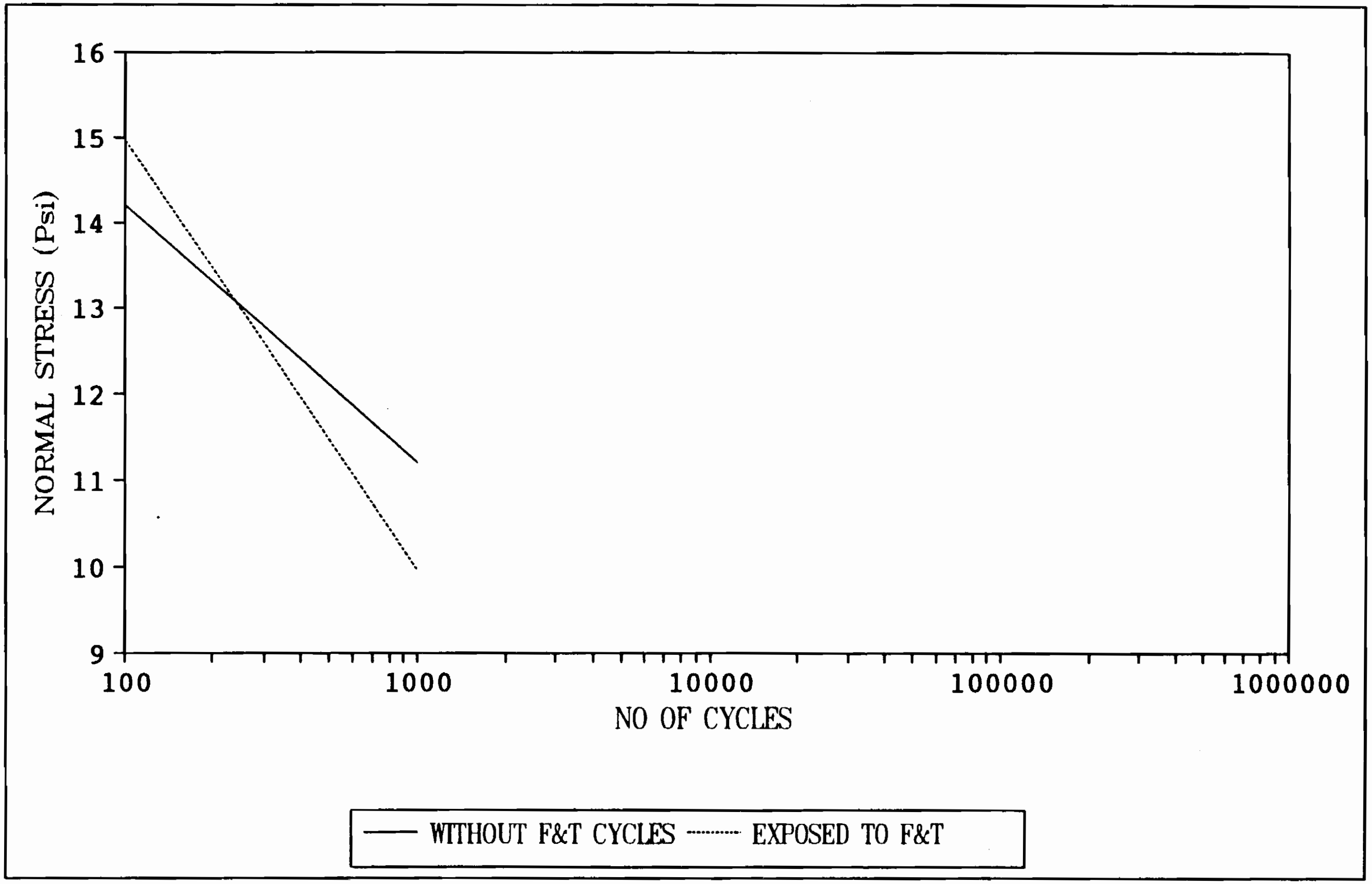


Fig. A.33 Effect of Freezing and Thawing Cycles on Sealant B Performance at 0.75 in. Joint Width Under Compression

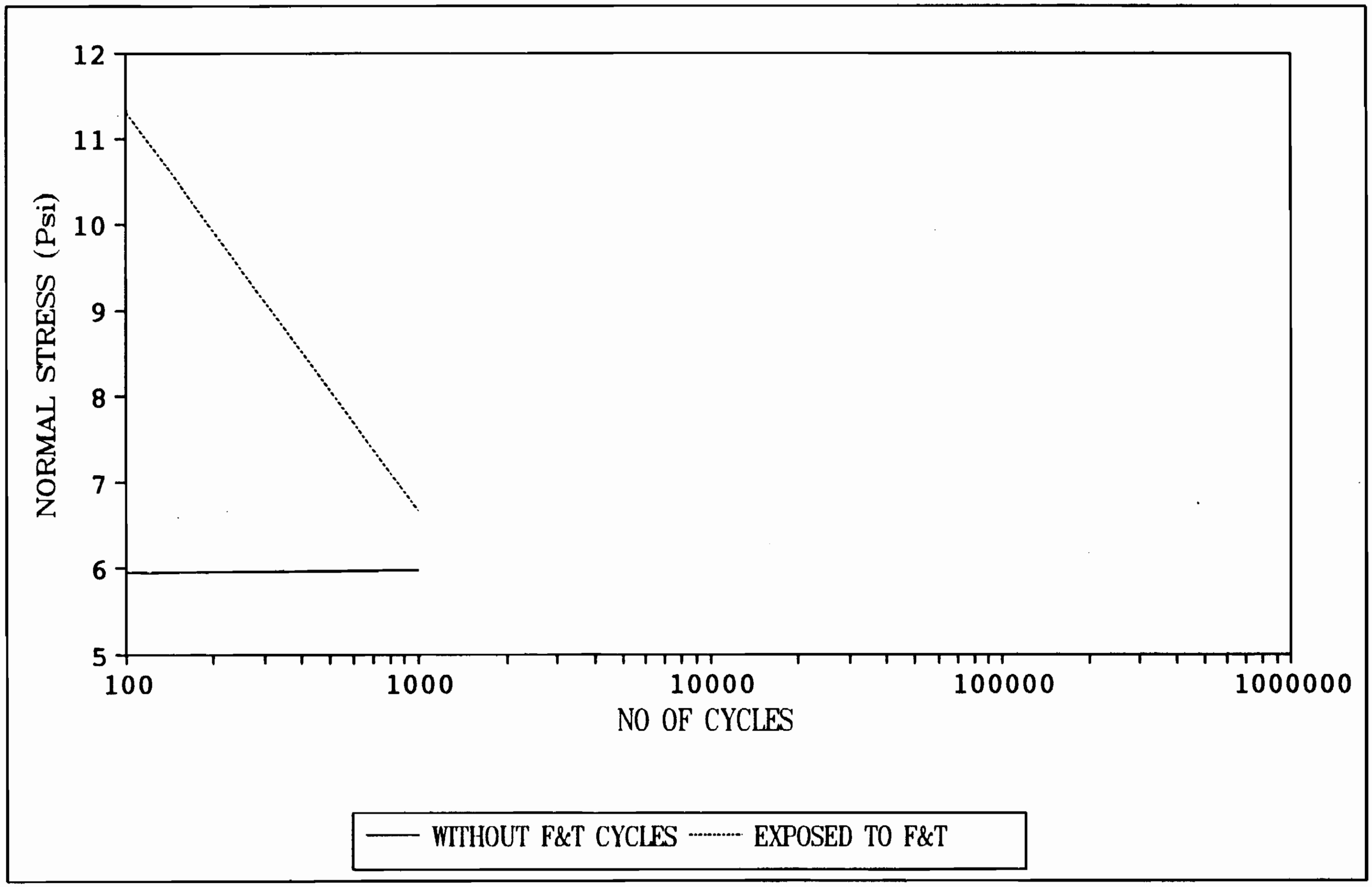


Fig. A.34 Effect of Freezing and Thawing Cycles on Sealant B Performance at 0.75 in. Joint Width Under Tension

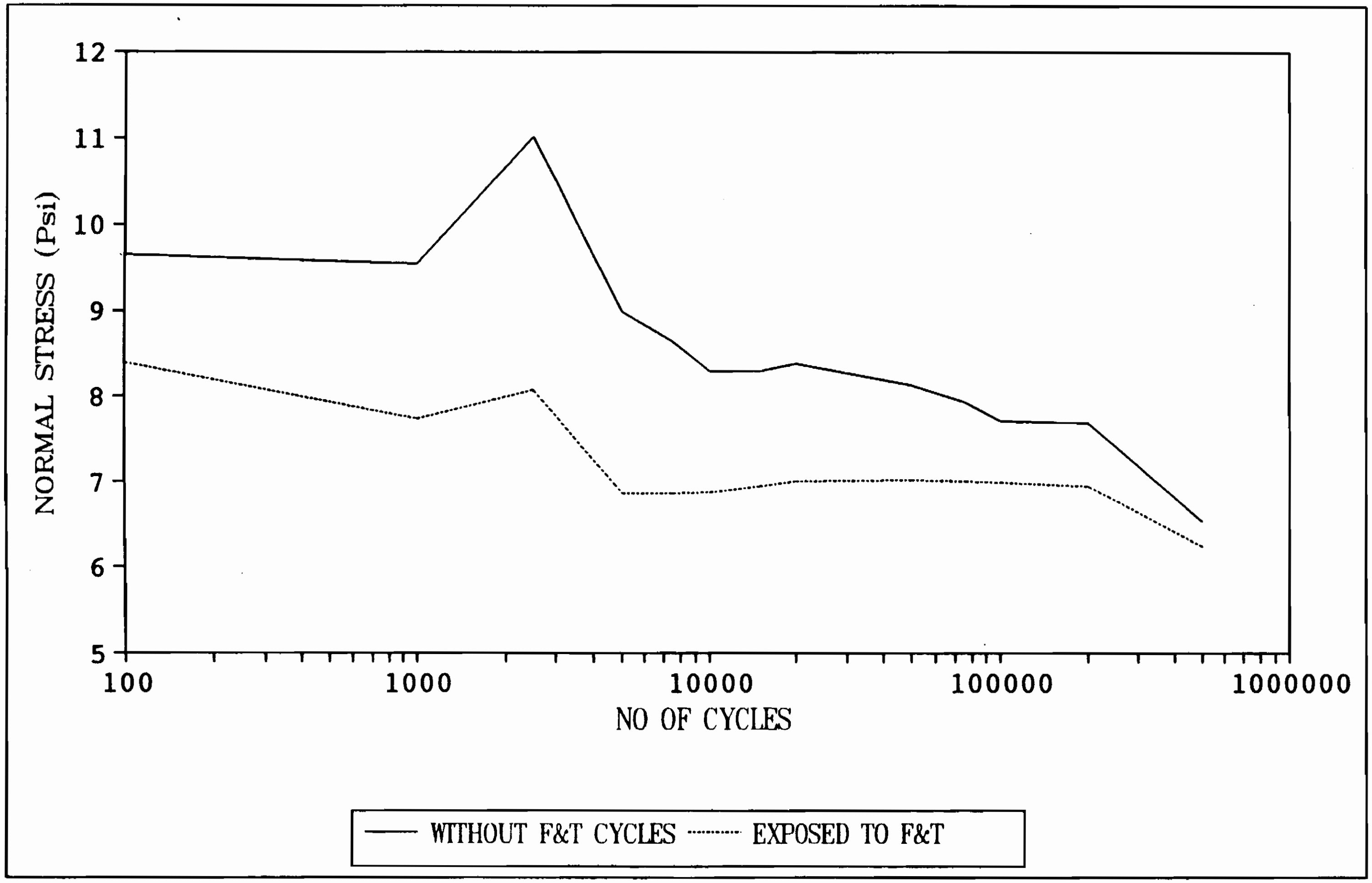


Fig. A.35 Effect of Freezing and Thawing Cycles on Sealant B Performance at 0.25 in. Joint Width Under Compression

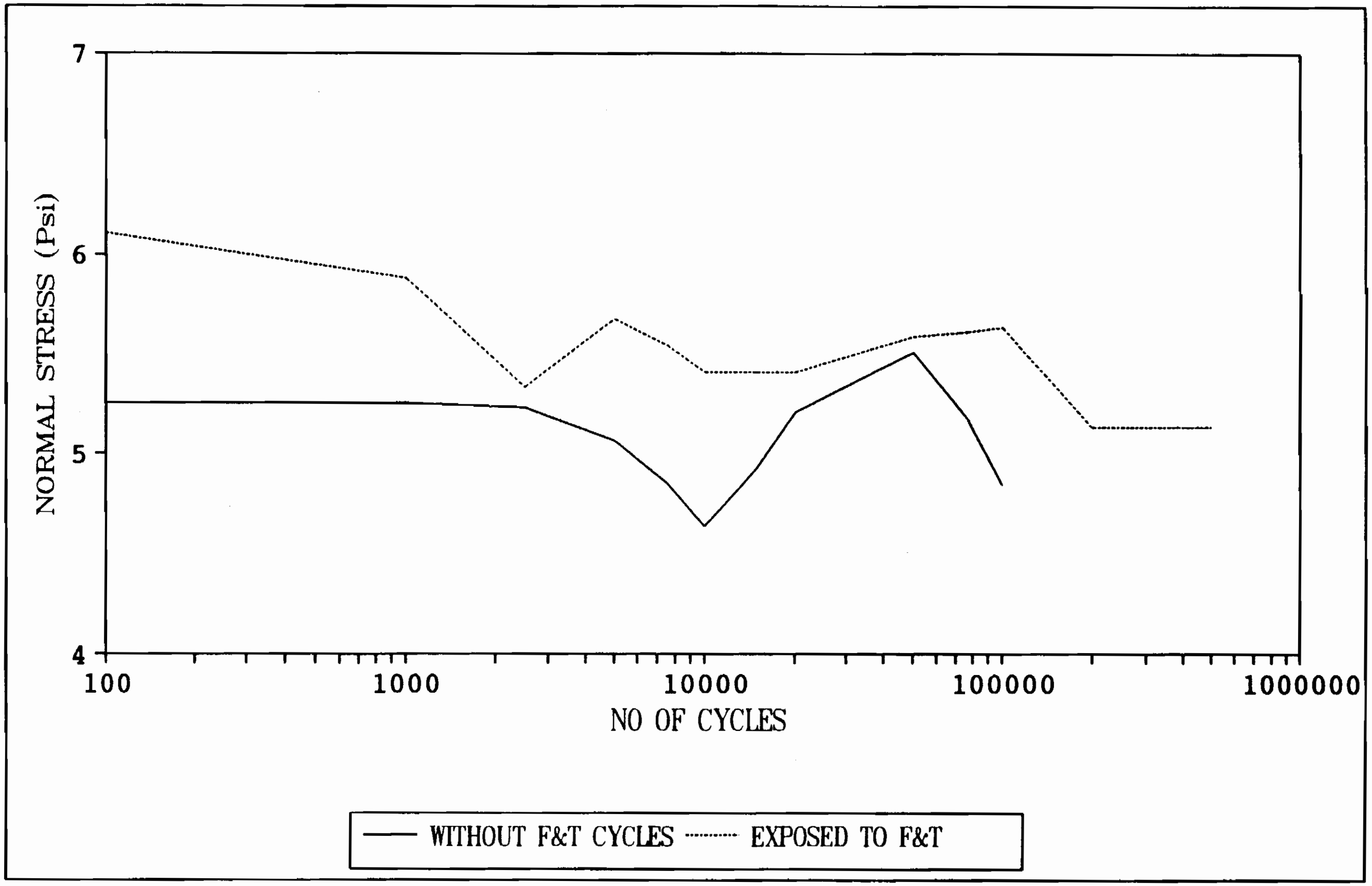
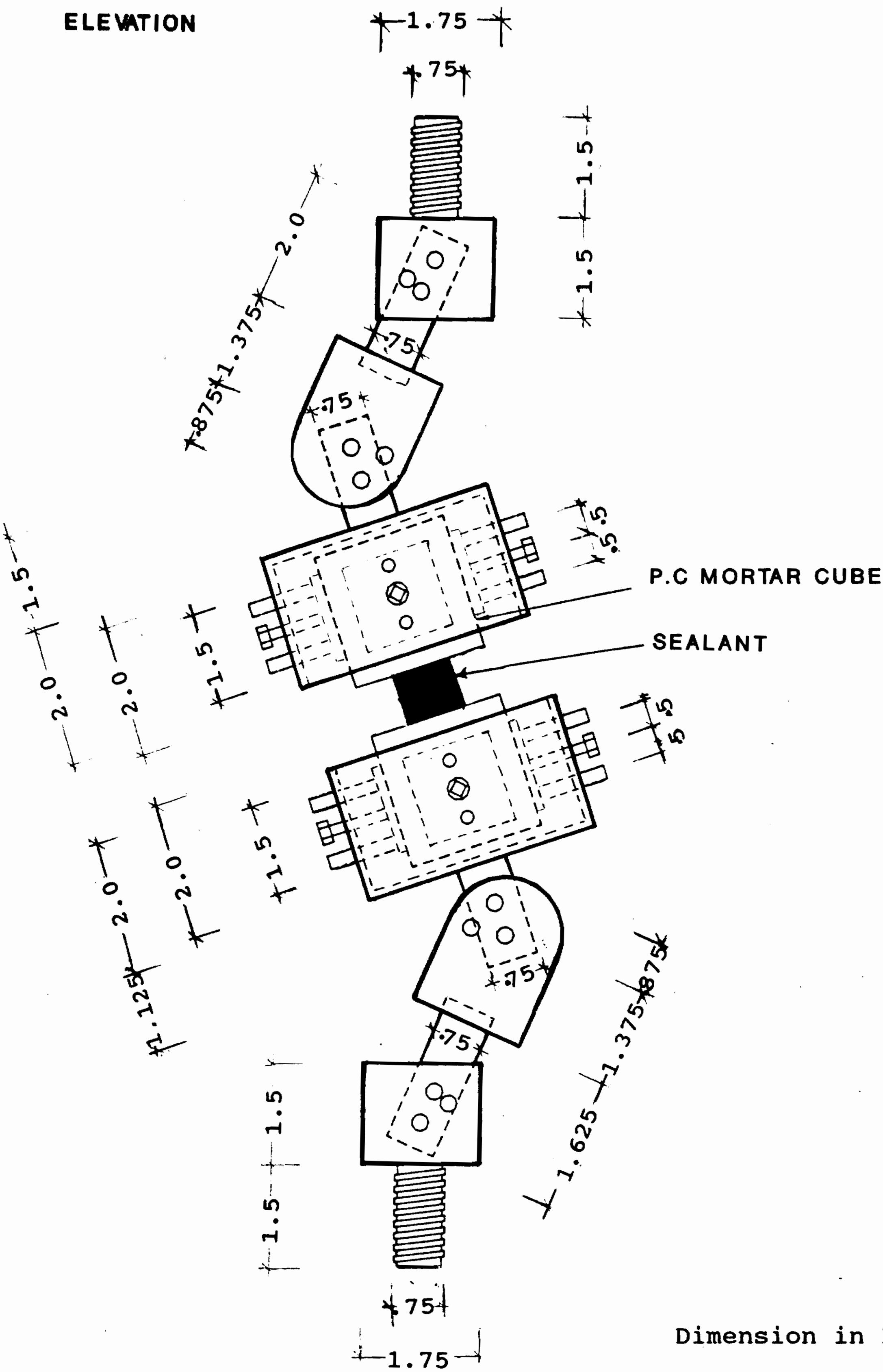


Fig. A.36 Effect of Freezing and Thawing Cycles on Sealant B Performance at 0.25 in. Joint Width Under Tension

APPENDIX B

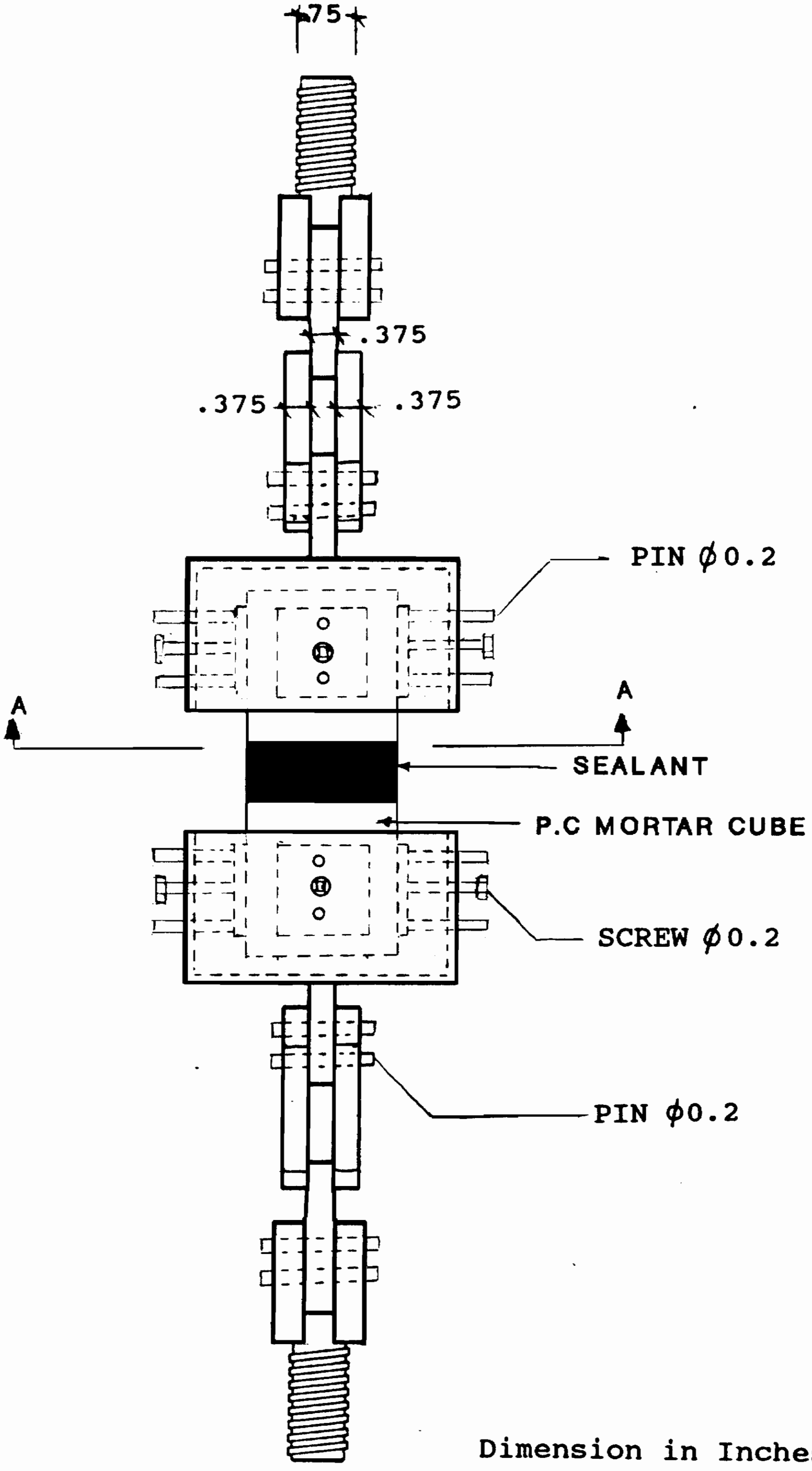
FIXTURE DETAILED DRAWINGS

ELEVATION



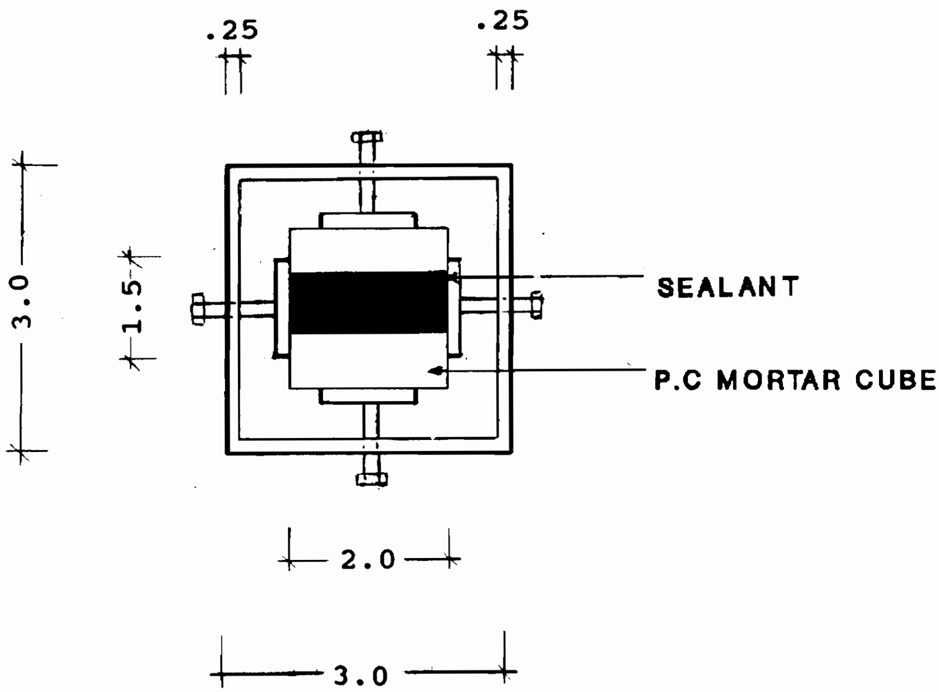
Dimension in Inches

SIDE VIEW



Dimension in Inches

SECTION A-A



Dimension in Inches

VITA

Saad Ahmad Abo-Qudais was born on March 17, 1968 in Irbid, Jordan. He graduated from Irbid Secondary School in June, 1985. In January of 1990 he received a Bachelor of Science degree in Civil Engineering from Jordan University of Science and Technology.

He entered graduate school in the Department of Civil Engineering at Jordan University of Science and Technology (JUST) in January, 1990 to pursue his Master of Science. He worked as a teaching assistant for Soil Mechanics, Construction Management, and Civil Engineering Material courses. In January 1991, Mr. Abo-Qudais transferred to Virginia Polytechnic Institute and State University (VPI & SU) and joined the Transportation and Materials Division of the of the Civil Engineering Department as a Master of Science candidate. While attending graduate school at VPI & SU, he worked as a graduate research assistant, on sealant project sponsored by Center for Adhesive and Sealant Science at VPI & SU, A Master of Science is expected in August 1992. Mr. Abo-Qudais has been admitted to the Ph.D program of Civil Engineering at Virginia Tech.

Saad Abo-Qudais

Saad Ahmad Abo-Qudais