CHEMCRETE-MODIFIED HOT MIXED ASPHALT MIXTURES

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I. INTRODUCTION

Hot mixed asphalt (HMA) mixtures constitute over ninety percent of the two million miles of paved roads in the United States. Rehabilitating the existing HMA surfaces along with new constructions consume over 500 million tons of HMA mixtures annually at a cost of 15 billion dollars. This makes the HMA industry a significant contributor to the nation=s mobility and economic prosperity. Therefore, the performance of HMA mixtures placed on road surfaces are very crucial to the future of the entire nation. Good performance of a pavement is defined as a long service life without major interruptions to the traveling public and surrounding businesses.

A good performing pavement would show good resistance to the prevailing failure modes. Rutting failure is characterized by permanent depressions in the wheeltracks. Cracking failures are caused by three factors: fatigue, thermal, and aging. Fatigue cracking is characterized by longitudinal and interconnected cracks in the wheeltracks. Thermal cracking is characterized by transverse cracking across the pavement surface. Age cracking is characterized by block cracks covering the entire pavement surface. The resistance of HMA surfaces to these failures is dependent upon proper selection of materials (asphalt binder and aggregates), good mixture design, proper construction and adequate structural thickness design.

However, prior to designing HMA pavements that are resistant to these failures, it is important that a full understanding of the causes of these failures be achieved. Rutting of HMA pavements can be caused by either the shear failure of the HMA mixture or the compressibility of the supporting layers (e.g. base course and subgrade). The shear failure of the HMA mixture is controlled by the magnitude of its shear strength at elevated temperatures while the compressibility of the base and subgrade layers are controlled by their resistance to compressive strains. Fatigue cracking of HMA mixtures is caused by the repeated tensile strains. The resistance of the HMA mixture to fatigue cracking is measured in terms of its ability to resist cracking under repeated loads generating a given level of a tensile strain. Thermal cracking of the HMA mixture is controlled by its ability to resist the tensile stresses generated by the shrinking of the HMA surface under freezing temperatures. Block cracking of the HMA mixture is controlled by its aging characteristics. As the asphalt binder ages, it becomes brittle and incapable of absorbing the load/environment induced deformations which leads to the cracking of the HMA surface. Aging of the asphalt binder is caused by a process called oxidation which forces volatiles out of the binder as it is exposed to oxygen in the air. The farther down the mixture is located from the pavement surface, the less exposed to oxygen will be, which reduces its susceptibility to oxidative aging.

It should be recognized that not all pavements are required to resist all combinations of the failure modes. Each pavement has a unique set of prevailing failure modes that it must resist which are controlled by the traffic loads and environmental conditions that the pavement will be subjected to. For example, a pavement section in a desert environment with heavy traffic loads should be designed to resist rutting, fatigue cracking, and block cracking, while a pavement in a cold environment subjected to the same traffic loads should be designed to resist thermal and fatigue cracking. Therefore, the primary goal of a mix design and analysis procedure is to eliminate or minimize the prevailing failure modes of a pavement section.

I.1 Objectives

The study documented in this report has two objectives: a) review and document previous efforts and b) evaluate HMA mixtures used on a Caltrans project.

a. Review and document previous efforts: conduct a thorough review of the previous studies that evaluated Chemcrete-modified HMA mixtures, and

b. Evaluate HMA mixtures used on a Caltrans project: conduct a laboratory evaluation of two mixtures used on a Caltrans project: a Chemcrete-modified mixture and a control mixture.

I.2. Scope

The review of previous research/evaluation efforts to evaluate the performance of Chemcrete-modified HMA mixtures covers activities that were conducted within the past 20-years. These activities conducted laboratory and field experiments which compare the relative performance of Chemcrete-modified mixtures with unmodified mixtures (control). The findings of the previous activities will be documented and assessed relative to their contributions toward the state of knowledge about Chemcrete-modified mixtures.

The evaluation of Chemcrete-modified mixture used on a Caltrans project presents the data generated from a laboratory experiment which assessed the fatigue resistance and moisture sensitivity of HMA mixtures and the rheological properties of the Chemcrete-modified binder. The evaluation process will use the laboratory data along with mechanistic analyses to assess the relative performance of Chemcrete-modified mixtures and the control mixtures. Mechanistic pavement designs will be conducted to identify the impact of the Chemcrete-modified mixtures toward the final design.

II. PREVIOUS RESEARCH/EVALUATION EFFORTS

II.1. Chemcrete Modifier

The Chemcrete modification process was introduced into the HMA industry in the early 1980's in Germany. The Chemcrete modifier is a bimetallic catalyst in liquid form that significantly increases the stiffness of the HMA mixture. The Chemcrete modifier is injected at a rate of 2% by weight of asphalt binder directly into the binder feed line at the mixing plant via the Chemcrete Automatic Dosing System. The asphalt binder and the Chemcrete modifier then pass through a static mixer installed in the binder feed line to insure proper mixing and uniform results on the road. Thereafter, all normal procedures and practices can be used for mixing, placing, and compacting the Chemcrete-modified HMA mixtures.

In 1984 Chemcrete International began its activities in Europe. Since this technology was unknown at the time, the first two years were spent doing extensive laboratory testing and research followed by four years of road testing that is required in cold climate areas. These efforts led to governmental approvals and commercial usage of Chemcrete-modified HMA mixtures in Germany, Switzerland, and Italy. Also in 1984, Chemcrete International opened offices in Brussels to manage the European operation, the most advanced area of Chemcrete usage. In 1989, offices were established in Hong Kong, Kula Lumpur, Manila, and Taiwan. The operation in Mexico was started in 1991, and in South America by 1994. Chemcrete International also opened offices in Poland and Russia in 1995. To date, Chemcrete-modified HMA mixtures have been used on over 3,100 highway and road projects. It is important to notes that, although these roads were built in all climates, no base course failures have occurred.

During the 1980s, Chemcrete-modified HMA mixtures showed a lot of success as binder course materials in various applications in Europe and Asia. During the same time period, Chemcrete-modified HMA mixtures were introduced in the United States as wearing course materials. Several of the U.S. projects experienced premature fatigue and raveling failures indicating that the aging characteristics of the Chemcrete-modified binder prohibits its in wearing courses. Currently, the Chemcrete-modified mixtures are only being recommended for use in binder courses where their success has been well documented through earlier field applications.

II.2 Previous Studies

The previous studies on the performance of Chemcrete-modified HMA mixtures presented in this report will be broken into two groups: laboratory studies and field studies. Both groups of studies share similar testing and evaluation methods which are described below.

Evaluation Methods

The Chemcrete modifier is usually used to modify HMA mixtures placed within the binder course. By definition the binder course is the layer underlying the wearing course of a flexible pavement. Typically the wearing course is about 1-2" thick constructed to provide good skid resistance, smooth ride, and reduce tire noise. The binder course (sometimes referred to as the base course) constitutes the main structural layer of the HMA surface. It is usually 4-8" thick constructed to provide resistance to rutting and cracking under the combined action of traffic loads and environment. Figure 1 shows a sketch of a flexible pavement structure identifying the various nomenclature. It should be noted that the nomenclatures in Figure 1 are the commonly used ones but they are not the only ones used throughout the pavement industry.

The underlaying premise of the Chemcrete modification process is to provide a stable binder course which reduces the magnitude of the stresses and strains throughout the pavement structure generated by traffic loads. By reducing the stresses and strains generated by traffic loads, the pavement structure is protected against rutting and fatigue failures. This concept was followed in all of the previous efforts that were conducted to evaluate the effectiveness of the Chemcrete-modified HMA mixtures. The majority of the previous studies used the resilient modulus (Mr) and the flexural fatigue tests to assess the mechanical properties of the Chemcrete-modified and unmodified HMA mixtures. The following represents a brief description of the Mr and the fatigue tests.

The resilient modulus property is evaluated using the ASTM D4123 test method. The resilient modulus is measured by applying a repeated haversine vertical load (P) along the diametral direction of the specimen. The load duration is for 0.1 seconds followed by a rest period of 0.9 seconds. The corresponding horizontal deformation (δ) is measured using two linear variable differential transducers (LVDTs) attached to the sample 180 degrees apart. The resilient modulus (Mr) is calculated using the following equation:

$$Mr = \frac{0.62\ P}{\delta T}$$

The tensile strength is also measured in the same test method by applying an increasing compressive load at a rate of 2"/min, along the diametral direction of the specimen until failure. The load at failure is referred to as Pult and the tensile strength (TS) is calculated as:

$$TS = \frac{2\ Pult}{3.14DT}$$

Where, D is sample diameter and T is the thickness of the sample.

The flexural fatigue test is used to evaluate the resistance of HMA mixtures subjected to repeated loads. The test is performed on a 2 inch thick by 2.5 inch wide by 15 inch long beam. Figure 2 shows a schematic of the flexural fatigue test. The beam is subjected to four point bending with free rotation and horizontal translation at both load and reaction points. Repeated loading is applied through a sinusoidal wave form at frequencies between five and ten Hertz. The test is performed in the strain or stress controlled mode. In the strain controlled mode the magnitude of the applied load varies during the test to maintain a constant strain level in the sample. In the stress controlled mode, the magnitude of the applied load is kept constant to maintain a constant stress level in the sample.

The flexural stiffness of the specimen is monitored throughout the test. The specimen is considered failed when its stiffness is reduced to fifty percent of its initial value. HMA beams are usually tested at two strain/stress levels to develop a relationship between the applied tensile strain/stress and number of cycles to failure (N_f).

Laboratory Studies

In 1980, researchers at the American University of Beirut conducted a laboratory study to evaluate the effect of Chemcrete modification on the stiffness-temperature response of HMA mixtures (1). The Marshall compaction hammer was used to prepare HMA samples which were used to conduct creep testing. The overall objective of the study was to develop a relationship between mix stiffness at 0.02 seconds loading time and temperature. The mix stiffness at 0.02

seconds loading was selected since it is required by the Shell method of pavement design as a representative stiffness value under traffic loading of 30-40 mph. The HMA mixtures were prepared with a 85-100 grade binder, 3/4" maximum aggregate size, at an asphalt binder content of 4.5% by dry weight of aggregate. The samples were compacted to an average air void of 8.25%. The measured Marshall stabilities were 4,225 lb and 2,334 lb for the Chemcrete-modified and unmodified mixtures, respectively.

In order to obtain the mixtures stiffness at 0.02 loading time as a function of temperature, the researchers conducted static creep load tests at various temperatures. The data from the static creep load tests were then used in conjunction with the Shell nomograph and the Van der Poel=s revised charts to obtain the stiffness at 0.02 seconds loading time versus temperature relationship.

Table 1 summarizes the static creep data in terms of the creep stiffness of the mixtures at various loading times. The data in Table 1 show that the creep stiffness of the Chemcrete-modified mixtures is1.5 to 2 times the creep stiffness of the unmodified mixtures. Figure 3 shows the stiffness at 0.02 seconds loading time versus temperature relationship for the Chemcrete-modified and unmodified mixtures. The study concluded that the Chemcrete-modified HMA mixtures exhibit higher stiffness as a function of temperature, and therefore, would offer better resistance to stresses generated by traffic loading.

In 1980, researchers at Oregon State University conducted a study to evaluate Chemcrete in Oregon=s HMA mixtures (2). The researchers used the diametral test to measure the resilient modulus property, the fatigue resistance, and permanent deformation resistance of the HMA mixtures at 70^{o}F. The diametral test for resilient modulus measurement is the same one described in the previous section. The use of the diametral test for fatigue is, however, different than the flexural fatigue test described previously. Using the diametral test to measure the resistance of HMA to fatigue consists of applying repeated loads to a cylindrical sample (same loads and samples used for the resilient modulus test) in the diametral direction and monitoring the number of load repetitions prior to cracking. While conducting the diametral fatigue testing, the Oregon researchers monitored the permanent deformations accumulated in the sample under repeated loads. The accumulated permanent deformations were then used as a measure of the mixtures resistance to rutting.

Figures 4, 5, and 6 show the resilient modulus, fatigue resistance, and permanent deformation characteristics of the evaluated HMA mixtures at 70^{o}F, respectively. The study concluded that the resilient modulus of HMA mixtures increases as the Chemcrete modifier is used. However, the increase in the Mr is a function of the asphalt binder content, the higher the binder content the smaller the increase in the Mr value (figure 4). The average fatigue life of the Chemcrete-modified mixtures is about three times the fatigue life of the unmodified mixtures (figure 5). In the case of diametral permanent deformation, the study showed that the Chemcrete-modified mixtures performed better than the unmodified mixtures (figure 6).

In 1993, researchers at the Center De Recherches Routieres in Belgium conducted a study to assess the impact of using Chemcrete-modified mixtures on the recommended structural design of flexible pavements (3). The study used the resilient modulus and fatigue properties of the Chemcrete-modified mixtures in the standard pavement design method of the Belgian Ministry of Public Works. The goal of the study was to show the impact of Chemcrete-modified mixtures on reducing the required thickness of the binder course when compared to unmodified mixtures. It was assumed that a wearing course of 2 inch is used on all structures. The following process was used to show the impact of using Chemcrete-modified HMA mixtures:

a. Assume a pavement structure with 2 inch wearing course with unmodified HMA mixtures and a binder course of unmodified HMA mixtures with H being the total thickness of the wearing and binder courses.

b. Vary the thickness of the binder course with unmodified mixtures and calculate the number of load repetitions required to cause fatigue failure using the resilient modulus and fatigue properties of the unmodified HMA mixtures in conjunction with the Belgian pavement design method.

c. For each combination of unmodified wearing and binder courses, determine the equivalent thickness of a Chemcrete-modified binder course required to obtain the same fatigue life. In this case the resilient modulus and fatigue characteristics of the Chemcrete-modified HMA mixtures are used for the binder course.

Using the above process on three different types of subgrade soils (CBR values of 2, 4 and 8) a coefficient K was determined representing the ratio of the thickness of the Chemcrete-modified binder course to the thickness of the unmodified binder course. Figure 7 shows a relationship between K and the number of load repetitions to failure. The relationship shows that depending on the desired fatigue life (load repetitions to fatigue cracking) the use of Chemcrete-modified HMA mixtures could reduce the required thickness of the binder course by a factor between 5 and 25%. For example, the data in Figure 7 show that if a fatigue life of 10 million load repetitions is desired, an unmodified binder course can be replaced by a Chemcrete-modified binder course having a thickness equal t0 75% of the unmodified binder course thickness.

In 1995, a study was conducted in Germany to evaluate the impact of using Chemcrete-modified mixtures on the location and magnitude of the tensile strains within the HMA layer (4). The study used the multi-layer elastic solution BISAR to evaluate the location and magnitude of the tensile strain within the HMA layer. The study concluded that the use of the Chemcrete-modified mixtures in the binder course shifts the location of the tensile strains downward and reduces their magnitudes. The study reported that the first location at which the strains generated by traffic loads become tensile is 4.7" from the surface when a Chemcrete-modified binder course is used as compared to 2.7" from the surface when an unmodified binder course is used. This observation leads to the fact that a Chemcrete-modified binder course would shift the tensile strains into the binder course layer where they can be better resisted to reduce the cracking potential. In the case of the tensile strains magnitude, the study evaluated the additional thickness required from an unmodified binder course in order to reduce the magnitude of the tensile strain to the same level achieved by using a 6" Chemcrete-modified binder course. The data showed that an unmodified base thickness of 8.5" will be required which represents a 42% increase.

In 1981, Kennedy et al. prepared a state of the art paper on the impact of Chemcrete modification on binders and mixtures (5). The paper reviewed numerous previous studies similar to the ones that have already been discussed in this report and also presented some additional information on the temperature susceptibility of Chemcrete-modified binder and the impact of Chemcrete on the Marshall and Hveem stabilities of HMA mixtures. Figure 8 presents the penetration-temperature relationship for modified and unmodified binders which indicates that the modified binders exhibit better temperature susceptibility than the un-modified binders. Figure 9 presents the Marshall stability of modified and unmodified mixtures which shows that the Marshall stability of the modified mixtures increases at a higher rate than the unmodified mixtures at various curing periods. Table 2 summarizes the impact of Chemcrete on the Hveem stability of the HMA mixtures which shows that the modified mixtures exhibit higher Hveem stability and cohesion.

In 1981, Brown and Brodrick conducted a laboratory study to evaluate the relative performance of Chemcrete-modified and unmodified HMA mixtures (6). The study evaluated the fatigue life and dynamic stiffness of the mixtures using an axial repeated load test set up. It should be noted that the axial fatigue testing is not commonly used on HMA mixtures. In addition, for reasons not explained in the report, the Chemcrete-modified mixtures were cured for six weeks at 45°C while the unmodified mixtures were not. The data generated from this study indicated that Chemcrete-modified mixtures have shorter fatigue lives when tested in the strain-controlled mode using the axial fatigue set up. On the other hand, the dynamic stiffness of the Chemcrete-modified mixtures evaluated from the same data were twice the stiffness of the unmodified mixtures. The researchers concluded that the significant increase in the dynamic stiffness of the Chemcrete-modified mixtures would result in lower tensile strains under traffic loads, and therefore, a better pavement fatigue life will be realized.

In 1985, Kennedy and Epps evaluated the properties of Chemcrete-modified HMA mixtures through a laboratory study (7). The experiment evaluated three aggregate sources, two asphalt binder sources, and three asphalt binder grades. This study used a higher percentage of the Chemcrete modifier than other studies, between 4 and 10 percent by weight of the binder. Properties evaluated were tensile strength, resilient modulus, Marshall and Hveem stability. In addition, the moisture sensitivity of the HMA mixtures was evaluated in terms of the retained strength ratios (tensile strength and resilient modulus ratios). Figures 10 and 11 show typical results from this study presenting tensile strength and resilient modulus properties at various temperatures and as a function of modifier content. Based on this study, Kennedy and Epps concluded that the Chemcrete modifier increased the tensile strength and resilient modulus of the mixtures and improved the temperature susceptibility of the mixtures. Also the Chemcrete modifier increased both the Marshall and Hveem stabilities. The Chemcrete modifier did not jeopardize the moisture sensitivity of the HMA mixture which is known to be highly related to the aggregate source being used.

Field Studies

In 1984, the German Road Authority constructed a Chemcrete-modified HMA section on Kassel Road (8). The mix consisted of 0.5 inch maximum size granite aggregate with and 80-100 pen asphalt binder. The Chemcrete-modified layer was a 4 inch binder course underneath a 2 inch un-modified HMA wearing course. The Chemcrete-modified mixtures were sampled annually between 1989 and 1993 and evaluated in terms of the hardening characteristics of the extracted binder using the ring and ball test. The following data present the softening temperatures of the Chemcrete-modified binders extracted at various time intervals.

Date	Softening Temperature (°C)
6-20-89	46.0
12-19-89	50.5
12-20-90	62.0
7-2-91	59.0
2-20-92	52.0
2-5-93	55.5

The above data show that the softening point of the Chemcrete-modified binder did not change significantly over the ten years period (constructed in 1984). This indicates that the Chemcrete-modified binder is not susceptible to extensive aging when used in binder courses.

In September 1988, a Chemcrete-modified section was constructed on the German Autobahn A8 in Stuttgart (9). Again, the section consisted of a 4 inch Chemcrete-modified binder course underneath a 2 inch wearing course. The following data present the softening temperatures of the Chemcrete-modified binders extracted at various time intervals.

Date	Softening Temperature (°C)

3-3-89	50.5
10-2-89	50.5
10-2-90	51.5

The softening temperatures of the extracted Chemcrete-modified binder showed that less than nominal hardening of the binder took place during the two year period following construction.

Figure 12 shows the resilient modulus-temperature relationships for Chemcrete-modified and un-modified HMA mixtures that were constructed in Tennessee in 1993 (10). The data show that the Mr of the Chemcrete-modified mixture is 2.5 times the Mr of the un-modified mixture at high temperature while the Chemcrete-modified mixture is only 15% stiffer than the un-modified mixture at the low temperature. The data indicate that the Chemcrete-modified mixture has better temperature susceptibility than the un-modified mixture which would provide better performance under a wide range of environmental conditions.

A recent study completed by the Dromex Company in Poland showed that the creep modulus of the Chemcrete-modified mixtures are almost double the creep modulus of unmodified mixtures (11). The rutting resistance of the mixtures were evaluated in the wheel tracking device which showed that the Chemcrete-modified mixtures significantly outperformed the unmodified mixtures. The study also showed that the Chemcrete-modification maintains good temperature susceptibility of the HMA mixtures.

III. EVALUATION OF CHEMCRETE-MODIFIED MIXTURES ON A CALTRANS PROJECT

III.1. Project Description

On October 15, 1999, Caltrans constructed a HMA project to compare the performance of Chemcrete-modified HMA mixtures with unmodified mixtures under actual traffic/environmental conditions. The project was constructed on State Route 70 (SR 70) in Nicholas of Fetter County, California. The project consisted of milling 6" of the existing HMA layer and replacing it with 6" of new HMA layer. A Chemcrete test section (500 feet) was installed as part of this project in the northbound lane. The test section consisted of a 4" base course of Chemcrete-modified HMA mixture and a 2" wearing course of unmodified HMA mixture. The rest of the project consisted of a 6" layer of unmodified mixture. Throughout this report, the Chemcrete-modified mixture will be referred to as AChemcrete mix@ and the unmodified mixture will be referred to as Acontrol mix@.

As mentioned earlier, the Chemcrete-modifier can be added at any point during the production process as long as it is thoroughly blended at a rate of two percent by weight of the asphalt binder. Storage of the Chemcrete-modified binder is not a problem since no reaction takes place until it is mixed with the aggregate at the hot mix plant. The amount of the Chemcrete modifier present in the binder can be measured prior to mixing with the aggregate using the Atomic Absorption process. Chemcrete-modified mixtures can be designed using the standard Caltrans Hveem mix design procedure. The use of Chemcrete-modified binder is not expected to significantly impact the selection of the optimum binder content.

Table 3 summarizes the aggregate gradations for the Chemcrete and control mixes used on this project. The control mix consisted of an AR-4000 asphalt binder mixed with 3/4" maximum medium type A/B Caltrans gradation. The optimum binder content as determined by the Caltrans Hveem mix design method was at 5.0% by dry weight of aggregate. The Chemcrete mix uses the same gradation and optimum binder content except that the AR-4000 binder was modified with 2% Chemcrete by weight of binder. The contractor for the project was Granite Construction Co. Both mixtures were produced at Granite=s Elkhorn Plant.

III.2. Experimental Program

The objective of this experimental program was to evaluate the engineering properties of the Chemcrete and control mixes that were placed on SR 70. Two types of materials were sampled during the construction of the project: field produced mixtures and raw materials of aggregate and binder. The field produced mixtures represent materials sampled from the job site and were compacted in the laboratory prior to testing. The field produced mixtures will be referred to as Afield mixed-lab compacted (FMLC)@. The raw materials were sampled from the hot plant during construction and were mixed and compacted in the laboratory prior to testing. The laboratory produced mixtures will be referred to as Alab mixed-lab compacted (LMLC)@.

The FMLC mixtures were tested for the following properties:

$ Hveem stability at 140°F

$ Marshall stability at 140°F

$ Resilient modulus (Mr) at 77 and 104°F

The LMLC mixtures were tested for the following properties:

$ Fatigue resistance using the flexural beam fatigue test under the constant strain condition.

$ Moisture sensitivity using the AASHTO T283 test with one cycle of freeze/thaw

The Hveem and Mrashall stabilities were measured on the Chemcrete mix alone while the Mr and fatigue properties, and moisture sensitivity were measured on both the Chemcrete and control mixes.

In addition to mixtures properties, some of the Chemcrete-modified binder=s properties were also measured including:

$ Viscosity at 135^{o}C
$ Ductility at 25^{o}C
$ Flash point
$ Rheological properties (SSD and SSV)
$ Rheological properties at low temperature

III.3. Data Analysis

The following sections present the analysis of the laboratory data that were measured on both the FMLC and LMLC mixtures and the Chemcrete-modified binder. Wherever possible, the data will be used to predict the potential fatigue and rutting resistance of the Chemcrete and control mixtures.

II.3.a Mixtures Properties

Stabilities and Resilient Modulus Properties

Table 4 summarizes the Hveem and Marshall stability and the resilient modulus data that were measured on the FMLC mixtures. The Hveem and Marshall stabilities were measured according to the standard ASTM methods D1560 and ASTM D1559, respectively, by personnel in the Sacramento County Materials Laboratory. The resilient modulus properties were measured according to ASTM D4123 as described in section II. The Mr properties were measured at 77 and 104°F to assess the temperature susceptibility of the HMA mixtures.

Since the Hveem and Marshall stabilities were not measured on both mixtures, the only comments that can be made are that the Hveem stability is well within the Caltrans specification of 40-43 while the Marshall stability is well above the acceptable range of 2200-2600 lbs. This indicates that the Chemcrete mix exhibits excellent properties.

The Mr properties can be used to compare the temperature susceptibility of the two mixtures. The temperature susceptibility of HMA mixtures is measured in terms of the slope of the Mr versus temperature relationship. The flatter the relationship is the less temperature susceptible the HMA mixture will be. The temperature susceptibility of HMA mixtures is critical because it represents how a mixture will behave as it is subjected to traffic loads under various environmental conditions. The 77°F represents normal operating temperatures while the 104°F represents hot summer periods. A desirable HMA mixture would exhibit high Mr properties at both the 77 and 104°F temperatures. A higher Mr property at 77°F would reduce the tensile strains in the HMA layer and therefore reduce the potential for fatigue cracking while a higher Mr property at 104°F would reduce the shear strains within the HMA layer and reduce the potential for rutting failure.

Figure 13 presents the Mr property as a function of temperature for the Chemcrete and control mixtures. The data in Table 4 and Figure 13 indicate that the Chemcrete modification of the HMA mixtures used on SR 70 increased the Mr at 77°F by 14% and the Mr at 104°F by 40%. The larger increase in the Mr at 104°F shows that the Chemcrete modification improved both the magnitude of the resilient modulus property and the temperature susceptibility of the mixtures. It is expected that these improvements will translate into better resistance to fatigue and rutting failures.

The contribution of the Chemcrete modification to the fatigue resistance of the SR 70 HMA mixtures will be evaluated using the fatigue data generated in this study.

Fatigue Properties

The fatigue properties of the LMLC Chemcrete and control mixtures were measured using the flexural fatigue test described in section II (figure 2). Reed and Graham Laboratories of San Jose California conducted the fatigue testing of the mixtures. The beam fatigue samples were obtained from laboratory compacted slabs under the rolling wheel compactor. The fatigue tests were conducted at 68°F using two levels of strain with three replicates at each strain level. Tables 5 and 6 summarizes the fatigue data for both mixtures and Figure 14 compares the fatigue curves for the two mixtures.

The data in Tables 5 and 6 show that the variabilities of the air voids, the applied strains, and measured flexural modulus are excellent (coefficients of variation < 10%). The variability of the number of cycles to failure is relatively high which reflects the complex relationship among the various factors that impact such a response. Even though the CVs for the number of cycles to failure are as high as 38%, this still within the expected variability of the flexural fatigue test. Since the air voids among the two mixtures are very close, the fatigue responses of the two mixtures can be compared. Using the fatigue data presented in Tables 5 and 6, the following relationships between the number of load cycles to failure (N_f) and the tensile strain ε were developed:

Chemcrete Mix: $$N_f = 9.8x10^{16} (1/\varepsilon)^{4.83} \qquad (1)$$

Control Mix: $$N_f = 8.1x10^{15} (1/\varepsilon)^{4.36} \qquad (2)$$

Where:

N_f = number of load repetitions to fatigue failure

ε = tensile strain at the bottom of the HMA layer (microns)

Figure 14 plots the two curves representing the fatigue relationships for the Chemcrete and control mixtures. When evaluating the data presented in Tables 5 and 6, Figure 14, and equations 1 and 2, the first question to be answered is: do these two curves represent significantly different mixtures? Statistical analyses were used to answer this question. The statistical analysis was conducted using the F-test with a confidence level of 95%. Using a confidence level of 95% results in an $\alpha = 0.05$ (5%). Using all the replicates data, the statistical analysis calculates a P-value which is an indication on how the two curves compare to each other. If the P-value is larger than α then the two curves are not statistically different, on the other hand if the P-value is smaller than α, then the two curves are statistically different. Using all the replicates data for both mixtures, a P-value = 0.237 was calculated which indicates that the fatigue curves of the Chemcrete and control mixtures are not statistically different.

Putting all of the above analyses together, it can be concluded that the Chemcrete modification did not significantly impact the fatigue characteristics of the HMA mixtures used on SR 70 when tested under the control strain mode at 68°F.

Structural Analysis

The final objective of evaluating the fatigue characteristics and resilient modulus of HMA mixtures is to be able to conduct structural analysis of the pavement system under standard axle loading and to predict its potential performance life. Using the resilient modulus properties of the HMA mixtures in the multilayer elastic solution, the state of stresses and trains under standard axle loading can be evaluated throughout the pavement structure.

The analysis conducted in this effort used the multilayer elastic solution and is based on the following assumptions:

Chemcrete Pavement Structure: 2" control mix
4" Chemcrete mix
6" crushed aggregate base (CAB)

Control Pavement Structure: 6" control mix
6" crushed aggregate base

Fatigue Analysis: Mr of Chemcrete mix at 77^{o}F: 1,240,000 psi
Mr of control mix at 77^{o}F: 1,090,000 psi
Mr of crushed aggregate base: 30,000 psi
Mr of Subgrade: 7,500 psi

Both the Chemcrete and control pavement structures will be loaded with a standard 18,000 lb single axle load. The maximum tensile strain at the bottom of the 6" HMA layer will be calculated and used in the fatigue relationship to estimate the number of load repetitions to failure for each structure. It should noted here that the thickness of the CAB and properties of the subgrade and CAB may not the exact ones for SR 70. However, since this is a comparative analysis of the two structures: Chemcrete and control, and as long as the properties and thickness of the CAB and subgrade are kept constant for both structurers, then the comparison will be valid.

The multilayer elastic solution predicted the maximum tensile strains at the bottom of the 6" HMA layer as follows:

Chemcrete Pavement Structure: ε_{tmax} = 112 microns

Control Pavement structure: ε_{tmax} = 121 microns

The above data show that the Chemcrete modification of the 4" base mixture resulted in a 8% reduction in the tensile strain at the bottom of the HMA layer. Using the calculated tensile strains at the bottom of the HMA layer in the fatigue relationship would predict the impact of the Chemcrete modification on the fatigue life of the pavement structure. Since the two fatigue relationship were statistically the same and to be conservative, the fatigue relationship for the control mix will be used to predict the fatigue life of both pavement structures.

Chemcrete Pavement Structure: $N_f = 8.1x10^{15}(1/112)^{4.36} = 9{,}416{,}600$ ESALs

Control Pavement Structure: $N_f = 8.1x10^{15}(1/121)^{4.36} = 6{,}722{,}700$ ESALs

The above fatigue performance analysis shows that the Chemcrete modification of the HMA mixture increased the fatigue performance of the pavement structure by 40%. This analysis shows clearly how the Chemcrete modification improves the performance of HMA mixtures: 1) the Chemcrete modification does not significantly impact the fatigue characteristics of the HMA mixture and 2) the Chemcrete modification improves the resilient modulus of the HMA mix which in turns reduces the tensile strains at the bottom of the HMA layer. The combination of these two phenomenons translates into a significant improvement in the fatigue life of flexible pavements.

The mechanistic analysis presented in this report showed that the combination of the improved Mr property of the Chemcrete-modified mixture coupled with its fatigue characteristics, which are similar to the un-modified mixture, have resulted in a significant increase in the performance life of the pavement (40% increase in pavement life).

Moisture Sensitivity

The moisture sensitivity of the LMLC Chemcrete and control mixtures were measured using the AASHTO T283 test procedure with one freeze/thaw cycle. Reed and Graham Laboratories of San Jose California conducted the moisture sensitivity testing of the mixtures. In summary, the AASHTO T283 compacts HMA samples to air voids between 6 and 8 % and evaluates the tensile strength of the compacted samples at the dry and moisture conditioned stages. Moisture conditioning consists of saturating the compacted samples between 55 and 80% and subject them to a 16 hours cycle of freezing followed by a 24 hours of thawing at 60^{o}C. The tensile strength ratio is evaluated as the ratio of the TS of the moisture conditioned samples over the TS of the dry samples. Typical moisture sensitivity specifications call for a minimum value of the dry TS of 90 psi and a minimum TS ratio of 80%.

Table 7 summarizes the moisture sensitivity properties of the LMLC Chemcrete and control mixtures. The data include air voids, TS, and TS ratios for both mixtures. The data presented in table 7 show that the Chemcrete mixtures have far superior TS properties than the control mixtures at both the dry and moisture conditioned stages. Both mixtures fail to meet the typically required TS ratio of 80%. However, the Chemcrete mix offers a moisture conditioned TS which exceeds the typically required dry TS. On the other hand, the moisture conditioned TS for the control mix falls below the acceptable level of TS for HMA mixtures.

This evaluation presents a unique situation of moisture sensitivity of HMA mixtures. The Chemcrete mixture provides a high dry TS and maintained a good level of conditioned TS. However, the Chemcrete mix did not meet the required TS ratio of 80%. The question to be asked at this point is how important it is to meet the minimum TS ratio in a case where both the dry and conditioned TS are well above the recommended minimum value ? The answer to this question should consider other factors such as the impact of the high TS on the fatigue and low temperature cracking resistance of the HMA mix. As this study already showed, the fatigue characteristics of the Chemcrete mix is similar to the control mix and the low temperature properties of the Chemcrete-modified binder are well above the recommended properties for the SR 70 project location (data will be presented in the next section).

Considering all of the above data, it can be concluded that the moisture sensitivity of the Chemcrete mixture should not present any problems. In addition, it should be noted that the moisture sensitivity of HMA mixtures is a function of the aggregates properties which in this case impacted both mixtures. The positive note here is that the Chemcrete-modified binder helped improve the performance of the mix at the moisture conditioning stage (Chemcrete mix=s conditioned strength is double the control mix=s strength, Table 7). This conclusion coincides very well with the findings of a 1981 Army Corps of Engineers study which showed that the Chemcrete-modified binder can be successfully used to improve the moisture sensitivity of marginal aggregates (12).

Thermal Cracking

The thermal cracking resistance of the LMLC Chemcrete and control mixtures were measured using the thermal stress restrained specimen test (TSRST). Reed and Graham Laboratories of San Jose California conducted the TSRST testing of the mixtures. In summary, the TSRST subjects beam samples (2"x2"x10") to thermal stresses by dropping the specimen temperature at a 10°C/hour while restraining it from any movements. As the sample is cooled down, internal tensile stresses are generated. Thermal cracking occurs when the internal stresses exceed the tensile strength of the mixture. The temperature at which cracking occurs is referred to as the Afracture temperature@ and the stress at cracking is referred to as the Afracture stress@. The fracture temperature controls the in service low temperature that the mixture can withstand prior to experience thermal cracking while the fracture stress represents the expected spacing of the thermal cracks. The resistance of HMA mixtures to thermal cracking is controlled by the properties of the asphalt binder. As the asphalt binder ages and becomes more brittle, it is expected to crack under warmer temperatures.

Samples of the Chemcrete and control mixtures were short-term aged for 2 hours at 135^{o}C prior to compaction to simulate field conditions. Following the aging process, mixtures were compacted using the rolling wheel compactor into slabs with air voids between 5 and 7 percent. The TSRST samples were then cut from rolling wheel compacted slabs. Table 8 summarizes the TSRST data for the Chemcrete and control mixtures. The TSRST data show that there is not any significant difference between the Chemcrete and control mixtures resistance to thermal cracking. The TSRST data indicate that the Chemcrete-modified binder has similar low temperature characteristics to the un-modified binder.

III.3.b. Binder Properties

As mentioned earlier, some conventional and rheological properties of the Chemcrete-modified binder were evaluated. Table 9 summarizes the measured properties of the Chemcrete-modified binder used on SR 70 project along with Caltrans= PBA specification limits wherever applicable. The viscosity and flash point properties of the Chemcrete-modified binder indicate that the Chemcrete modification produces a binder that fits well within the Caltrans=s PBA specification.

The data in Table 9 show that the Chemcrete modification maintained good rheological properties of the binder at the low temperature. Using the bending beam rheometer (BBR) data, a low temperature grade was established for the Chemcrete-modified binder to be -22^{o}C. The measured low temperature grade of the Chemcrete-modified binder of -22^{o}C is well within the environmental requirements at the SR 70 project location.

IV. SUMMARY AND RECOMMENDATIONS

IV.1. Previous Efforts

Within the past twenty years, numerous research efforts have been conducted to evaluate the impact of Chemcrete modification on the performance of HMA mixtures. Several of these efforts used laboratory testing procedures to evaluate the creep, fatigue, and resilient modulus properties of Chemcrete-modified HMA mixtures and compared them to unmodified mixtures. Almost all of the previous efforts concluded that the Chemcrete modification improves the fatigue, creep, and resilient properties of HMA mixtures. Some efforts evaluated the properties of the Chemcrete-modified binder extracted from field cores. These efforts concluded that the Chemcrete-modified binder experiences only nominal aging under extended field conditions.

Only one study evaluated the impact of Chemcrete modification on the moisture sensitivity of HMA mixtures (7). This laboratory study showed that the Chemcrete modification neither improved nor damaged the moisture sensitivity of HMA mixtures. The most recent study out of Poland evaluated the performance of Chemcrete-modified HMA mixtures under a wheel tracking device which showed that the Chemcrete modification improves the resistance of HMA mixtures to rutting under wheel track loading.

IV.2. Current Effort

The current research effort documented in section III of this report evaluated Chemcrete-modified and unmodified HMA mixtures used on a Caltrans project on SR 70. The evaluation program consisted of measuring the temperature susceptibility of the FMLC mixtures, the fatigue characteristics, and moisture sensitivity of the LMLC mixtures. The properties of the Chemcrete-modified binder were also evaluated. The data generated in this research effort showed that the Chemcrete modification of HMA improves the resilient modulus properties at intermediate and elevated temperatures. Since the Chemcrete modification improves the resilient modulus at the elevated temperature of 104°F more significantly than the resilient modulus at the intermediate temperature of 77°F, it resulted in a better temperature susceptibility than the unmodified mixtures. In the case of fatigue properties, the Chemcrete modification maintained excellent fatigue characteristics of HMA mixtures. However, when the impact of Chemcrete modification on the resilient modulus property is combined with the fatigue characteristics of the HMA mixtures, the Chemcrete modification showed to improve the expected fatigue performance of the pavement by 40%.

In the case of moisture sensitivity, the Chemcrete modification produced a mix that is better capable to resist moisture damage than the control mix through significantly higher dry and moisture conditioned TS values. Normally when HMA mixtures are produced with TS values two times higher than the control mix TS values, the design engineer would express concerns about the impact of such high properties on the fatigue and low temperature cracking properties such a mix. In this case, the laboratory data measured on the Chemcrete-modified mixtures showed that the Chemcrete modification of the SR 70 HMA mixture was successful in accomplishing both tasks: significantly increasing the dry TS while maintaining good fatigue and low temperature cracking properties.

In the case of thermal cracking, both the mixture=s and binder=s tests show that the Chemcrete modification maintained good low temperature properties. Based on both the TSRST and rheological testing, the Chemcrete mixtures showed a resistance to thermal cracking which is well within the environmental requirements at the SR 70 project location.

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5. Kennedy, T.W., Cummings, L.O., and White, T.D., A Changing Asphalt Through New Chemistry@ Transportation research Board Annual Meeting, Washington DC, February 16-18, 1981.

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11. Written Communication from Chemcrete International on July 9, 2000.

12. Perkins, J.D., ALaboratory Evaluation of Chem-Crete Processed Asphalt for use with Marginal Construction Material,@ U.S. Army Waterways Experiment Station, Vicksburg, Miss., January 1981.

Table 1. Stiffness as a function of time and temperature of Chemcrete-modified and unmodified HMA mixtures (1).

Stiffness of Mixtures in N/m^2 x 10^8

Time of Loading	**2°C**		**23°C**		**45°C**		**60°C**	
	Chemcrete	Control	Chemcrete	Control	Chemcrete	Control	Chemcrete	Control
30 sec	24.2	16.5	14.7	7.2	3.5	1.2	0.60	0.16
1 min	22.0	14.3	13.0	6.0	2.9	0.90	0.47	0.14
2 min	20.0	13.1	10.5	5.2	2.2	0.71	0.40	0.12
5 min	18.1	11.5	9.2	4.3	1.9	0.55	0.30	0.10
10min	16.1	10.1	7.7	3.3	1.6	0.46	0.26	0.081
30 min	12.6	8.3	6.4	2.8	1.4	0.37	0.20	0.070
5 hrs	10.2	7.0	5.2	2.0	1.2	0.29	0.15	0.063

Table 2. Hveem properties of Chemcrete-modified and unmodified HMA mixtures (5).

Source	**Stability**		**Cohesion**	
	Chemcrete	**Control**	**Chemcrete**	**Control**
Nevada	53	44	1381	457
California (valley)	45	37	558	240
California (coastal)	51	37	872	256
California (air refined)		58		1076
Idaho	37	25	189	133
Oklahoma	34	27	210	65
Arizona	61	49	892	373

Table 3. Aggregate gradations used in Chemcrete and control mixes.

<table>
<tr><th colspan="2">Stockpile</th><th colspan="2">Percent</th></tr>
<tr><td colspan="2">Washed Sand</td><td colspan="2">10</td></tr>
<tr><td colspan="2">1/4"x Dust</td><td colspan="2">35</td></tr>
<tr><td colspan="2">3/8" x No.4</td><td colspan="2">20</td></tr>
<tr><td colspan="2">2" x 3/8"</td><td colspan="2">16</td></tr>
<tr><td colspan="2">3/4" x 1/2"</td><td colspan="2">19</td></tr>
<tr><th>Sieve</th><th>Design</th><th>Operating Range</th><th>Contract Compliance</th></tr>
<tr><td>1"</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td>3/4"</td><td>99</td><td>95-100</td><td>90-100</td></tr>
<tr><td>3/8"</td><td>73</td><td>65-80</td><td>60-85</td></tr>
<tr><td>No. 4</td><td>53 = x</td><td>48-58</td><td>45-61</td></tr>
<tr><td>No. 8</td><td>38 = x</td><td>33-43</td><td>30-46</td></tr>
<tr><td>No. 30</td><td>18 = x</td><td>13-23</td><td>10-26</td></tr>
<tr><td>No. 200</td><td>5</td><td>3-8</td><td>0-11</td></tr>
</table>

Table 4. Hveem and Marshall Stabilities and Mr properties of FMLC mixtures.

Mix	**Hveem Stability at 140°F**	**Marshall Stability (Lbs) at 140°F**	**Mr (ksi)* at 77°F**	**Mr (ksi) at 104°F**
Chemcrete	42	4420	1,240	155
Control	na	na	1,090	111

Table 5. Summary of the fatigue data at 68°F for the Chemcrete mix.

Sample	**Air Voids (%)**	**Strain Level**	**Strain (microns)**	**Cycles to Failure**	**Initial Modulus (ksi)**	**Final Modulus (ksi)**
Chemcrete Mix						
1	6.3	high	465	2.10E4	1,340	670
2	6.1	high	459	9.29E3	1,420	710
3	6.5	high	418	1.58E4	1,370	685
Average	6.3		447	1.54E4	1,377	688
STD*	0.2		26	5.87E3	40	20
CV**	3		6	37	3	3
1	6.0	low	260	1.35E5	1,510	755
2	6.2	low	258	3.03E5	1,520	760
3	6.4	low	251	2.30E5	1,590	795
Average	6.2		256	2.23E5	1,540	770
STD	0.2		5	8.42E4	44	22
CV	3		2	38	3	3

* STD: Standard deviation
** CV: Coefficient of variation = (standard deviation/average)x100

Table 6. Summary of the fatigue data at 68^{o}F for the control mix.

Sample	Air Voids (%)	Strain Level	Strain (microns)	Cycles to Failure	Initial Modulus (ksi)	Final Modulus (ksi)
Control Mix						
1	6.5	high	473	1.30E4	1,270	635
2	6.5	high	446	2.06E4	1,130	565
3	6.2	high	441	2.77E4	1,130	565
Average	6.4		453	2.04E4	1,177	588
STD*	0.2		17	7.35E3	81	40
CV**	3		4	36	7	7
1	6.5	low	282	1.95E5	1,430	715
2	6.9	low	271	1.98E5	1,210	605
3	6.5	low	271	1.67E5	1,240	620
Average	6.6		275	1.87E5	1,293	647
STD	0.2		6	1.71E4	119	60
CV	3		2	9	9	9

* STD: Standard deviation
** CV: Coefficient of variation = (standard deviation/average)x100

Table 7. Summary of the moisture sensitivity data of the Chemcrete and control mixtures.

Mix Type	Mix Condition	Air Voids (%)	Saturation (%)	Tensile Strength (psi)	Average TS (psi)	TS ratio (%)
Control	Dry	6.0 5.9 7.1	na na na	129 132 148	136	40
	Conditioned	5.9 6.6 6.3	67 73 67	50 55 57	54	
Chemcrete	Dry	6.9 8.0 6.8	na na na	232 192 218	214	49
	Conditioned	6.2 7.3 8.0	58 63 55	96 118 98	104	

Table 8. Summary of the thermal cracking data of the Chemcrete and control mixtures.

Mix Type	Air Voids (%)	Fracture Temperature (C)	Average Frac. Temp. (C)	Fracture Stress (kPa)	Average Frac. Str. (kPa)
Control	6.0 5.8 5.4	-13.9 -14.0 -15.7	-14.5	2858 3327 3018	3068
Chemcrete	5.5 6.8 5.1	-15.2 -14.4 -13.9	-14.5	3240 2835 3055	3043

Table 9. Properties of the Chemcrete-modified binder

Test	Temperature (C)	Result	Caltrans PBA Spec
Original Chemcrete-Modified binder			
Kinematic Viscosity (AASHTO T201)	135	250	2000 max.
Ductility (AASHTO T51)	25	105+	
Flash Point (AASHTO T48)		283	232 min.
DSR ,SSD (CTM 381)	25	-6.300	
DSR, SSV (CTM 381)	25	-0.083	
RTFO+PAV Aged Chemcrete-Modified Binder			
BBR, Stiffness (AASHTO TP-1)	-6.0 -12.0 -18.0	119 261 431	300 max
Failure Temp.*	**-24.2**		
BBR, m-value (AASHTO TP-1)	-6.0 -12.0 -18.0	0.367 0.293 0.242	0.3 min
Failure Temp.*	**-21.7**		

* Failure temperatures represent the test temperature at which the stiffness reaches a value of 300 MPa and the m-value is at 0.3 minus10^{o}C.

The warmer of the two failure temperatures represent the low temperature grade of the binder.

Typical Pavement Structure

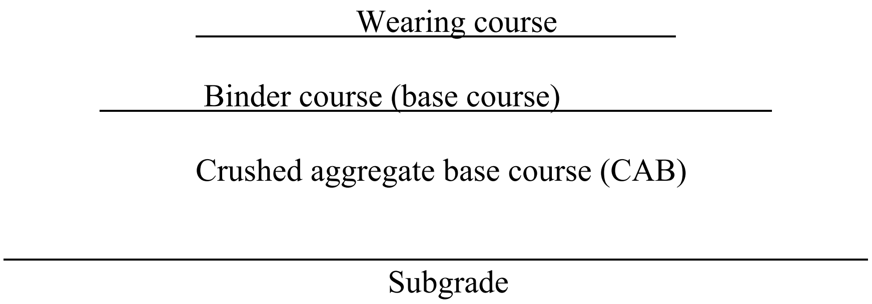

Figure 1. Sketch of a flexible pavement structure.

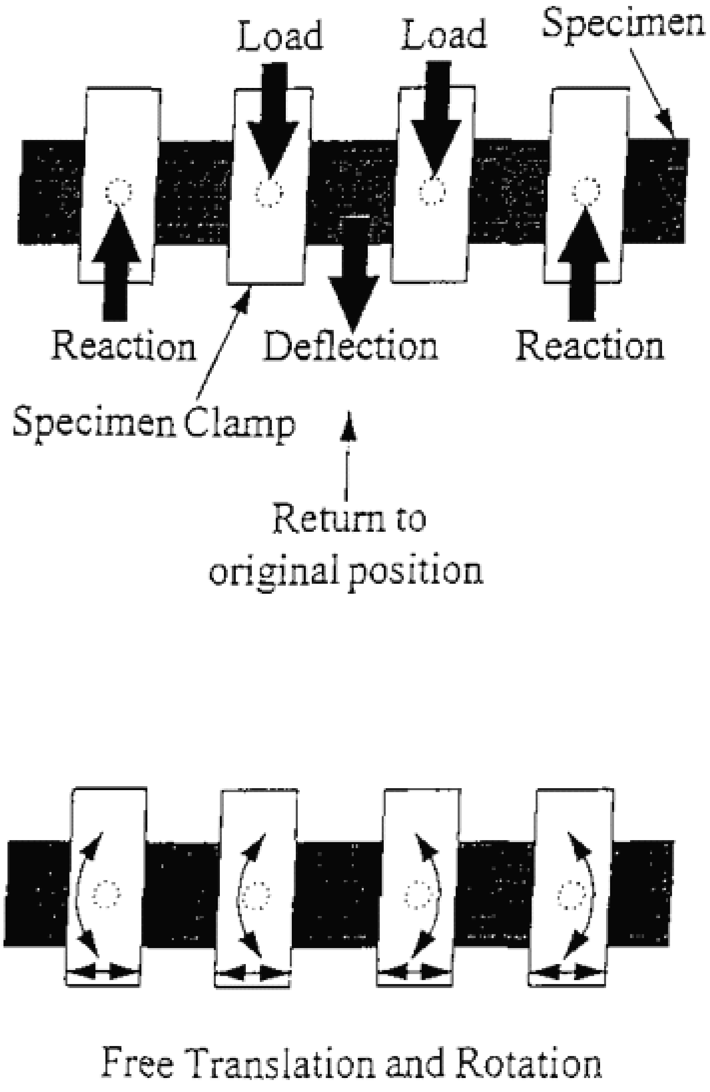

Figure 2. Schematics of the flexural fatigue test.

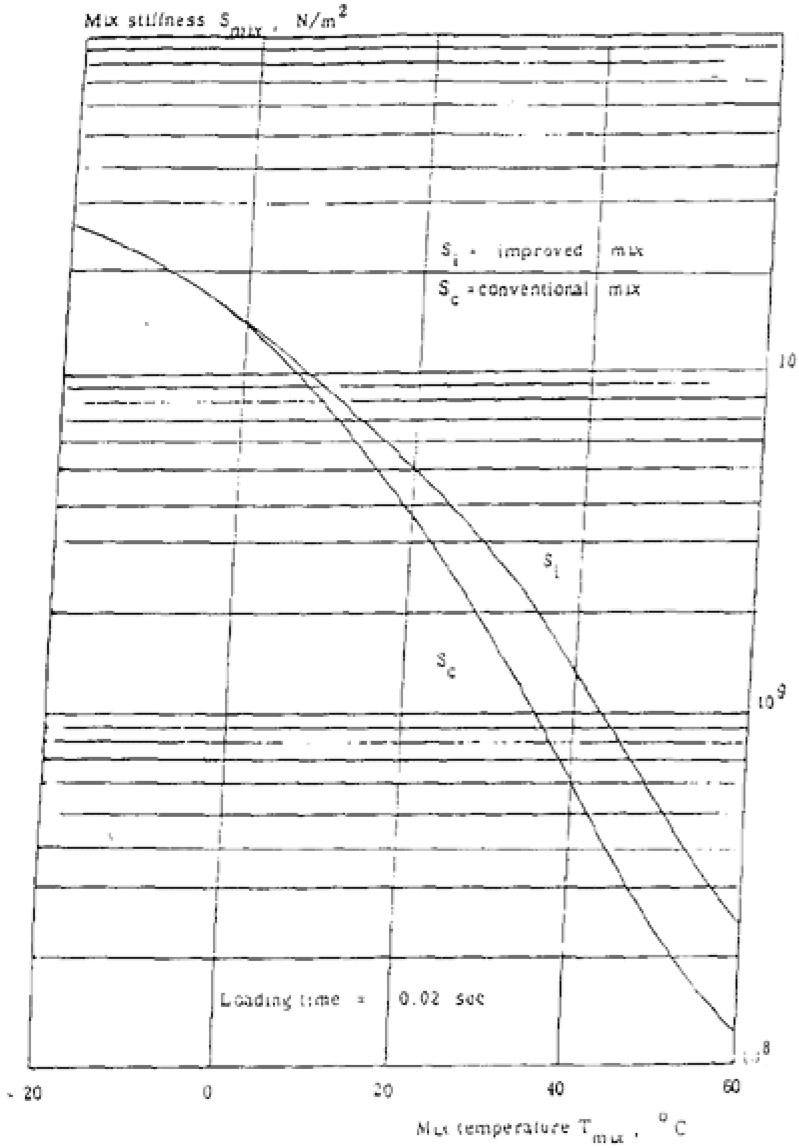

Figure 3. Impact of Chemcrete modification on the stiffness of HMA mixtures (1).

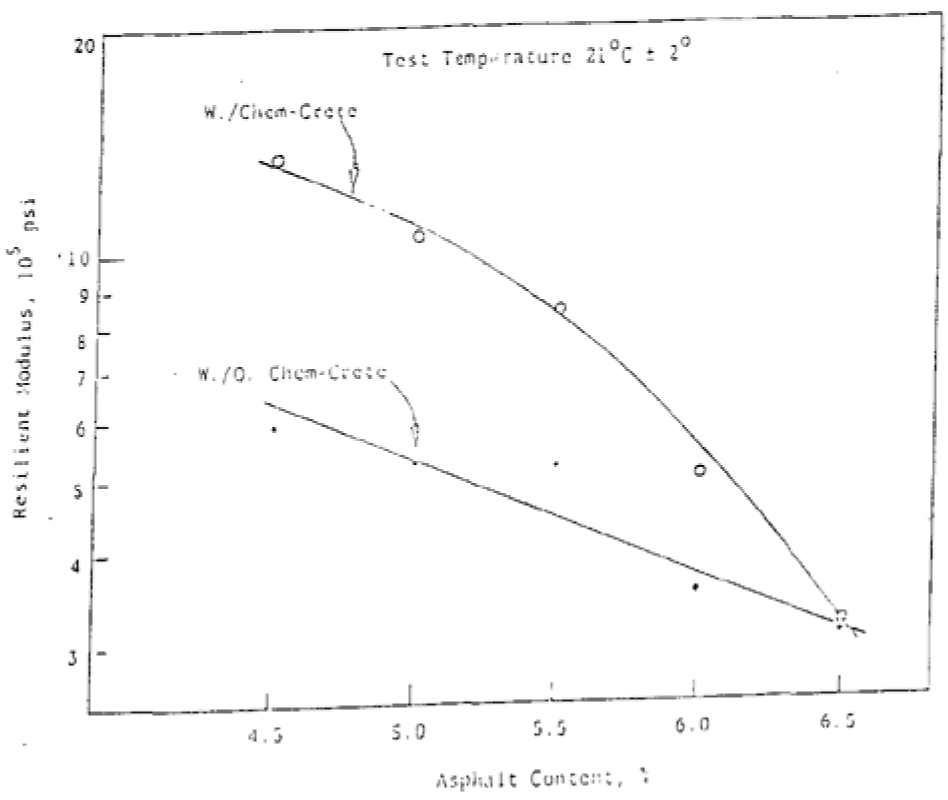

Figure 4. Resilient modulus as a function of binder content for modified and unmodified HMA mixtures (2).

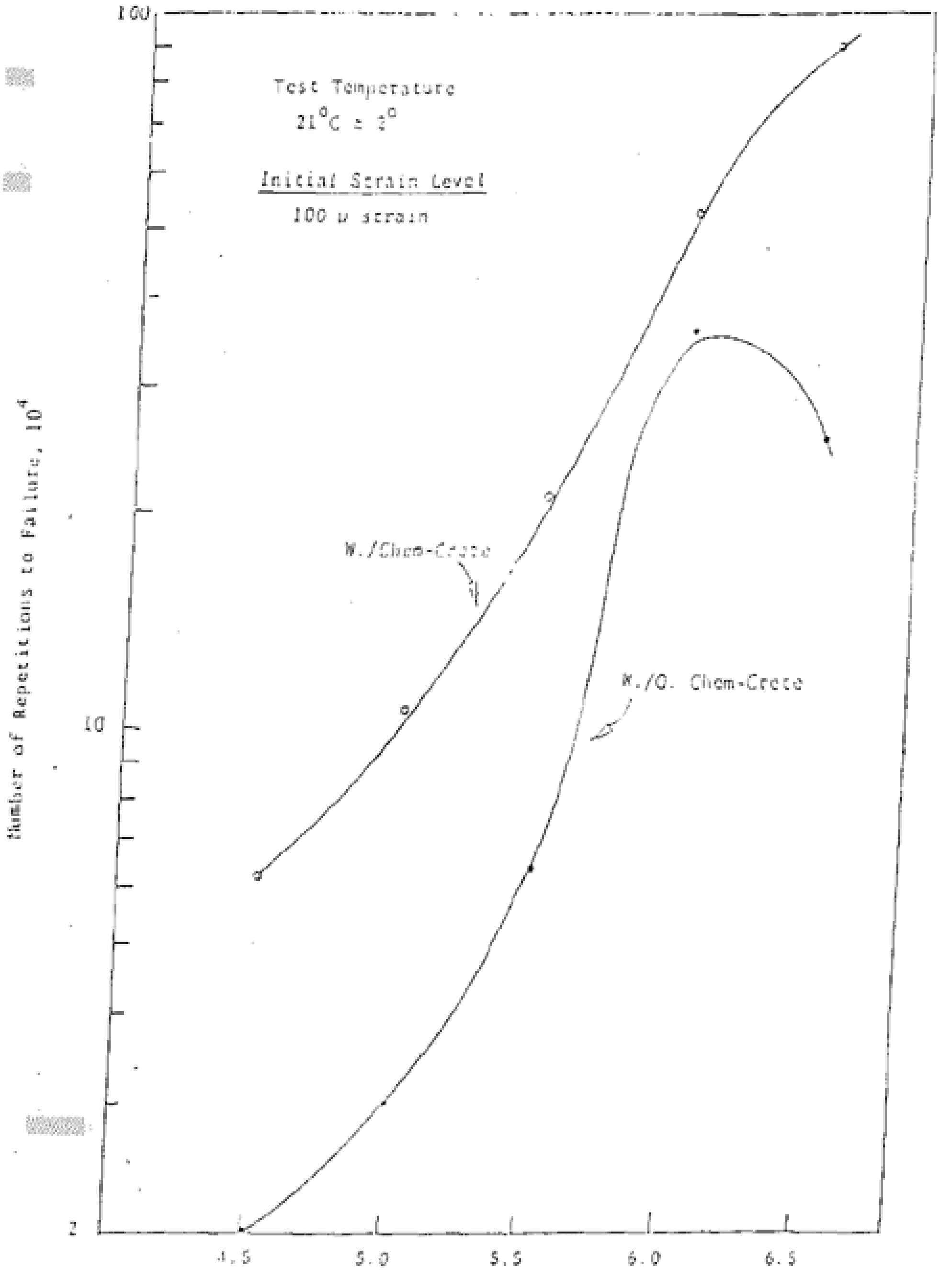

Figure 5. Fatigue life as a function of binder content for modified and unmodified HMA mixtures (2).

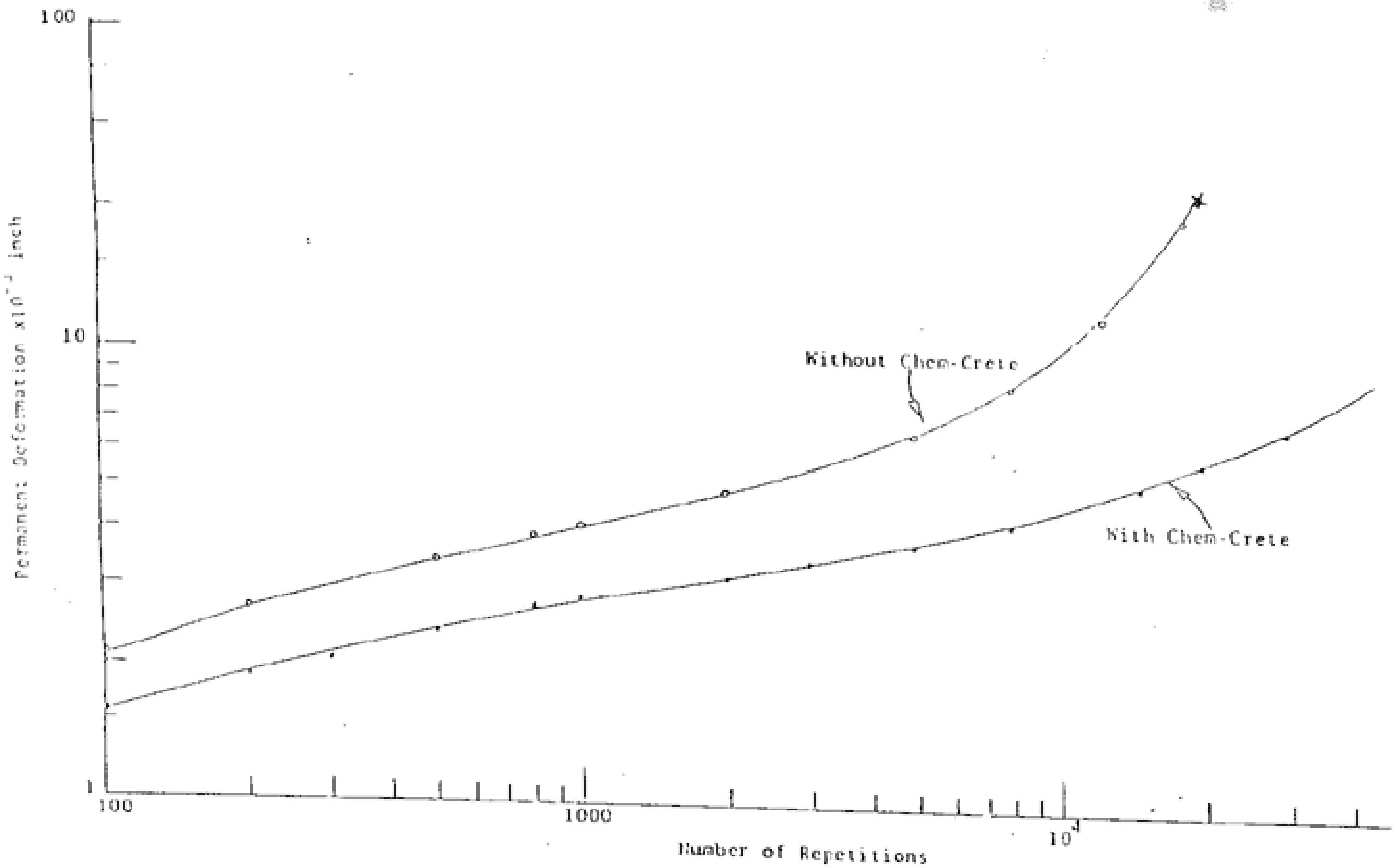

Figure 6. Rutting resistance for modified and unmodified HMA mixtures (2).

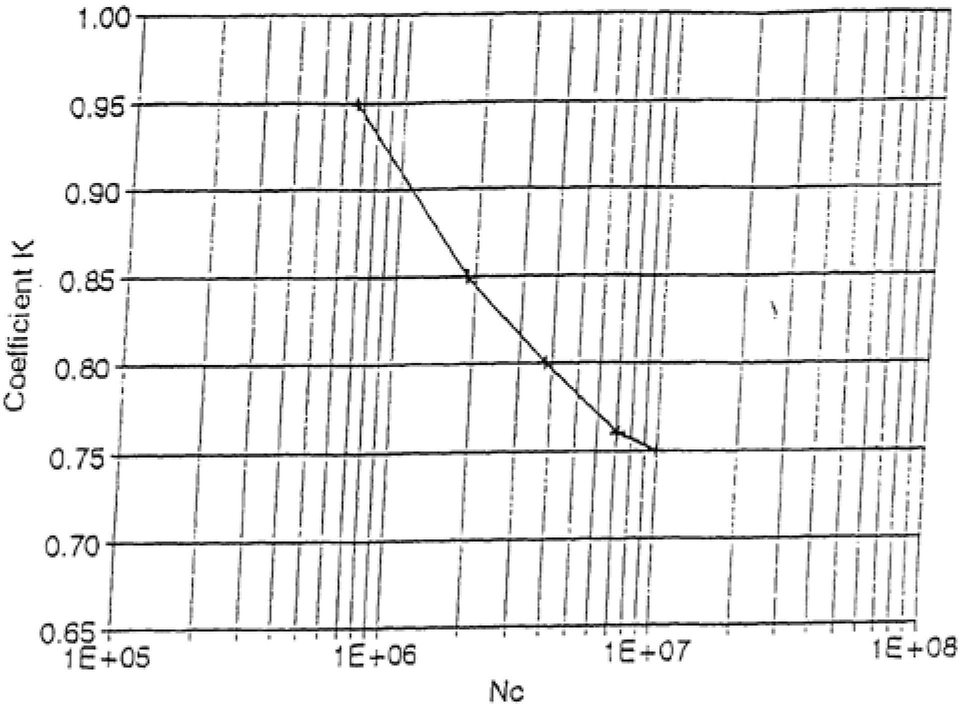

Figure 7. Base course thickness reduction coefficient as a function of fatigue life (3).

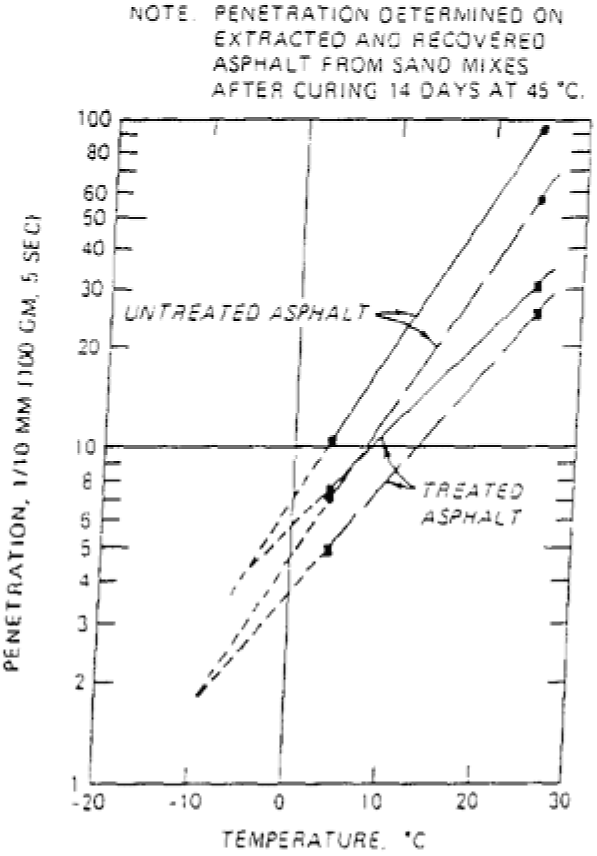

Figure 8. Penetration of modified and unmodified binders as a function of temperature (5).

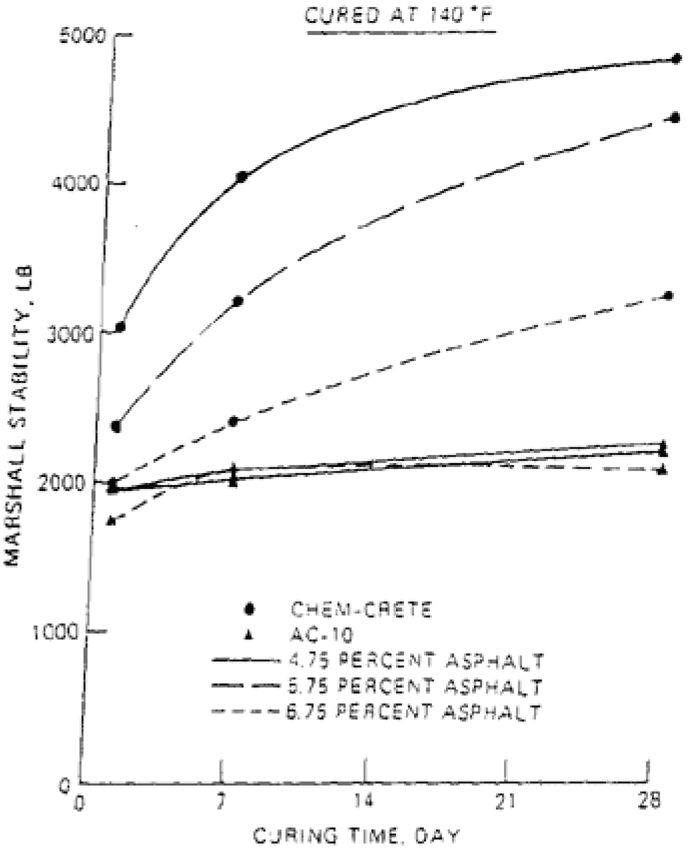

Figure 9. Impact of curing time on the Marshall stability of modified and unmodified HMA mixtures (5).

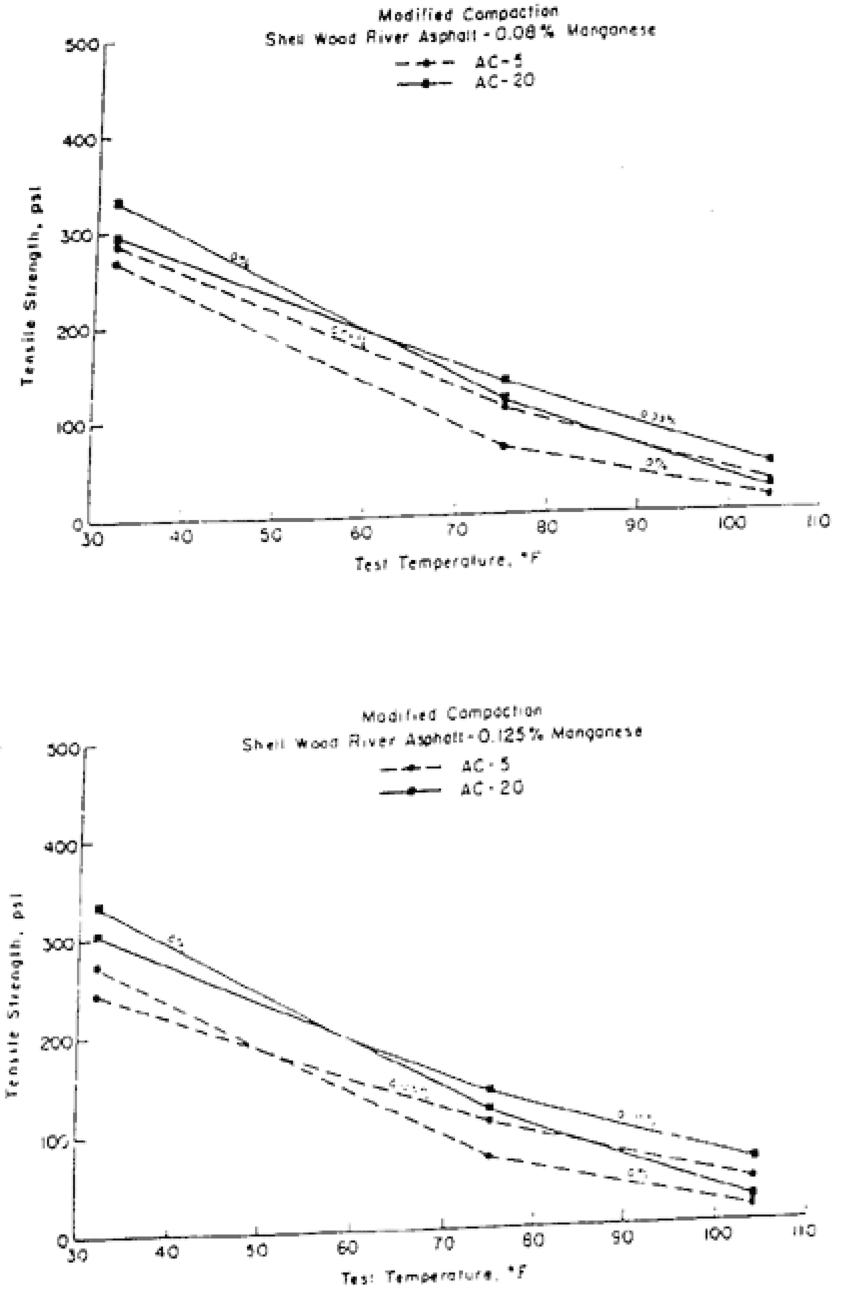

Figure 10. Tensile strength properties of modified and unmodified HMA mixtures with Eagle Lake aggregate (7).

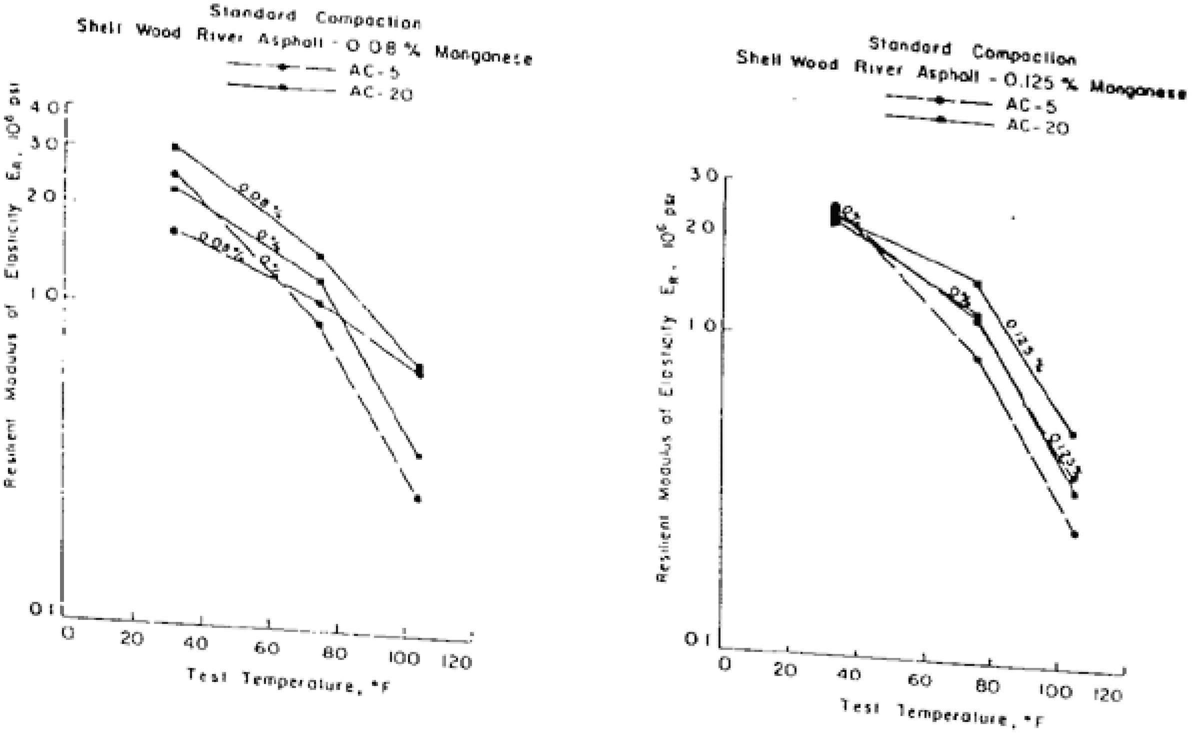

Figure 11. Resilient modulus properties of modified and unmodified HMA mixtures with Eagle Lake aggregate (7).

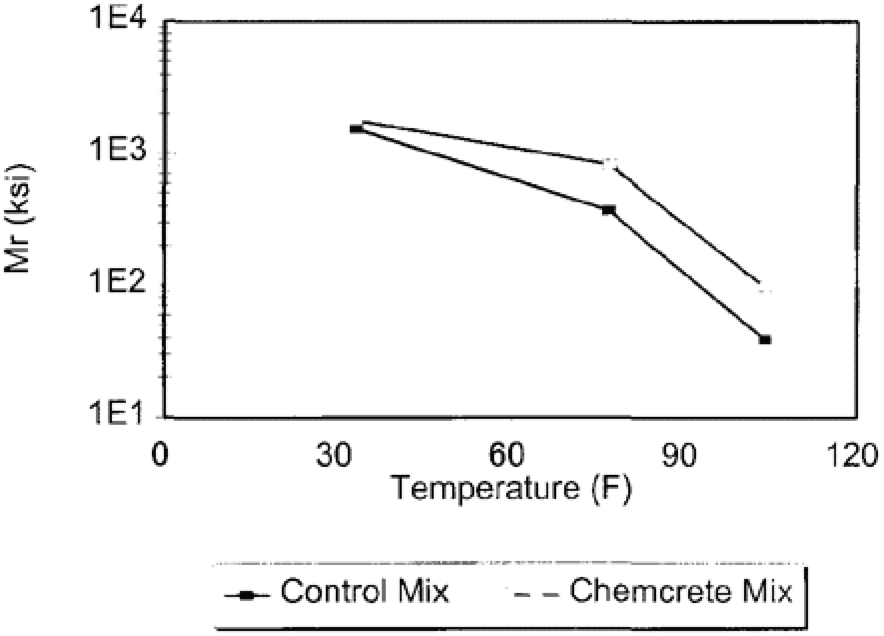

Figure 12. Temperature susceptibility of Chemcrete-modified and unmodified HMA mixtures on Tennessee road (10).

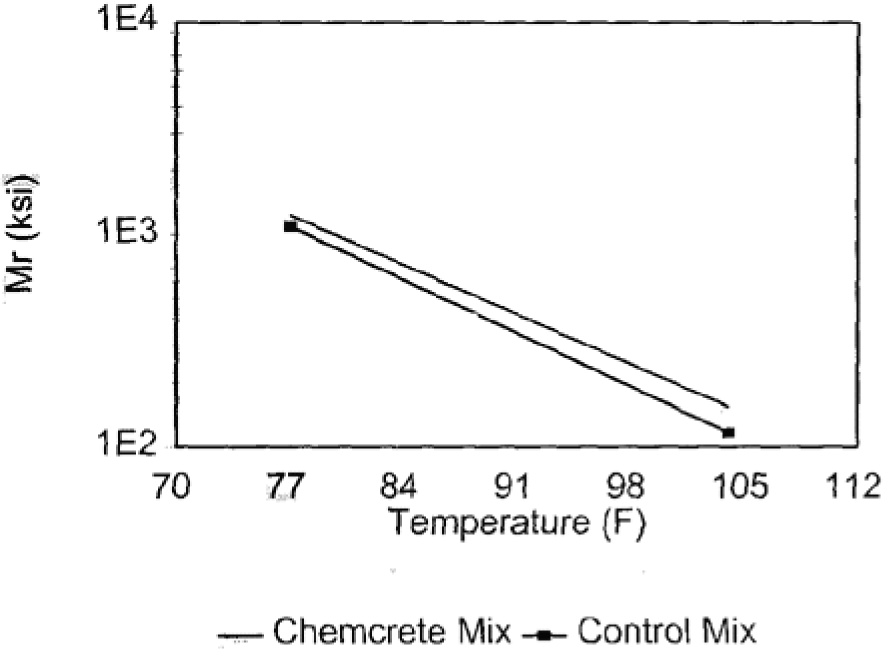

Figure 13. Temperature susceptibility of Chemcrete-modified and unmodified HMA mixtures on Caltrans SR 70.

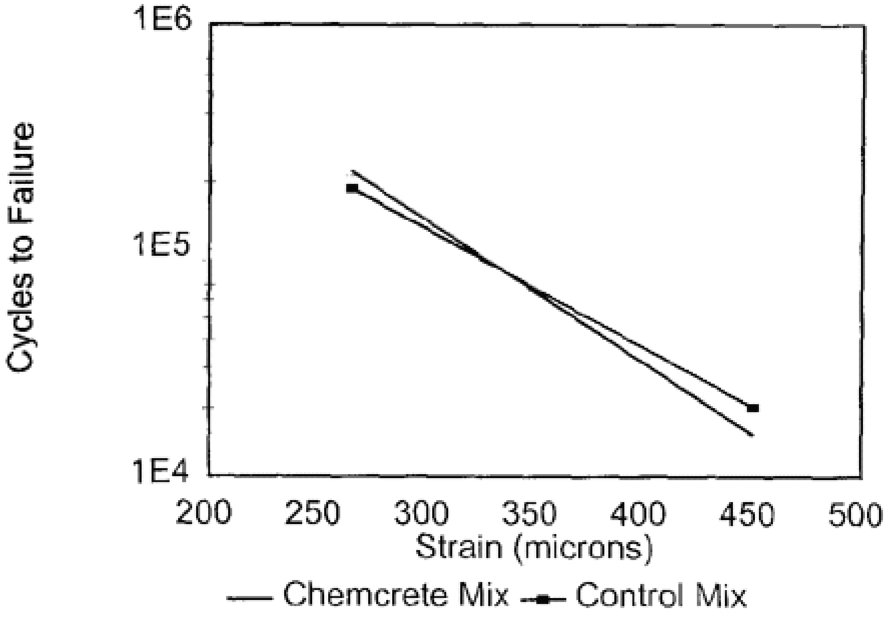

Figure 14. Relationship between cycles to failure and strain level for Chemcrete-modified and unmodified HMA mixtures on Caltrans SR 70.