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Design methods for pavement mixtures containing recycled asphalt concrete have been explored in many studies. Most methods of design are modelled after procedures originally developed for conventional construction with virgin raw materials. The unique properties of aged asphalt as raw material are rarely considered when applying conventional procedures. The approach developed by Witco Chemical assumes that each recycling project requires design and additives to compensate for aging effects.

The purpose of this investigation was to ascertain if (1) the simplified method of design developed by Witco Chemical can be employed uniformly in all recycling operations using aged asphalt concrete as the main ingredient of the new mix, and (2) dynamic and fatigue testing are helpful in the evaluation of the recycled mix. The result of the study was an affirmative answer to both questions. A prerequisite for successful recycling, it was found, is the use of a recycling agent which provides for high mixing efficiency to restore the durability and consistency.

The experiments carried out were in conjunction with a hot-mix recycling project on Interstate 90 near Ellensburg, Washington. Laboratory tests were performed on samples of the aged asphalt concrete before recycling and on mixtures containing added new aggregate to duplicate the mixtures used at the Ellensburg project. The recycling agents were added to the mixture by direct incorporation into the recovered asphalt (termed reconstituted asphalt) and by addition of the recycling agent and new aggregate to the crushed aged pavement. A mixture was also prepared with a virgin asphalt having the same viscosity at 60 C (140 F) as the reconstituted asphalt.

A simple formula was used to determine the optimum asphalt content. This value compared favorably with the average of the Marshall and Hveem mix design values.

Resilient moduli, permanent vertical deformations and fatigue life were determined by dynamic testing of the two recycled mixes and the two control mixes. Static tensile strength tests were also performed. The results indicated the resilient modulus for each mix to be within an acceptable range for bituminous pavements. The recycled mixtures showed lower plastic deformations than the completely fluxed reconstituted control mix. The recycled mixes and the reconstituted control mix showed higher fatigue resistance than the virgin control mix. The virgin control and reconstituted mixes showed a higher tensile strength than the recycled mixes. All values were still within an acceptable range for bituminous pavements.

Evaluation of a Unified Design for Asphalt Recycling by Means of Dynamic and Fatigue Testing

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EVALUATION OF A UNIFIED DESIGN FOR ASPHALT RECYCLING BY MEANS OF DYNAMIC AND FATIGUE TESTING

INTRODUCTION

The idea of pavement recycling is not new. Literature documenting the development of the pavement recycling concept from the 1930's to the present have previously been reported (1,2). Recently, work performed by Epps, et al. (3,4) has sought to provide guidelines to determine the "best" recycling method for a given situation.

The Federal Highway Administration conducted a demonstration project to implement recycling in actual construction projects. Case histories documenting successful recycling operations resulted from this program (5). A common characteristic of the mix design methods identified in the case histories was that they were modelled after procedures originally developed for conventional paving materials. Typically, several combinations of crushed asphalt concrete, virgin aggregate, a recycling agent, and, at times, additional virgin asphalt were mixed and tested. Selection of "optimum" amounts of the four possible components was a difficult and time-consuming task. Additionally, there was, and continues to be, some question whether design criteria originally developed for conventional paving mixtures are applicable for recycled mixes.

The purpose of this research is to compare a previously reported simplified method of recycled asphalt concrete mix design developed by Witco Chemical (1) with the Marshall and Hveem methods. A second major objective is to evaluate several properties of the mixtures designed by the simplified method. These properties include the resilient modulus, permanent deformation and fatigue characteristics under repeated loading, and the tensile strength under static loading.

The experiments were performed using crushed asphalt concrete and virgin aggregate sampled from a recent hot-mix recycling project on Interstate 90 near Ellensburg, Washington. This was desirable since the laboratory findings could subsequently be compared with actual field performance of the materials. Two recycled mixes and two controls provided the four sample types used in the laboratory study. Each of the two recycled mixes contained a recycling agent directly incorporated into a mixture of crushed old pavement and virgin aggregate, as illustrated in Figure 1. One recycled mixture used a non-emulsified form of the recycling agent, while the other used an emulsified form. Otherwise, the two recycled mixes were identical. The two controls were composed of asphalts incorporated into an aggregate mixture. The aggregate mixture was a combination of virgin aggregate and aggregate recovered from the crushed pavement. One of the asphalts, termed "reconstituted" asphalt, was a blend of recovered asphalt and the non-emulsified form of the recycling agent. Development of this product is illustrated in Figure 2. The second asphalt was a virgin material, viscosity-matched at 60 C (140 F) to the reconstituted asphalt. Figure 3 shows the ingredients used to make the control mixes.

The following section is a brief review of the construction project which provided raw materials used in the laboratory research.

FIELD CONSTRUCTION PROJECT

PROJECT DESCRIPTION

Crushed asphalt concrete and virgin aggregate samples were obtained from recycling nearly four miles of I-90 pavement in the State of Washington. This project was undertaken by the Washington State Department of Transportation in the late summer of 1978 (6).

The cross-section prior to recycling consisted of an asphalt concrete base topped by levelling and wearing courses. By 1977, ten years following original construction, the pavement surface exhibited extensive structural cracking, generally confined to the wearing course. This observation, coupled with low Benkelman Beam deflections, suggested that rehabilitation could be accomplished through removal and recycling of the wearing course. Further analysis demonstrated this recycling alternative to be lower in cost than a conventional overlay.

MATERIAL TESTING

Material Testing Prior to Construction

A material testing program was initiated by Washington DOT on asphalt concrete chunks obtained in 1977 to determine the suitability of the old pavement for recycling. Gradations of the recovered rock were determined following asphalt extraction. The recovered asphalt was tested for its properties and chemical composition. Several blends of recovered asphalt and a recycling agent were investigated to ascertain the changes in viscosity and penetration resulting from higher concentrations of recycling agent in the mixture. A target viscosity of 180 Pa•s (1800 Poises) at 60 C (140 F) was selected. It was predicted that this mixture would stiffen to approximately 400 Pa•s (4000 Poises) after mixing and laydown. In addition, a preliminary Hveem mix design was performed.

Immediately prior to starting construction, a final mix design was performed on material milled from six different locations within the project. The results of this design are displayed in Table 1. Based on the previous testing, the most recent mix design, and initial construction experience, the following material combination was recommended: old asphalt concrete, 78.5 - 78.7%; virgin aggregate, 20%; recycling agent, 1.0 - 1.2%; and virgin AR-4000W asphalt, 0.3 - 0.5%. The percentages shown are by weight of total mix.

Addition of virgin aggregate was recommended to reduce both the percent passing the 0.074 mm (No. 200) sieve and the percentage of fluid in the mix, and to "open up" the aggregate gradation, thereby producing a stable mix. Table 1 demonstrates the success of this approach. Higher percentages of virgin aggregate led to decreased asphalt contents and increased void contents and stabilometer values. The specified size range for the virgin aggregate was 6 mm to 16 mm (1/4 in to 5/8 in).

Testing During Construction

During construction, material tests were performed on the crushed asphalt concrete prior to mixing, on control samples following mixing, and on pavement cores obtained following laydown. Complete results are presented in Reference (6). Selected test results are displayed in Tables 2 and 3.

Comparison of the void contents for the field mix and core samples following the recycling shows a difference between laboratory and field compaction. Void contents of cores, shown in Table 3, were nearly twice those obtained during laboratory compaction of loose mix samples obtained during construction, as shown in Table 2.

Resilient modulus values (7), obtained for load durations of 0.05 and 0.10 seconds, were in a range considered acceptable for asphalt concrete mixes. The resilient modulus values of the field cores were lower than those obtained for the laboratory compacted specimens. Since the gradations and recovered asphalt properties were similar, the lower densities seemed to be primarily responsible for these differences.

At the present time (1981), the pavement is performing in a satisfactory manner (8). Walter (6) indicates that further testing will be continued as the pavement ages. At this time, insufficient data exist to make a conclusive statement regarding the change in recovered asphalt or asphalt mix properties.

LABORATORY STUDIES -- MIX DESIGNS

Comparisons between the Witco Chemical mix design method (i.e. the simplified method) and the Marshall and Hveem methods were the first objective of the research, and are the subjects of this section. Prior to discussing the design methods, results, and analysis; selected material properties of the aggregates, recovered asphalt and recycling agents are highlighted. Treatment of the reconstituted and viscosity matched virgin asphalts is deferred until after discussion of the simplified method.

MATERIALS

Aggregates

Asphalt extraction was performed by Witco Chemical on samples of the old pavement, and the gradation of the recovered aggregate was determined. The virgin aggregate obtained was also tested for gradation and was nearly uniform, as expected.

To duplicate the field mix, virgin aggregate was added so that, of the total aggregate in the mix, 82.5% was recovered aggregate and 17.5% was virgin aggregate. While this percentage was slightly different from that reported by Washington DOT, a comparison of the final aggregate gradations showed little difference. Figure 4 illustrates this comparison. It is noted that the calculated gradation using the percentages shown above, together with the gradations determined by Witco, yield essentially the same gradation as actual blends tested by

Washington DOT during construction and by Oregon State University prior to this testing.

Recovered Asphalt

Properties of the asphalt cement recovered from the crushed pavement were determined by Witco. The results of these tests are presented in Table 4. In spite of the fact that the asphalt concrete was in service for ten years, the higher viscosities associated with the rolling thin film conditioning (RTFC) (ASTM D2872) indicate that the material was still susceptible to aging effects. Asphalt content of the crushed pavement averaged 4.8% by total weight of the mix.

Recycling Agents

Asphalts are made up of two basic groups, asphaltenes and maltenes. The maltenes are composed of four components: nitrogen bases, N; first acidaffins, A_1; second acidaffins, A_2; and paraffins, P. During aging, chemical changes take place such that the percentage of asphaltenes is increased at the expense of the maltenes. The physical effects of this chemical change include hardening, ravelling, cracking, and spalling. The susceptibility of any asphalt to these changes is related to the value of the compositional parameter. This parameter, $(N + A_1)/(A_2 + P)$, is a ratio of the more reactive to the less reactive of the components which comprise the maltenes group. Lower values would indicate asphalts tending to be less susceptible to aging (i.e. more durable).

The function of any recycling agent is to restore the asphalt to a chemical composition in which the percentage of maltenes is increased, thus decreasing the percentage of asphaltenes. Reference (14) contains an excellent discussion of the fractional components in asphalt and the compositional parameter, and their relationship to asphalt concrete recycling.

Non-emulsified and emulsified forms of Cyclogen, a commercially available one-component recycling agent, were used in the experiments. Development of this product was based on the work of Rostler and coworkers (9,10,11,12), and has been described in the literature (13). The oil phase of the emulsified product was 63%. Table 5 presents the proposed specifications for the three types available; L, M, and H; which essentially differ only in viscosity. The recycling construction project used Cyclogen L, while the laboratory investigation used Cyclogen M and ME.

As explained by the Washington DOT, there were two reasons for using Cyclogen L in the field applications. First, the recovered aged asphalt had a high viscosity and did not require a recycling agent thickened by asphaltenes, particularly since the design called for using additional virgin asphalt. Second, the use of Cyclogen L, which contains no asphaltenes and thus a higher amount of the effective ingredients (N, A_1, A_2, and P) which contribute to improvement of durability, was more cost effective than the use of Cyclogen M.

The compositional parameter is 0.45 for Cyclogen L and 0.87 for Cyclogen M. The viscosity at 60 C (140 F) of Cyclogen M is similar to that of the Cyclogen L - virgin asphalt blend used in the field.

MIX DESIGN METHODS

Simplified Method

Comparatively straightforward mix design procedures utilizing several widely used tests have been developed by Witco Chemical Laboratories, based on laboratory and field testing (1). The design procedure involves extracting the asphalt from a crumbled pavement specimen, sieving the recovered aggregate, and determining penetration and viscosity of the recovered asphalt. Asphalt demand of the recovered aggregate - virgin aggregate mixture is determined by either the CKE procedure or an equation based on gradation. The type and weight percentage of Cyclogen are selected through the use of nomographs, such as that shown in Figure 5. Knowing the viscosity of the aged asphalt and desired final viscosity range of the blend, the type and amount of recycling agent can be selected (13). The values shown in Figure 5 pertain to the present investigation.

As shown in Table 4, the aged asphalt viscosity at 60 C (140 F) was approximately 4660 Pa•s (46,600 Poises). Final recovered asphalt viscosity, based on field mix and core samples obtained during construction was 224 Pa•s (2240 Poises). A target viscosity of 220-230 Pa•s (2200-2300 Poises) was selected for the blend to parallel the construction project and, as seen in Figure 5, this viscosity was predicted by adding 31% (by total weight of asphalt in mix) Cyclogen M.

Asphalt demand for the simplified method was determined by an equation based on gradation. The calculated asphalt demand was 5.8% for the recovered aggregate - virgin aggregate blend. This asphalt content, and all others reported in this laboratory investigation, are calculated on the basis of the total weight of mix. Combining this with the results of Figure 5 indicated that 1.8% of the total mix (31% of the total asphalt) would be composed of Cyclogen. Figure 6 shows the gradations, the equation used in calculating the asphalt demand, and the results. The asphalt content of the pavement to be recycled (i.e. the mixture of crushed asphalt concrete and virgin aggregate) is 4.0%. This value is correct because in addition to containing crushed asphalt concrete with an asphalt content of 4.8%, the mixture contains virgin aggregate, with an asphalt content of 0%. The proportions of the two materials used in the study yields a final asphalt content of the mixture of 4.0%.

Viscosity tests were run on the reconstituted asphalt, both in an as-received condition and after RTFC. These results are shown in Table 6. The measured viscosity of 228 Pa•s (2280 Poises) is within the viscosity range predicted by the nomograph in Figure 5. Virgin asphalt used in the second control sample was viscosity-matched to the reconstituted asphalt at 60 C (140 F). Table 7 presents the virgin asphalt properties.

The reconstituted and virgin asphalt penetration and viscosity test results are summarized in Figure 7. Development of this chart is described by Heukelom (15). Since the two materials were viscosity matched at 60 C (140 F), the values are equal at that temperature. However, the properties of the virgin material display a greater sensitivity to temperature changes, as evidenced by the steeper slope of its line. As a consequence, the virgin material is less stiff at 135 C

(275 F) and stiffer at 25 C (77 F).

Assuming all else is equal, the properties of mixes made with these materials would be similar at 60 C (140 F). Mixing and compacting the mixes, which takes place at nearly 135 C (275 F), would be more efficient with the less viscous virgin material and slightly lower void ratios would be expected. Finally, at 25 C (77 F), mixes made with the virgin material would be expected to be stiffer.

It has been shown that the heating and mixing of asphalt materials in field operations increases its viscosity as measured at standard temperatures. The laboratory test to represent this condition is rolling thin film conditioning. Figure 7 also illustrates the properties of the virgin and reconstituted materials following rolling thin film conditioning. The reconstituted material shows a greater stiffness gain as a result of the conditioning and is stiffer at all three temperatures of interest. Therefore, if laboratory mixing and compacting accurately duplicate stiffness increases from RTFC, it would be expected that the reconstituted mixes would consistently display properties characteristic of stiffer mixes at the three temperatures of interest. As is shown in the results, this is not the case and consequently the conclusion is reached that laboratory mixing and compaction do not age materials to the degree represented by rolling thin film conditioning.

Conventional Mix Designs -- Hveem and Marshall Methods

The 5.8% asphalt content, containing 4.0% old asphalt and 1.8% Cyclogen, served as a starting point for the Hveem and Marshall mix design methods. Material blending for the two controls was identical to a conventional mix design using virgin materials. Constant proportions of recovered and virgin aggregates were batched (82.5% recovered aggregate to 17.5% virgin aggregate) for all the asphalt contents to be examined. Changes in final asphalt content were accomplished by increasing or decreasing the amounts of reconstituted or virgin asphalt added. In contrast, changes in asphalt content for the recycled mixes were achieved by adjusting the proportions of old asphalt concrete and virgin aggregate while keeping constant the Cyclogen-to-total-asphalt ratio. Figure 8 demonstrates the variation in aggregate gradation resulting from this approach.

An alternate method of adjusting asphalt content is to keep the crushed asphalt concrete-virgin aggregate proportions constant and only change the amount of Cyclogen added. For the final asphalt contents used in the designs, this procedure would have resulted in weight percentages of Cyclogen to total asphalt that vary from about 5% to over 40%. As illustrated in Figure 9, predicted viscosities would have ranged over one order of magnitude. This variation would have dominated the results of the mix design, and consequently the first approach discussed was followed.

The Marshall mix design was performed at Oregon State University. Standard procedures for performing the mix design (16) were used whenever possible. Three samples were prepared at five asphalt contents, ranging from 4.7 to 6.7% for the recycled mixes and 4.8 to 6.8% for the control mixes. Successive increments of 0.5% were used for all sample types. Proper heating time for the old asphalt concrete prior to mixing was critical. The minimum time necessary to bring the asphalt concrete to temperatures suitable for mixing was desirable to limit the aging of the old asphalt in the laboratory procedures. Based on the careful monitoring of several samples, a ninety-minute heating time was considered appropriate. Mixing temperatures were maintained at 129 ± 3 C (265 ± 5 F). The material was hand mixed for a period of 120 ± 5 seconds and compacted 50 blows per side. The recycled mixes utilizing emulsified Cyclogen were oven cured for 24 hours prior to performing the Marshall stability test. Average results for the tests performed in the design are presented in Table 8.

The Hveem mix designs were performed in Vancouver, Washington, in accordance with standard procedures (16) by the Federal Highway Administration. Mixing and compaction temperatures were 135 and 110 C (275 and 230 F), respectively. The ranges of asphalt contents investigated in the Hveem design were 4.2% to 6.2% for the recycled mixes and 4.3% to 6.3% for the control mixes. Results of the tests performed for the Hveem mix design are presented in Table 9.

The optimum asphalt contents based on the two mix designs are summarized in Table 10.

ANALYSIS OF RESULTS

Optimum asphalt contents for all of the sample types are considerably higher for the Marshall design than for the Hveem design. This difference can be best explained by the difference in densities, which is highlighted in Table 11. At similar asphalt contents, the Hveem specimens have significantly higher densities and corresponding lower void contents than the Marshall specimens. Maximum specific gravity values are nearly identical for the two mix designs, as expected.

The three criteria used in both designs; stability, density, and air voids; are all controlled by specimen compaction. Higher compaction leads directly to higher density and lower air voids. Mix stability tends to increase with decreasing void content until some maximum value is reached. At that point, further decreases in void content lead to lower stabilities.

Compaction temperatures or different compaction procedures could account for the difference. Compaction temperatures were controlled in performing both mix designs, and consequently compaction temperature should not be the cause. The compaction type was different, as the Hveem design used kneading compaction, while the Marshall design used static compaction.

A comparison of the Marshall and Hveem mix design test results at the 5.8% asphalt content recommended by the simplified method is difficult. In the Marshall design, asphalt contents of approximately 5.8% for the recycled mixes yielded rather low-density, high-void mixes. Stabilities were less than the maximum, while the flow was about the same as the other mixes. The control mixes were fairly stable at the 5.8% asphalt content. Voids were high (slightly over 5%), but stabilities peaked at this asphalt content. Flow values remained relatively uniform at all asphalt contents.

The Hveem design yielded substantially different mixes at the asphalt content recommended by the simplified method. At 5.8%, the control mixes were characterized by low void contents, with corresponding low stabilities. The recycled mixes were slightly lower in density and higher in void content than the controls. The stability of the recycled mix with Cyclogen M was comparable to the control mixes. The emulsified recycled mix had an acceptable Hveem stability of 32.

One conclusion that can be drawn from these data is that mix designs originally developed for virgin materials may not be dependable guides for designs with recycling materials.

LABORATORY INVESTIGATION OF ASPHALT CONCRETE MIX MATERIAL PROPERTIES

TEST PROGRAM

The second objective of the laboratory investigation was to evaluate several significant material properties of the four sample types at the optimum asphalt content specified in the simplified procedure. These properties include resilient modulus, permanent deformation, and fatigue characteristics of the mixes, as measured by the repeated load indirect tensile test. In addition, the static load indirect tensile test was employed to determine the tensile strength of each of the sample types. The theory related to the development of working equations used in the indirect tensile test has been adequately discussed by others (17,18). The relative advantages of the indirect tensile test have also been previously reported. The test equipment, test conditions and procedures are discussed below.

Test Equipment

A testing device constructed at Oregon State University was used for the repeated load tests and is illustrated in Figure 10a. Horizontal deformations were measured using a device described by Rimsritong (19). A typical setup used to perform the resilient modulus test in conjunction with the test for permanent vertical deformation is shown in Figure 10b. Loads were applied to the specimen by the 12.7 mm (1/2 in) wide top loading strip. The loading strip was curved to keep constant the area over which the load was applied to the specimen during loading. Horizontal deformations produced by the vertical load pulse were measured by transducers in the yoke attached to the specimen. Individual deformations on each side of the specimen were measured and recorded separately on a strip chart recorder. Resilient and permanent horizontal deformations could be measured separately on the strip chart recorder output.

Permanent vertical deformation was recorded using a dial gauge. This gauge was positioned so that any change on the dial gauge represented the decrease in specimen diameter along the axis of loading.

For fatigue tests, a low-voltage DC current passed through aluminum foil strips attached to the sides of the specimen. At failure, the strip broke and the DC current was interrupted, automatically stopping the loading.

Static tensile strength tests were performed using an MTS closed-loop electrohydraulic loading system. The 12.7 mm (1/2 in) wide curved loading strips were also used to apply the load to the specimen in this test.

Test Procedures

Table 12 summarizes the test conditions. All dynamic tests were stress controlled. A preloading of 50 repetitions at test conditions to seat the loading strips on the specimen properly has been suggested by Kennedy (17) and was utilized in this study. Since the resilient modulus and permanent deformation tests were run simultaneously, the preloading for the resilient modulus test served as the preload for the permanent vertical deformation test. Values of accumulated permanent deformation were obtained after 100, 200, 500, 1000, 2000, 5000, and 10,000 repetitions. For the fatigue testing, load frequency was doubled to 1 Hz to reduce testing time to failure. Load duration remained constant at 0.1 second.

Static tensile strength tests were performed by applying a constant deformation rate of 2 inches per minute to the specimen. Load and deformation were recorded on an X-Y plotter. Peak vertical load was used in the equation for tensile stress to determine tensile strength.

The equations used to calculate the values of resilient modulus, accumulated vertical compressive strain, tensile strength, and tensile strain are summarized in Table 13. Poisson's ratio of 0.35 has been shown to be a reasonable value for asphalt concrete (2) and was used in all calculations.

PREPARATION OF INDIRECT TENSILE TEST SPECIMENS

Mix proportions used for test specimens are presented in Table 14. Procedures and temperatures for mixing and specimens were identical to those employed in preparing the Marshall mix design specimens. However, kneading compaction at 107 ± 3 C (225 ± 5 F) was employed using procedures slightly modified from those used for preparing Hveem mix design specimens (16). The modification was that the 6890 kPa (1000 psi) static load was applied immediately following kneading compaction.

As shown in Table 15, the average densities and void contents for the indirect tensile test specimens were between the values obtained in the Marshall and Hveem mix designs. These data reinforce the explanation that different compaction equipment at least partially explains the different densities obtained in the mix designs.

TEST RESULTS

All tests were performed at an ambient temperature of 23 ± 3 C (74 ± 5 F).

Resilient Modulus

Resilient modulus data are summarized in Table 16. Asphalt concrete resilient modulus is affected by variability in many factors, including asphalt, aggregate, mix environment and test conditions (i.e. load stress, load frequency, etc.). Several of these variables were measured during the test program and are identified in Table 16. Average values of density, voids, and testing temperature are also listed in the table.

Modulus values for the recycled mixes are similar. The slightly lower average values observed for both mixes during the fatigue testing can be explained on the basis of higher test temperatures. For the Cyclogen ME recycled mix, the increasing void content added to this effect; while in the Cyclogen M recycled mix samples, the decreasing void content slightly offset the decrease in modulus due to increased temperature.

The reconstituted control samples yielded very low modulus values when measured in conjunction with the permanent deformation testing.

While this difference appears to be primarily the result of the higher testing temperatures, the reconstituted control also yielded the lowest modulus value during fatigue testing, even though average testing temperatures for all sample types were similar. The modulus value for this mix was lower than that for each of the recycled mixes, in spite of the fact that void content was 12 to 27% less.

Modulus values for the virgin control samples were similar to the recycled mixes for the tests performed during the permanent deformation testing, and were higher than the reconstituted control. However, during the fatigue tests, this sample type yielded a substantially higher average modulus value than any of the other three sample types. This was attributed in part to the void content. Average percent voids of the control-virgin sample were 40 to 50% lower than the recycled mixes and 30% lower than the other control.

The effect of test temperature on the individual modulus values obtained during fatigue testing is shown in Figure 11. A wide variability exists among the sample types; however, some patterns emerge when the figure is divided into three areas, as shown. The two lines drawn enclose over 60% of the total samples. Eighty percent of the virgin control samples fall above the top line, and comprise all of the samples plotted above the line. Nearly 90% of the recycled samples fall below the bottom line. Considering these data, it appears that the virgin control samples were stiffer than the two recycled mixes and the reconstituted control mix.

All the modulus values shown appear slightly lower, but still in fairly good agreement with those given by Walter (6) for samples obtained during construction. (See Table 3.) Modulus values for laboratory compacted samples of recycled mix average 2900 MPa (420,000 psi), with a range of 2000 to 4760 MPa (290,000 to 690,000 psi). These values were obtained using a load duration of 0.10 seconds. Density and void content for these specimens average about 2460 kg/m^3 (153 pcf) and 4.1%, respectively. The average field asphalt content of 4.9% is lower than the 5.7 and 5.8% used in the dynamic testing performed in this study.

Resilient modulus data are also presented by Walter (6) for pavement cores obtained immediately following construction. Average resilient modulus values are about 50% lower, averaging 1380 MPa (200,000 psi). This decrease is best explained by the slightly higher asphalt contents (5.4% -vs- 4.9%), and the significantly lower densities and higher void contents attained in field compaction. Density and void content of the field cores average 2273 kg/m^3 (141.9 pcf) and 11.2%, respectively.

All samples of both recycled mixes were subjected to an extended period of oven curing at 60 C (140 F) to investigate the effect on modulus. During the cure period, four specimens of each of the recycled mixes were removed from the oven, allowed to cool to ambient temperature, and tested to determine resilient modulus. Tests were performed after 0, 50, 140, and 317 hours of oven cure. The results are plotted in Figure 12. Ambient temperatures during modulus testing ranged from 21 to 24 C (70 to 76 F). The temperature during each of the tests is indicated on the figure. The data points on the far right of Figure 12 represent the average modulus values obtained during testing performed following the oven cure.

The change in modulus value is slight with increasing cure time. The interpretation is more difficult because of the changes in test temperature, as noted in the figure. One hypothesis on the slight increase in modulus is that the interparticle spaces are initially occupied by the low viscosity recycling agent, then it is dispersed into the aged asphalt. Therefore, modulus values increase with time, finally leveling out. Probably for the same reason (time of reaction), the modulus values for the emulsion recycled mix are consistently lower than for the Cyclogen M recycled mix.

The effect of stress level on resilient modulus was investigated at the conclusion of the permanent deformation test. Data were obtained at tensile stress levels resulting from applied loads ranging between 220 and 890 N (50 to 200 lb). The results indicate that stress levels in this range have little influence on modulus.

Permanent Deformation

Permanent vertical deformations are expressed in terms of:

$$\varepsilon_c = I\, N^s \tag{1}$$

where: ε_c = the accumulated vertical compressive strain,

I = vertical strain associated with one load application,

N = the total number of load applications, and

s = the slope of the best-fitting straight line when ε_c and N are plotted on a log-log plot.

Tabulated values of I, s, and average test temperature and void content for each of the four sample types are given in Table 17. The coefficient of determination, r^2, is also shown in the table. Plots of each of the best-fitting straight lines are shown in Figure 13.

The data indicate that the slope and intercept of the straight line relationships are directly related to the test temperature and the void content, respectively. This is logical when considering asphalt concrete behavior. Higher test temperatures lead to lower modulus values, and consequently increased permanent strains for a given stress level. Higher void contents lead to greater initial strains, as shown by the data. Additionally, it is reasonable that higher void contents result in steeper slopes; however, the temperature differences for the different sample types mask this effect, and it is not evident in the data.

The results for the two recycled mixes are nearly identical. The relationship for the virgin control mix, while more steeply sloped, yielded essentially the same accumulated strain at 10,000 repetitions as the recycled mixes. The steeper slope associated with the reconstituted control mix can be explained to a large degree by the 10 to 15% higher temperature at which the samples were tested.

Fatigue Testing

Data from various studies have shown that a definite relationship exists between initial stresses or strains and number of repetitions to failure. Several of these equations take the form:

$$N_f = K_1 \, (1/\varepsilon_{init})^{n_1} \tag{2}$$

$$N_f = K_2 (1/\sigma_t)^{n_2} \tag{3}$$

$$N_f = K_2' (1/\Delta\sigma)^{n_2} \tag{4}$$

where: N_f = number of repetitions to failure,

σ_t = applied tensile stress,

$\Delta\sigma$ = stress difference, equal to $4\sigma_t$,

ε_{init} = initial tensile strain, and

K_1, K_2, K_2', n_1, and n_2 are constants determined during least square regressions.

Porter and Kennedy (18) have suggested that a more valid comparison between fatigue test results using different test methods is obtained if the stress state is expressed in terms of a stress difference, such as shown in Equation 4, rather than using the relationship shown in Equation 3.

Figure 14 shows the best-fitting straight lines for the relationship shown in Equation 2. Shown in the figure are the values of K_1 and n_1, together with average values of resilient modulus and testing temperature for the specimens tested. Values of r^2 ranged between 0.91 and 0.94.

The difference in fatigue results can be explained to some degree by the difference in modulus values. Figure 14 demonstrates that for initial tensile strains smaller than 150×10^{-6} in/in, the predicted fatigue life of the sample types increases inversely to modulus. The fatigue data again support the conclusion that the recycled mixes are similar. The fatigue behavior of the reconstituted control mix appears similar to the recycled mixes.

Table 18 compares the values of K_1, n_1, K_2', and n_2 with values obtained in other research using the indirect tensile test. The values obtained in this study show lower fatigue life than other reported values.

Tensile Strength

Average values of tensile strength, density, and void content are shown in Table 19. Values of tensile strength are plotted as a function of void content in Figure 15. A reasonably consistent relationship between void content and tensile strength exists for both recycled mixes and the reconstituted control mix. The higher tensile strengths of the reconstituted mix can be explained by the lower void content. Void content does not explain the high tensile strengths exhibited by the virgin control. Higher asphalt stiffness could explain this phenomenon.

All tensile strength results are within the range reported for other recycled materials. Kennedy (20) has reported tensile strength values of 840 to 2610 kPa (122 to 379 psi). Adedimila (18) found tensile strength to be approximately 965 kPa (140 psi) for laboratory prepared samples of conventional virgin materials at similar asphalt contents with similar void ratios.

SUMMARY OF RESULTS

COMPLETENESS OF MIXING

Complete crumbling of the old pavement was not achieved in the laboratory during mixing and compacting of the recycled mixes. If complete separation of the asphalt concrete particles does not take place, these agglomerates function as aggregates. Since the asphalt concrete particles are coarser than their components, this leads to a coarser, lower density, higher void mix. Observed void contents for the recycled mixes were higher than for either of the controls. In addition, the Cyclogen ME recycled mix yielded slightly higher void contents than the Cyclogen M recycled mix. This indicates delayed fluxing with the old pavement for the Cyclogen ME recycled mix.

OPTIMUM ASPHALT CONTENTS

A direct comparison of the optimum asphalt contents determined by the Hveem and Marshall mix designs for identical materials is difficult, primarily because of the different compaction procedures.

Calculation of optimum asphalt contents are dependent on the density and void contents. The compaction procedures used to prepare the indirect tensile test specimens was nearly identical to that used to prepare the Hveem specimens. However, this was the only deviation from the procedures for mixing and compacting the Marshall specimens. This change in compaction procedure resulted in a 40 to 50% decrease in void content.

It is noteworthy that the 5.8% optimum asphalt content determined by the simplified procedure (1,13) is between the values obtained with the Hveem and Marshall designs.

MARSHALL STABILITY

The Marshall stability of the emulsion recycled mixes was adversely affected by the test procedure. The low stabilities observed for the emulsion recycled mixes was due, at least in part, to immersing them into a 60 C (140 F) hot water bath prior to testing. It was observed during the testing that when these samples failed, they lacked the cohesion exhibited by the other three specimen types. Insufficient cure was thought to be the cause of the problem, and the second and third sets of samples were oven cured for up to 24 hours at 60 C (140 F) prior to testing, but stability values did not noticeably change. Curing time was probably insufficient for drying and fluxing.

CYCLOGEN M -vs- CYCLOGEN ME

The use of emulsified or non-emulsified forms of the recycling agent yielded mixtures with similar dynamic properties and tensile strengths. Differences in behavior, while slight, can be explained based on the less complete fluxing of the Cyclogen ME as compared to the Cyclogen M. For example, the stiffness of the Cyclogen ME recycled mix appeared to be slightly lower than that of the Cyclogen M recycled mix. The permanent deformation relationships are parallel for the two mixes. The Cyclogen ME recycled mix showed less permanent deformation than the Cyclogen M recycled mix, contrary to what is expected based on stiffness data. However, each of the sample types in this test was influenced by the behavior of one specimen that was not characteristic of the others. Elimination of these specimens would reverse the position of the two lines.

DYNAMIC PROPERTIES - RECYCLED MIXES -vs- CONTROLS

The principal material characteristics of the recycled mixes were more similar to the reconstituted control mix than to the virgin control mix. The recycled mixes appeared slightly stiffer than the reconstituted control mix, in spite of the lower void content of the control mix. The reconstituted control mix displayed better resistance to fatigue than the recycled mixes. The slopes of the best-fitting straight lines for fatigue resistance of the three mixes were similar. The higher tensile strength exhibited by the reconstituted control is a function of its higher density. Comparison of the permanent deformation behavior of the reconstituted mix with the recycled mixes is difficult because of the large variation in test temperatures.

The measured material characteristics of the two controls were different. The virgin control was stiffer, had poorer fatigue resistance and higher tensile strength, and exhibited less permanent vertical deformation.

ASPHALT AGING

Laboratory heating, mixing, and compaction do not age the asphalt materials to the degree obtained during rolling thin film conditioning. The behavior of both the control mixes in all tests was consistent with the asphalt properties measured before artificial aging. The lower viscosity of the virgin asphalt at 135 C (275 F) would result in lower void contents when mixed and compacted at nearly these temperatures. This was observed for the Marshall specimens at all but one asphalt content. This was also observed for the indirect tensile test specimens.

Viscosities at 60 C (140 F) were nearly identical. Therefore, stability tests at that temperature in the mix design were expected to be similar, and observed behavior proved this to be the case.

The virgin asphalt was more temperature susceptible than the reconstituted asphalt. At 25 C (77 F), it had a penetration nearly 30% lower than the reconstituted asphalt. The results of the dynamic modulus tests also indicated this, as the virgin control mix yielded a stiffer mix with substantially higher tensile strength.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The Marshall and Hveem methods, longtime proven methods for designing mixes with conventional materials, may not be dependable guides for designing recycled mixes. Use of these two design methods yielded substantially different optimum asphalt contents, in spite of the fact that the materials used in the designs were essentially identical.

Much of the strength and justification for the continued use of the Marshall and Hveem methods for the design of conventional mixes is the long history of observed field performance and its correlation with the results of the laboratory tests. Large-scale, hot mix asphalt recycling is still in an infant stage of development, and long-term field performance of recycled mixes is unavailable. There is a question whether the design criteria developed for conventional materials are applicable to recycled materials. Another serious drawback in the conventional mix designs is that they do not explicitly take into account the necessity for modifying the properties of the aged, hardened asphalt. This is obvious because they were not developed for this type of material. Typically, highway agencies faced with these problems have attempted to solve them by first investigating the modification in recovered asphalt properties resulting from several combinations of old asphalt and recycling agents. This essentially narrows the scope of the next step of the investigation.

Conventional mix designs, either Marshall or Hveem, are performed on several combinations of crushed asphalt concrete, virgin aggregate, recycling agent, and at times virgin asphalt. This can rapidly become an expensive, time-consuming project. There is a definite need for relatively simple, routine procedures for designing recycled asphalt concrete mixtures.

The uncomplicated mix design method proposed by Witco Chemical fulfills these requirements and, based on the favorable results reported in this research, appears to be appropriate for this field of limited experience. The required testing for asphalt properties and gradations consists of standard procedures familiar to any lab. Once these tests are performed, the designer, in a matter of minutes, can choose both the type and percentage of recycling agent necessary for his particular application. The major drawback to this design procedure is that this is where it stops. There is no explicit recommendation for the preparation of laboratory mixes and determination of the stability of those mixes.

RECOMMENDATIONS

It is recommended that the design procedure suggested by Witco Chemical be extended to explicitly include the preparation of laboratory mixes and determination of density, void content, and stability. The compaction method should be chosen to yield void contents similar to those obtained with field equipment on similar materials. It is further recommended that the resilient modulus be used as a measure of stability. In addition to being a better guide to mixture stability than the stability tests associated with the Marshall and Hveem design methods, it can be used in rational pavement structural design procedures. The indirect tensile test provides a rapid, non-destructive method for determining resilient modulus, and its use is recommended.

It is imperative in the design of any recycled asphalt mixture that laboratory mixes be made and tested so that minimum stability requirements can be met. For agencies not equipped to perform resilient modulus testing, stability tests associated with the Marshall and Hveem design methods are an acceptable, but less preferred, alternative.

The research reported here should be continued. It is recommended that cores from the field construction project be obtained for determination of resilient modulus and recovered asphalt properties.

All samples from the laboratory investigations, both mix designs and dynamic testing, have been retained. It is recommended that asphalt extractions be performed on representative specimens of all four sample types to determine if any significant changes in asphalt properties have occurred.

REFERENCES

1. Davidson, D.D., Canessa, William and Escobar, S.J., "Practical Aspects of Reconstituting Deteriorated Bituminous Pavements," *Recycling of Bituminous Pavements*, ASTM STP 662, L.E. Wood, Ed., American Society for Testing and Materials, 1978, pp. 16-34.

2. Terrel, R.L. and Fritchen, D.R., "Laboratory Performance of Recycled Asphalt Concrete," *Recycling of Bituminous Mixtures*, ASTM STP 662, L.E. Wood, Ed., American Society for Testing and Materials, 1978, pp. 104-122.

3. Texas Transportation Institute, *Guidelines for Recycling Pavement Materials*, NCHRP Report 224, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, 1980.

4. "Recycling Materials for Highways," *National Cooperative Highway Research Synthesis of Highway Practice 54*, Transportation Research Board, National Research Council, 1977.

5. "Recycling Asphalt Pavements," Federal Highway Administration Demonstration Project No. 39.

6. Walter, J.P., "Washington State Department of Transportation's Second Asphalt Concrete Recycling Project -- Yakima River to West Ellensburg Interchange," prepared for U.S. Department of Transportation, Federal Highway Administration, Office of Development, Implementation Division, Draft Copy, July 1979.

7. Schmidt, R.J., "A Practical Method for Measuring the Resilient Modulus of Asphalt Treated Mixtures," *Highway Research Record 404*, Highway Research Board, Washington, D.C., 1972.

8. Personal communication, J.P. Walter, 1980.

9. Rostler, F.S., "A Chemical Approach to the Problem of Maintenance of Asphaltic Pavements," U.S. Air Force Pavement Conference, Berkeley, California, 27-31 July 1959, pp. 333-354, U.S. Government Printing Office, 1969, 0-521079/66.

10. Rostler, F.S., U.S. Patent 3,162,101; 22 December 1964.

11. Rostler, F.S., U.S. Patent 3,344,056; 26 September 1967.

12. Rostler, F.S., U.S. Patent 3,432,321; 11 March 1969.

13. Davidson, D.D., Canessa, W. and Escobar, S.J., "Recycling of Substandard or Deteriorated Asphalt Pavements -- A Guideline for Design Procedures," Proceedings, AAPT Volume 46, 1977.

14. Canessa, William, "The Chemical Aspects of Asphalt Pavement Recycling Affecting Engineering Considerations," Proceedings, Association of Asphalt Paving Technologists, 1979.

15. Heukelom, W., "An Improved Method of Characterizing Asphaltic Bitumens with the Aid of Their Mechanical Properties," Proceedings, Association of Asphalt Paving Technologists, Volume 42, 1973.

16. "Mix Design Methods for Asphalt Concrete," The Asphalt Institute Manual Series 2, March 1974.

17. Kennedy, Thomas W., "Characterization of Asphalt Pavement Materials Using the Indirect Tensile Test," Proceedings, AAPT Volume 46, February 1977.

18. "Tensile Characterization of Highway Pavement Materials," Center for Highway Research, the University of Texas at Austin, Research Study 3-9-73-183, Interim Reports 183-3, 183-4, 183-5, 183-6, 183-7, 183-8.

19. Rimsritong, Sveng, "Wood Lignins Used as Extenders for Asphalt in Bituminous Pavements," PhD Dissertation, University of Washington, 1978.

20. Kennedy, T.W. and Perez, Ignacio, "Preliminary Mixture Design Procedure for Recycled Asphalt Materials," Recycling of Bituminous Pavements, ASTM STP 662, L.E. Wood, Ed., American Society for Testing and Materials, 1978, pp. 47-67.

APPENDIX

TABLE 1. Results of Final Mix Design for Construction Project (6)

Recycling Agent (%)	0	30	30	30	30
Virgin Aggregate 5/8 - 1/4 (5)	0	20	25	30	35
Gradation (% Passing) Size	Average of Milled Samples	Calculated Gradings			
5/8	100	100	100	100	100
1/2	100	97	96	96	95
3/8	98	86	83	80	77
1/4	85	69	64	60	56
#10	46	37	35	32	30
#40	20	16	15	14	13
#80	13	10	10	9	9
#200	8.5	7.0	6.6	6.2	5.8
Asphalt Content, %	5.0	5.2	4.9	4.6	4.2
Stabilometer (Ave. 6 Samples)	-	27	29	30	32
Void Content (%) (Ave. 6 Samples)	-	4.0	5.4	7.9	9.9

TABLE 2. Asphalt & Asphalt Mix Properties Before & After Addition of Virgin Aggregate & Recycling Agent

Properties	Crushed Asphalt Concrete Before Mixing		Recycled Mix[a] - 25% Recycling Agent		Recycled Mix[a] - 30% Recycling Agent	
	Average	Range	Average	Range	Average	Range
ASPHALT PROPERTIES						
Asphalt Content, %	5.3	4.4 - 5.8	5.0	4.8 - 5.1	4.8	4.8 - 4.9
Penetration, 77 F, dmm	12	6 - 16	66	60 - 71	80	78 - 81
Viscosity						
@ 140 F, poises	62494	28519 - 147187	2227	2123 - 2367	1538	1365 - 1605
@ 275 F, centistokes	1414	1332 - 1497	300	No Data	272	No Data
Durability Parameter, $(N + A_1)/(P + A_2)$	1.20	1.07 - 1.38	0.94	0.92 - 0.96	0.92	0.89 - 0.95
MIX PROPERTIES						
Resilient Modulus						
0.05 sec, $\times 10^5$ psi	19[b]	13 - 23	6.7	4.5 - 8.1	4.3	3.9 - 5.0
0.10 sec, $\times 10^5$ psi	14	11 - 16	5.0	3.2 - 6.9	3.2	2.9 - 3.6
HVEEM STABILITY	44	No Data	28	26 - 32	30	29 - 32
VOID CONTENT, %	8.8[b]	5.7 - 12.1	4.1	2.9 - 4.9	4.0	3.6 - 4.4

1 poise = 10^{-1} Pa•s, 1 cs = 10^{-6} m^2/s, 1 psi = 6895 Pa, $t_C = (t_F - 32)/1.8$

[a] Loose mix compacted in the laboratory.

[b] Resilient Modulus and void content data based on asphalt cores obtained from old pavement prior to startup of construction operations.

TABLE 3. Asphalt and Asphalt Mix Properties of Pavement Cores Immediately Following Construction

Properties	Recycled Asphalt Concrete Cores 25% Cyclogen L		Recycled Asphalt Concrete Cores 30% Cyclogen L	
	Average	Range	Average	Range
ASPHALT PROPERTIES				
Asphalt Content, %	5.4	5.2 - 5.5	5.3	4.6 - 6.1
Penetration, 77 F, dmm	58	51 - 66	77	73 - 83
Viscosity				
@ 140 F, poises	2928	2144 - 3543	1852	1608-2010
@ 275 F, centistokes	344	295 - 394	280	258 - 294
Durability Parameter, $(N + A_1)/(P + A_2)$	0.87	0.79 - 0.95	0.75	0.75 - 0.93
MIX PROPERTIES				
Resilient Modulus				
0.05 sec, x 10^5 psi	3.6	2.0 - 4.7	3.1	2.6 - 3.6
0.10 sec, x 10^5 psi	2.0	1.1 - 2.6	1.9	1.5 - 2.2
Density, pcf	141.0	132.1 - 147.4	144.3	142.6 - 146.6
Void Content, %	11.8	7.7 - 17.3	9.7	8.2 - 10.7

1 Poise = 10^{-1} Pa•s, 1 cs = 10^{-6} m^2/s, 1 psi = 6895 Pa, 1 pcf = 16 kg/m^3

TABLE 4. Recovered Asphalt Properties from Crushed Pavement

Tests Performed	Results	
	As Received	After RTFC
VISCOSITY		
Absolute Viscosity @ 140 F, poises	46,600	335,000
Kinematic Viscosity @ 275 F, centistokes	1,330	2,954
PENETRATIONS, dmm		
77 F, 100 g/5 sec	14	6
39.2 F, 200 g/60 sec	7	2
41 F, 100 g/5 sec	1	nil
DUCTILITY		
77 F, 5 cm/min (cm)	13	5
DURABILITY		
Asphaltenes, A	32.5	--
Nitrogen Bases, N	33.4	--
First Acidaffins, A_1	10.5	--
Second Acidaffins, A_2	13.5	--
Paraffins, P	10.1	--
Durability Parameter, $(N+A_1)/(P+A_2)$	1.86	--
RTFC Weight Loss	1.24	
(RTFC Absolute Vis)/(Recovered Absolute Vis)	7.2	

$t_C = (t_F - 32)/1.8$, 1 Poise = 10^{-1} Pa•s, 1 cs - 10^{-6} m^2/s

TABLE 5a. Proposed Specifications for Cyclogen™ Series

TESTS	FUNCTIONAL REASON	L	M	H
Viscosity at 140° F, cSt	Consistency	200 - 500	1,000 - 4,000	5,000 - 10,000
Flash Point, COC, Min.	Safety	350	350	350
Specific Gravity	Accounting	Report	Report	Report
ASTM D 1160 at 10 mm	Volatility			
IBP, °F, min.		300	300	300
2%, °F, min.		375	375	375
5%, °F, min.		410	410	410
ASTM D 2006				
N/P Ratio, min.	Compatibility	0.5	0.5	0.5
Ratio: $(N + A_1)/(P + A_2)$	Durability	0.4 - 1.2	0.4 - 1.2	0.4 - 1.2
Pumping Temperature, Min, °F	Transferability	130	160	180

Table 5b. Proposed Specifications for Cyclogen™ Emulsion Series

TESTS	FUNCTIONAL REASON	LE	ME	HE
Viscosity at 77°F, SSF	Handling Characteristics	15 - 85	15 - 85	15 - 85
Pumping Stability	Handling Characteristics	Pass	Pass	Pass
Sieve Test, %, maximum	Handling Characteristics	0.1	0.1	0.1
Particle Charge Test	Coating Characteristics	Positive	Positive	Positive
Cement Mixing Test, %, max.	Mixing Life	2.0	2.0	2.0
Distillation D244 Residue, % minimum	Accounting and Design	60	60	60
Storage Temperature, °F, min.	Handling Characteristics	40	40	40

Oils used for emulsification must meet the specifications for the recycling agents on Table 5a.

TABLE 6. Asphalt Property Modification with Cyclogen M Addition (Cyclogen M ÷ Total Asphalt = 0.31)

Test	Result	
	Aged Asphalt	Reconstituted
ABSOLUTE VISCOSITY @ 140 F, POISES		
As Received	46,600	2,280
After RTFC	335,000	7,310
PENETRATIONS, 77 F, 100 g/5 sec, dmm		
As Received	14	67
After RTFC	6	34
DUCTILITY, 77 F, 5 cm/min, cm		
As Received	13	150+
After RTFC	5	150+
DURABILITY PARAMETER, $(N + A_1)/(P + A_2)$	1.86	1.44

$T_C = (t_F - 32)/1.8$, 1 Poise = 10^{-1} Pa•s

TABLE 7. Virgin Asphalt Properties

Test	Result	
	As Received	After RTFC
VISCOSITY		
Absolute Viscosity @ 140 F, poises	2,280	3,970
Kinematic Viscosity @ 275 F, centistokes	268	339
PENETRATION		
77 F, 100 g/5 sec, dmm	48	30
39.2 F, 200 g/60 sec, dmm	13	8
41 F, 100 g/5 sec, dmm	2	1.5
DURABILITY		
Asphaltenes, A	8.7	--
Nitrogen Bases, N	44.2	--
First Acidaffins, A_1	16.1	--
Second Acidaffins, A_2	20.0	--
Paraffins, P	11.0	--
Durability Parameter, $(N + A_1)/(P + A_2)$	1.95	--
RTFC Weight Loss	0.09	
(RTFC Absolute Vis)/(Original Absolute Vis)	1.7	

$t_C = (t_F - 32)/1.8$, 1 Poise = 10^{-1} Pa•s, 1 cs = 10^{-6} m^2/s

TABLE 8. Average Values of Marshall Design Tests

	DENSITY (pcf)					VOID CONTENT (%)					VMA (%)				
Asphalt Content	4.7	5.2	5.7	6.2	6.7	4.7	5.2	5.7	6.2	6.7	4.7	5.2	5.7	6.2	6.7
Cyclogen M Recycled Mix	143.7	146.3	147.5	151.3	152.5	11.4	8.7	7.0	3.9	2.3	19.9	18.8	18.7	17.1	16.8
Cyclogen ME Recycled Mix	142.5	144.3	144.9	145.1	146.0	11.5	9.6	8.6	7.8	6.4	20.6	20.0	20.2	20.5	20.3
Asphalt Content	4.8	5.3	5.8	6.3	6.8	4.8	5.3	5.8	6.3	6.8	4.8	5.3	5.8	6.3	6.8
Reconstituted Control Mix	149.2 147.2	148.9	150.1	149.7	150.1	8.5	6.8	5.2	4.8	3.7	18.0	17.5	17.3	18.0	18.2
Virgin Control Mix	149.4 148.0	148.2	149.6	150.5	150.9	7.6	6.9	5.1	3.7	2.9	17.6	18.0	17.5	17.4	17.8

	STABILITY (lbs)					FLOW (× 10^{-2} in)				
Asphalt Content	4.7	5.2	5.7	6.2	6.7	4.7	5.2	5.7	6.2	6.7
Cyclogen M Recycled Mix	1372	1459	1523	2025	2034	12	12	12	14	14
Cyclogen ME Recycled Mix	891	1153	1178	1268	1225	15	13	13	12	12
Asphalt Content	4.8	5.3	5.8	6.3	6.8	4.8	5.3	5.8	6.3	6.8
Reconstituted Control Mix	1570	1764	1797	1598	1470	11	13	12	13	14
Virgin Control Mix	1711	1704	1830	1626	1601	11	11	14	14	14

TABLE 9. Hveem Mix Design Test Results

	DENSITY (pcf)					VOID CONTENT (%)				
Asphalt Content	4.2	4.7	5.2	5.7	6.2	4.2	4.7	5.2	5.7	6.2
Cyclogen M Recycled Mix	146.0	149.8	151.5	155.0	155.1	10.5	7.3	5.1	1.9	1.5
Cyclogen ME Recycled Mix	147.2	147.0	152.2	153.3	153.3	9.6	8.3	4.4	2.2	1.4
Asphalt Content	4.3	4.8	5.3	5.8	6.3	4.3	4.8	5.3	5.8	6.3
Reconstituted Control Mix	152.3	155.1	155.9	156.4	155.8	5.4	3.5	2.0	0.7	0.2
Virgin Control Mix	154.4	153.8	156.4	156.7	156.5	3.7	3.6	1.5	0.9	0.6

	"S" - VALUE				
Asphalt Content	4.2	4.7	5.2	5.7	6.2
Cyclogen M Recycled Mix	31	34	35	13	12
Cyclogen ME Recycled Mix	30	36	48	32	10
Asphalt Content	4.3	4.8	5.3	5.8	6.3
Reconstituted Control Mix	25	19	13	13	6
Virgin Control Mix	29	25	24	12	6

TABLE 10. Optimum Asphalt Contents as Determined by Conventional Mix Designs

Sample Type	Optimum Asphalt Content (Percent by Total Weight)	
	Hveem Design	Marshall Design
Cyclogen M Recycled Mix[a]	5.2	6.5
Cyclogen ME Recycled Mix[a]	5.0	6.5
Reconstituted Control Mix[a]	5.1	6.2
Virgin Control Mix[a]	5.1	6.2
Cyclogen L Recycled Mix[b]	5.2	---

[a] Hveem Design performed by FHWA Laboratory, Vancouver, Washington.

[b] Hveem Design performed as part of construction operation.

TABLE 11. Comparison of Densities & Void Contents in the Marshall & Hveem Mix Designs - All Sample Types

Asphalt Content %	Cyclogen M Recycled Mix						Cyclogen ME Recycled Mix					
	Density, pcf		Void Content, %		Max Spec Grav		Density, pcf		Void Content, %		Max Spec Grav	
	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem
4.7	143.7	149.8	11.4	7.3	2.60	2.59	142.5	147.0	11.5	8.3	2.58	2.57
5.2	146.3	151.5	8.7	5.1	2.57	2.56	144.3	152.2	9.6	4.4	2.56	2.55
5.7	147.5	155.0	7.0	1.9	2.54	2.53	144.9	153.3	8.6	2.2	2.54	2.51
6.2	151.3	155.1	3.9	1.5	2.52	2.52	145.1	153.3	7.8	1.4	2.52	2.49

Asphalt Content %	Reconstituted Control Mix						Virgin Control Mix					
	Density, pcf		Void Content, %		Max Spec Grav		Density, pcf		Void Content, %		Max Spec Grav	
	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem	Marsh	Hveem
4.8	147.2	155.1	8.5	3.5	2.58	2.57	148.0	153.8	7.6	3.6	2.57	2.56
5.3	148.9	155.9	6.8	2.0	2.56	2.55	148.2	156.4	6.9	1.5	2.55	2.54
5.8	150.1	156.4	6.2	0.7	2.54	2.53	149.6	156.7	5.1	0.9	2.53	2.53
6.3	149.7	155.8	4.8	0.2	2.52	2.50	150.5	156.5	3.7	0.6	2.51	2.52

1 pcf = 16 kg/m^3

TABLE 12. Summary of Testing Conditions for Indirect Tensile Measurement

TEST TYPE	PRELOAD	LOADING CONDITIONS			REPETITIONS	EQUATIONS USED[a]
		DURATION (sec)	MAGNITUDE (lbs)	FREQUENCY (Hz)		
RESILIENT MODULUS						
Before Permanent Deformation	50 Repetitions at Testing Conditions	0.1	100	1/2	As necessary to obtain good data for the resilient modulus calculation.	1
After Permanent Deformation	Not Necessary	0.1	50, 100, 150, 200	1/2		
Before Fatigue	50 Repetitions at Testing Conditions	0.1	Varies 70-510	1		
During Oven Cure of Recycled Specimens	50 Repetitions at Testing Conditions	0.1	100	1/2		
PERMANENT DEFORMATION TEST	50 Repetitions at Testing Conditions	0.1	100	1/2	10,000	2
FATIGUE TEST	50 Repetitions at Testing Conditions	0.1	Varies 70-510	1	As necessary to completely fracture specimen.	3
TENSILE STRENGTH TEST	5 to 10 lbs to seat load strips	Load applied at constant 2 in/min deformation rate until sample fails. Peak load = failure load.			Not Applicable.	4

[a] Refer to Table 13 for identification of the equations

1 lb = 4.45 N, 1 in = 25.4 mm

TABLE 13. Equations Used For Calculating Properties Using the Indirect Tensile Test

EQUATION NUMBER	PROPERTY	EQUATION[a]	DEFINITION OF SYMBOLS	REF.
1	Resilient Modulus	$M_R = \frac{P\ (\nu + 0.2732)}{t\ \Delta h}$	M_R = Resilient Modulus, psi ν = Poisson's Ratio	(7)
2	Accumulated Vertical Compressive Strain	$\varepsilon_c = Y_T\ \frac{-.1185 - \nu(.03896)}{-.8954 - \nu(-.0156)}$	t = Specimen Thickness, in. Δh = Total Resilient Horizontal Deformation, in.	(17)
3	Tensile Stress (Strength)	$\sigma_t = (P/t)(0.156)$	ε_c = Accumulated Vertical Strain, in./in. Y_T = Accumulated Permanent Vertical Deformation, in.	(17)
4	Horizontal Tensile Strain	$\varepsilon_T = \Delta h\ \frac{.03896 - \nu(-.1185)}{.0673 - \nu(-.2494)}$	σ_t = Tensile Stress, psi (σ_t = tensile strength when $P = P_{failure}$) ε_T = Horizontal Tensile Strain, in./in.	(17)

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[a] All constants apply to 4-inch diameter specimens only. (See Reference 17.)

TABLE 14. Mix Proportions Used for Indirect Tensile Test Specimens (Percentages are by Total Weight of Mix)

RECYCLED SAMPLES WITH NON-EMULSIFIED AND EMULSIFIED RECYCLING AGENTS			
Crushed Asphalt Concrete	81.9%	Old Aggregate[a]	78.0%
Virgin Aggregate	16.3%	Virgin Aggregate	16.3%
Recycling Agent	1.8%	Total Asphalt[a] (aged + recycling agent)	5.7%
TOTAL	100.0%	TOTAL	100.0%

CONTROL SAMPLES - RECONSTITUTED AND VIRGIN	
Recovered Aggregate	77.8%
Virgin Aggregate	16.4%
Asphalt (Reconstituted or Virgin)	5.8%
TOTAL	100.0%

[a] These proportions are equivalent to the proportions shown at the left, assuming that 4.8% of the crushed asphalt concrete is aged asphalt.

TABLE 15. Average Density and Void Content Comparison

SAMPLE TYPE	ASPHALT CONTENT %	MARSHALL MIX DESIGN		HVEEM MIX DESIGN		DYNAMIC TESTING	
		Density, pcf	Voids, %	Density, pcf	Voids, %	Density, pcf	Voids, %
Cyclogen M Recycled	5.7	147.5	7.0	155.0	1.9	152.0	4.1
Cyclogen ME Recycled	5.7	144.9	8.6	153.3	2.2	151.1	4.7
Reconstituted Control	5.8	150.1	6.2	156.4	0.7	153.2	3.3
Virgin Control	5.8	149.6	5.1	156.7	0.9	154.1	2.4

1 pcf = 16 kg/m^3

TABLE 16. Average Resilient Modulus Values

Sample Type	Data Obtained During Permanent Deformation Testing Load Frequency = 1/2 Hz						Data Obtained During Fatigue Tests Load Frequency = 1 Hz			
	Average Density (pcf)	Average Voids (%)	Average Temp., ^{o}F		Modulus, x 10^3 psi		Average Density (pcf)	Average Voids (%)	Average Temp. (^{o}F)	Modulus, x10^3 psi
			Initial	After 10^4 Reps	Initial	After 10^4 Reps				
Cyclogen M Recycled Mix	151.1	4.7	69	70	426	418	152.1	4.0	74	332
Cyclogen ME Recycled Mix	151.4	4.5	70	71	420	358	150.9	4.8	75	300
Reconstituted Control Mix	154.2	2.7	78	78	159	143	152.9	3.5	74	293
Virgin Control Mix	153.3	2.9	72	74	388	312	154.1	2.4	75	451

$t_C = (t_F - 32)/1.8$, 1 pcf = 16 kg/m^3, 1 psi = 6.89 kPa

TABLE 17. Summary of Permanent Vertical Deformation Test

Sample Type	REGRESSION DATA[a]			MIX DATA	
	I ($\times 10^{-4}$)	S	r^2[b]	Average Temp., °F	Average Voids, %
Cyclogen M Recycled Mix	1.5	0.34	0.75	69	4.7
Cyclogen ME Recycled Mix	1.3	0.35	0.79	70	4.5
Reconstituted Control Mix	0.34	0.56	0.86	79	2.7
Virgin Control Mix	0.61	0.44	0.80	73	2.9

[a] The equation relating permanent deformation to load applications is:

$$\varepsilon_c = I N^S$$

where: ε_c = accumulated vertical compressive strain,

N = number of load applications, and

I, S = regression constants identified in the table.

[b] r^2 is the coefficient of determination.

$t_C = (t_F - 32)/1.8$

TABLE 18. Comparison of Fatigue Data Regression Coefficients

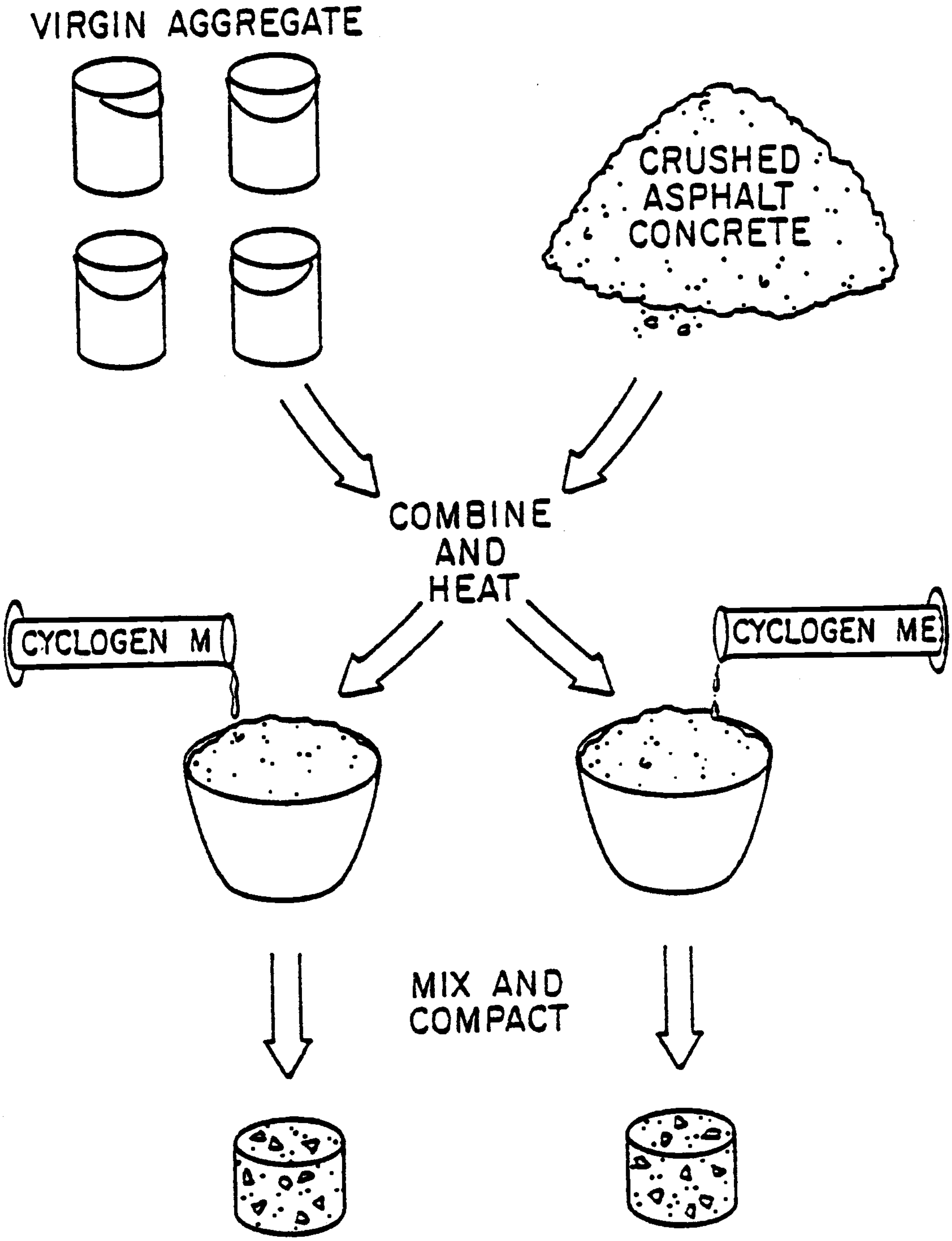
Sample Type	K_1	n_1	K_2'	n_2	Reference
Cyclogen M Recycled Mix	5.19×10^{-8}	3.01	2.33×10^{9}	2.57	--
Cyclogen ME Recycled Mix	1.33×10^{-5}	2.38	6.13×10^{8}	2.36	--
Reconstituted Control Mix	4.27×10^{-7}	2.84	1.37×10^{12}	3.98	--
Virgin Control Mix	6.08×10^{-3}	1.67	4.50×10^{7}	1.65	--
RECYCLED MIX SPECIMENS					
Minimum Values	---	--	3.96×10^{8}	2.15	20
Maximum Values	---	--	1.11×10^{23}	8.07	20
ASPHALT CONCRETE SPECIMENS					
Minimum Values	9.31×10^{-11}	2.86	3.33×10^{8}	2.86	18, 183-5
Maximum Values	4.49×10^{-8}	3.49	1.33×10^{10}	3.46	18, 183-5
DRYER DRUM SPECIMENS					
Minimum Values	---	--	7.05×10^{5}	1.24	18, 183-8
Maximum Values	---	--	2.52×10^{8}	2.28	18, 183-8
PRELIMINARY RECOMMENDATIONS FOR MIX DESIGN	---	--	$10^{11} - 10^{18}$	2 - 8	20

TABLE 19. Average Tensile Strength Values

SAMPLE TYPE	AVERAGE DENSITY (pcf)	AVERAGE VOIDS (%)	TENSILE STRENGTH (psi)
Cyclogen M Recycled Mix	151.4	4.5	107
Cyclogen ME Recycled Mix	151.3	4.6	108
Reconstituted Control Mix	154.2	2.7	140
Virgin Control Mix	153.0	3.1	197

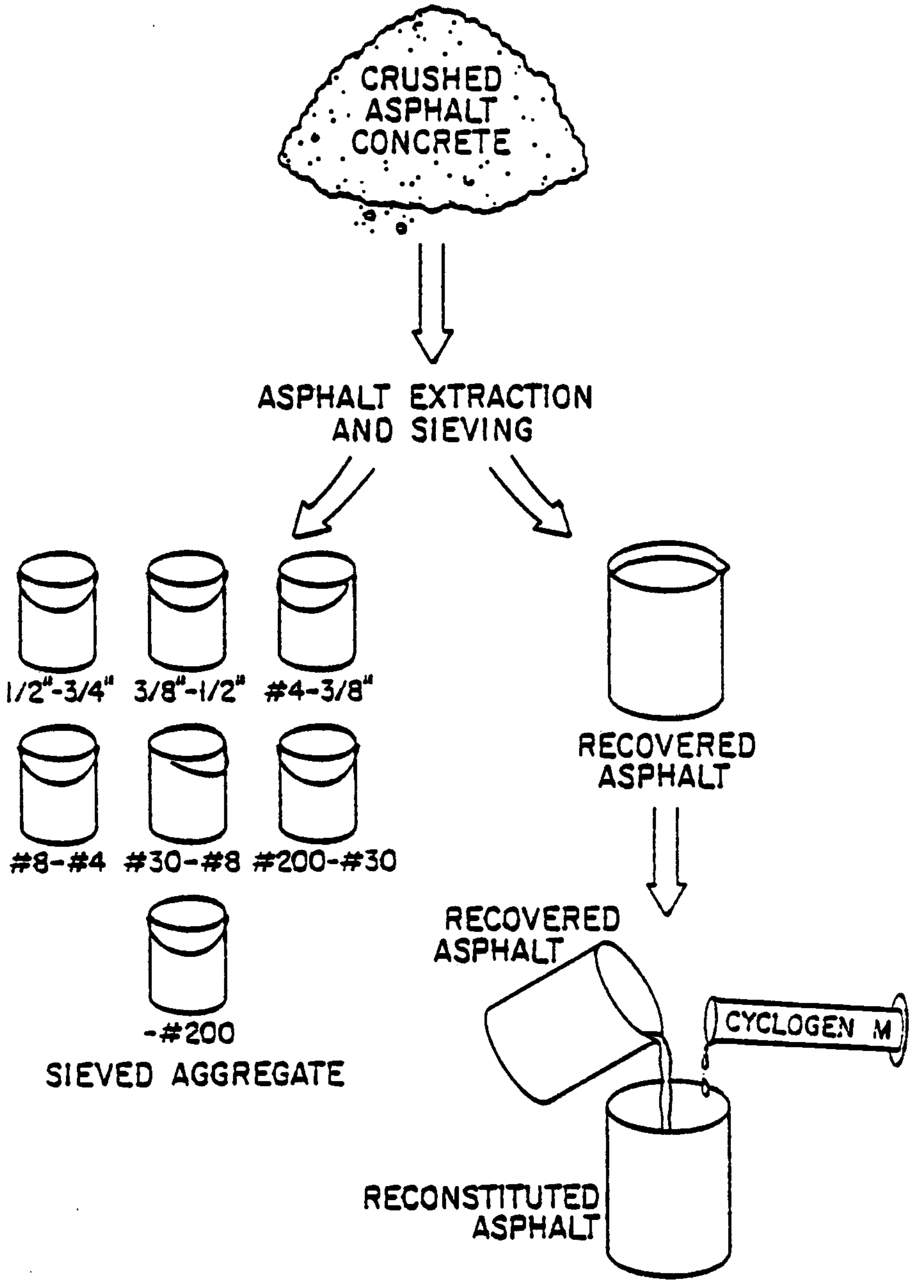
1 pcf = 16 kg/m^3

1 psi = 6.89 kPa



CYCLOGEN M - Non-emulsified form of recycling agent
CYCLOGEN ME - Emulsified form of recycling agent

FIGURE 1. Recycled Mixes Used in the Study



CYCLOGEN M - Non-emulsified form of recycling agent.

FIGURE 2. Development of Reconstituted Asphalt

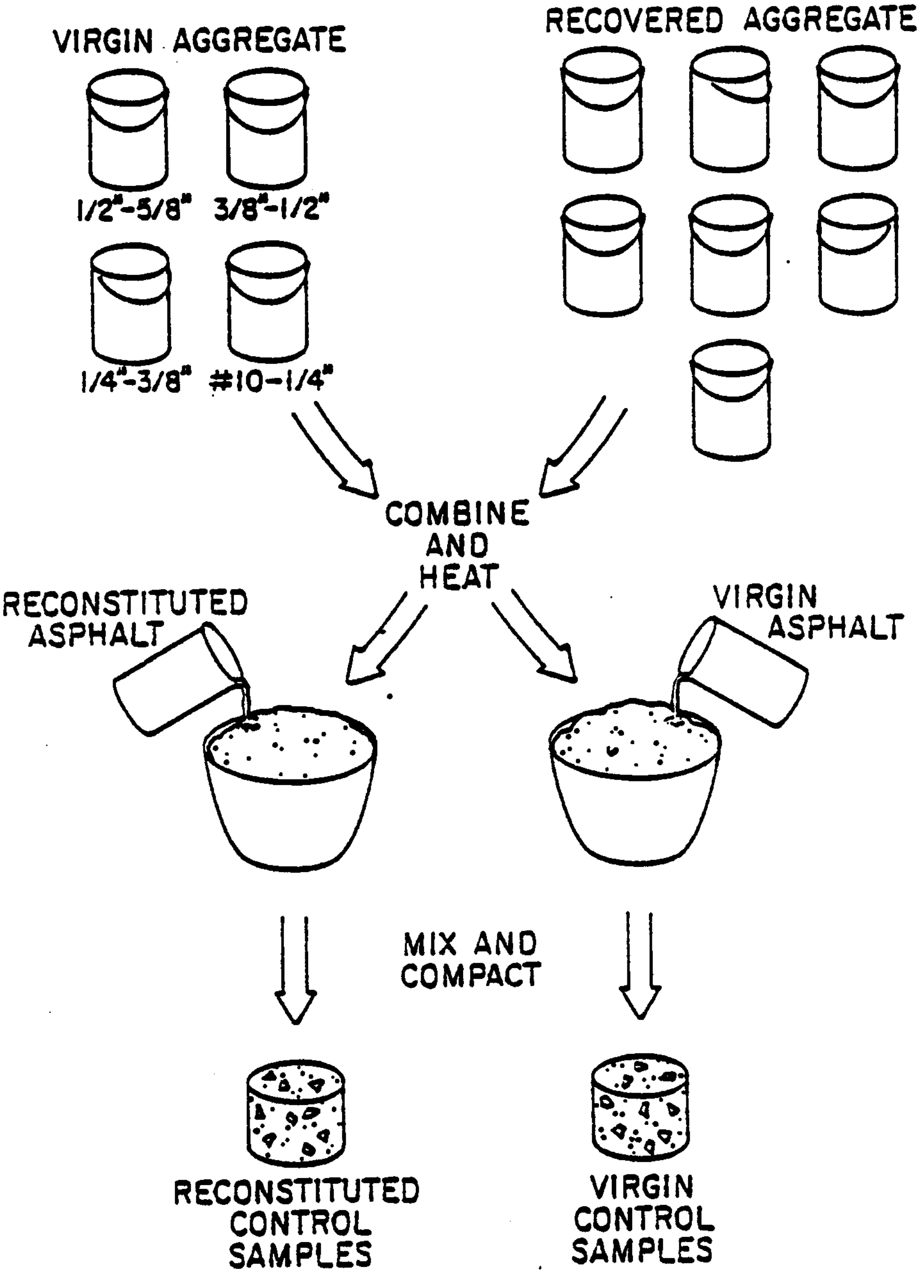


FIGURE 3. Control Mixes Used in the Study

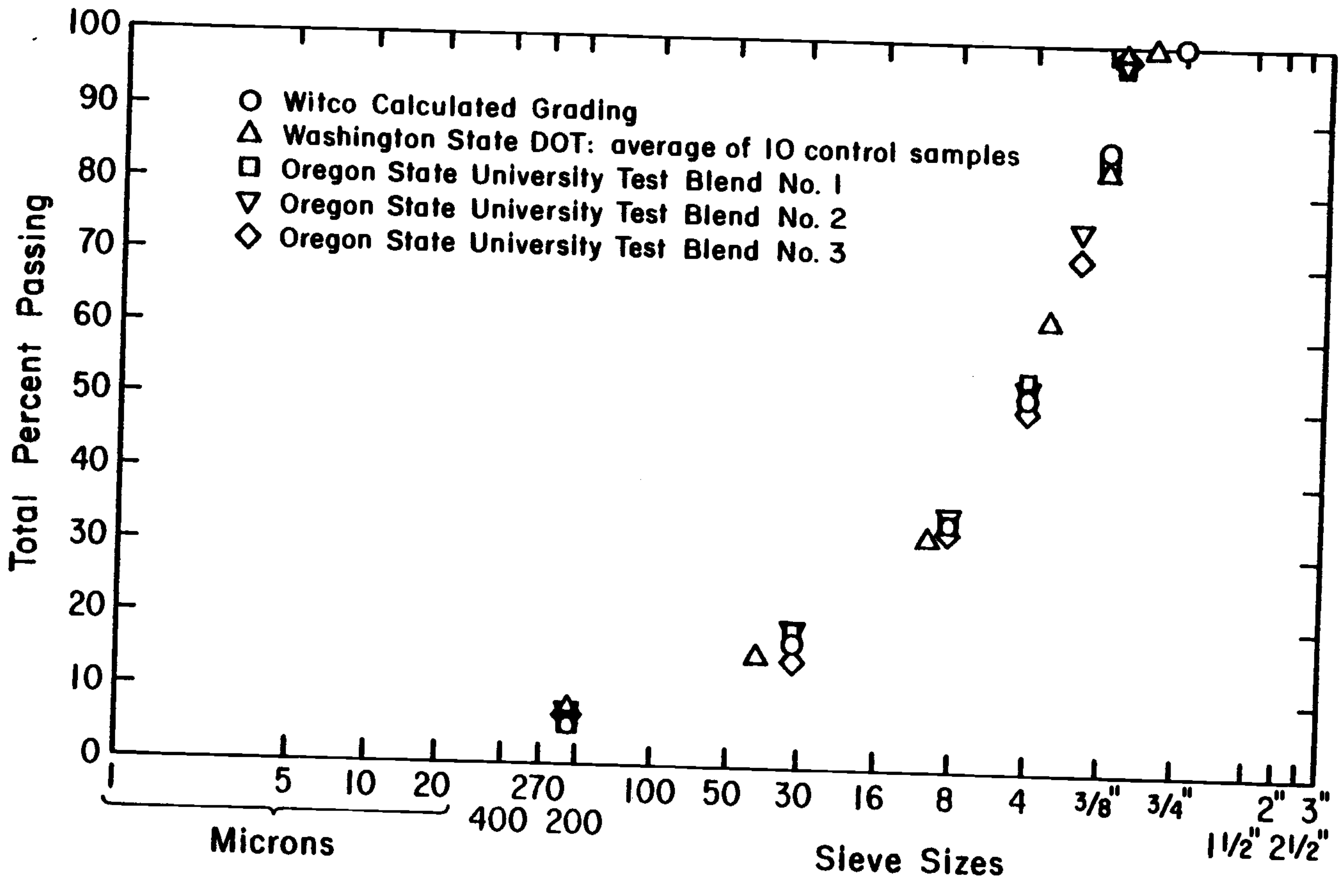


FIGURE 4. Comparison of Gradations

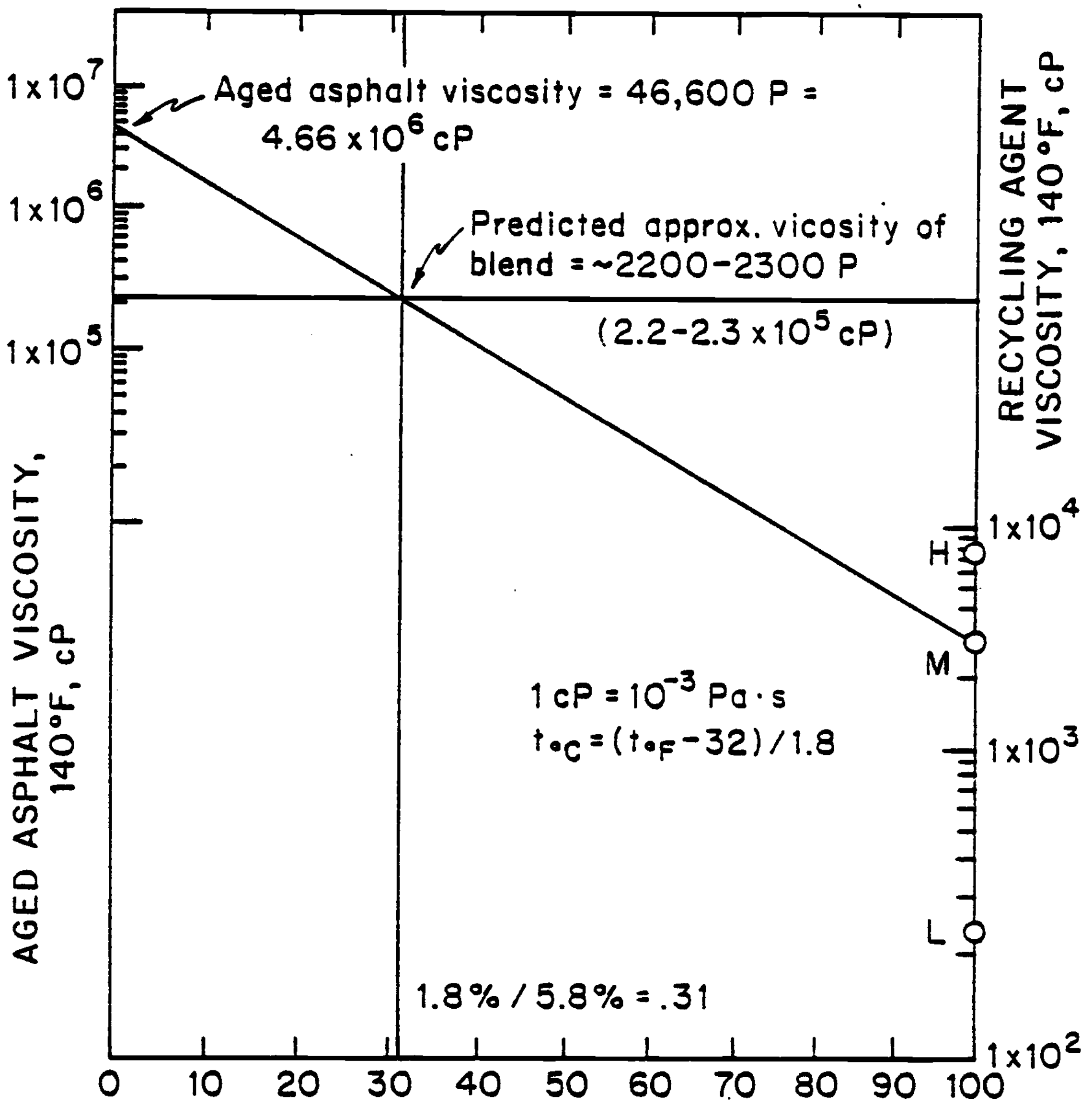
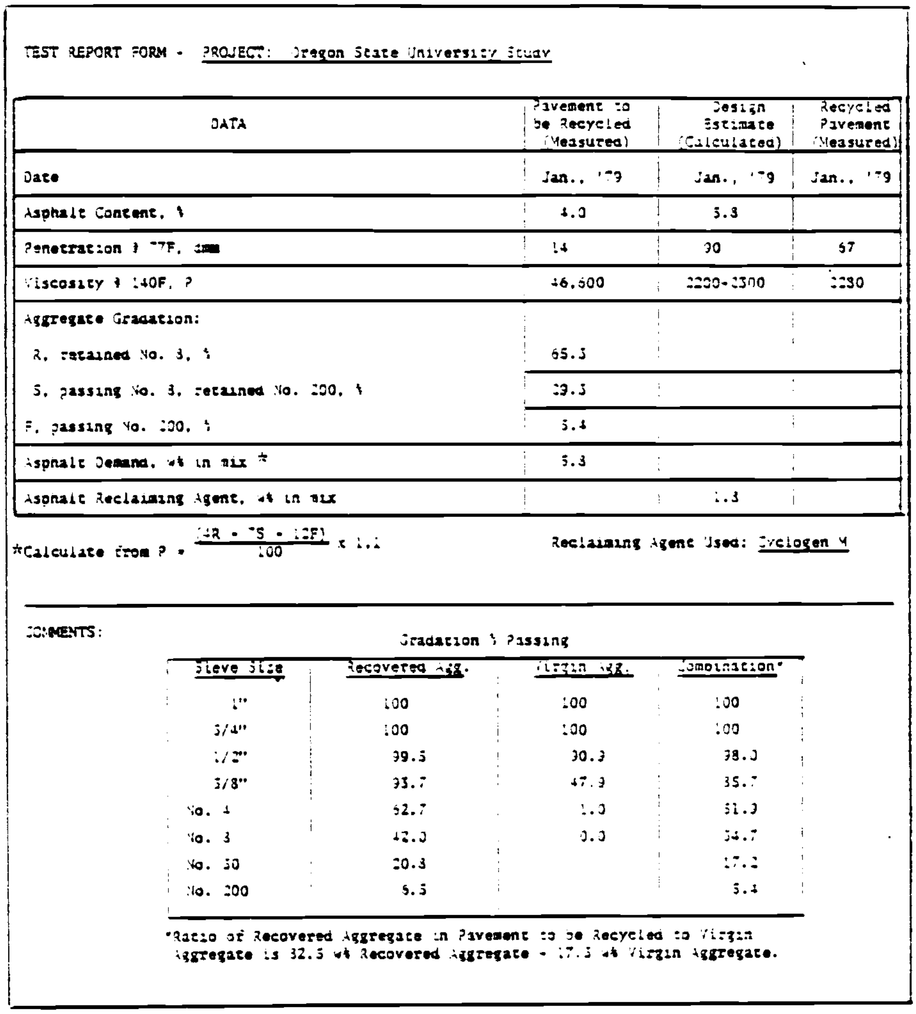


FIGURE 5. Nomograph for Viscosity - Final Design



TEST REPORT FORM - PROJECT: Oregon State University Study

DATA	Pavement to be Recycled (Measured)	Design Estimate (Calculated)	Recycled Pavement (Measured)
Date	Jan., '79	Jan., '79	Jan., '79
Asphalt Content, %	4.0	5.8	
Penetration @ 77F, dmm	14	90	67
Viscosity @ 140F, P	46,600	2200-2300	2230
Aggregate Gradation:			
R, retained No. 8, %	65.3		
S, passing No. 8, retained No. 200, %	29.3		
F, passing No. 200, %	5.4		
Asphalt Demand, wt% in mix *	5.3		
Asphalt Reclaiming Agent, wt% in mix		1.3	

*Calculate from $P = \frac{(4R + 7S + 12F)}{100} \times 1.1$

Reclaiming Agent Used: Cyclogen M

COMMENTS:

Gradation % Passing

Sieve Size	Recovered Agg.	Virgin Agg.	Combination*
1"	100	100	100
3/4"	100	100	100
1/2"	99.5	90.3	98.0
3/8"	93.7	47.9	85.7
No. 4	62.7	1.0	51.9
No. 8	42.0	0.0	34.7
No. 30	20.8		17.2
No. 200	6.5		5.4

*Ratio of Recovered Aggregate in Pavement to be Recycled to Virgin Aggregate is 82.5 wt% Recovered Aggregate - 17.5 wt% Virgin Aggregate.

$t_{°C} = (t_{°F} - 32)/1.8$
1 Poise = 10^{-1} Pa·s
1 in = 25.4 mm

FIGURE 6. Test Report Form - Final Design

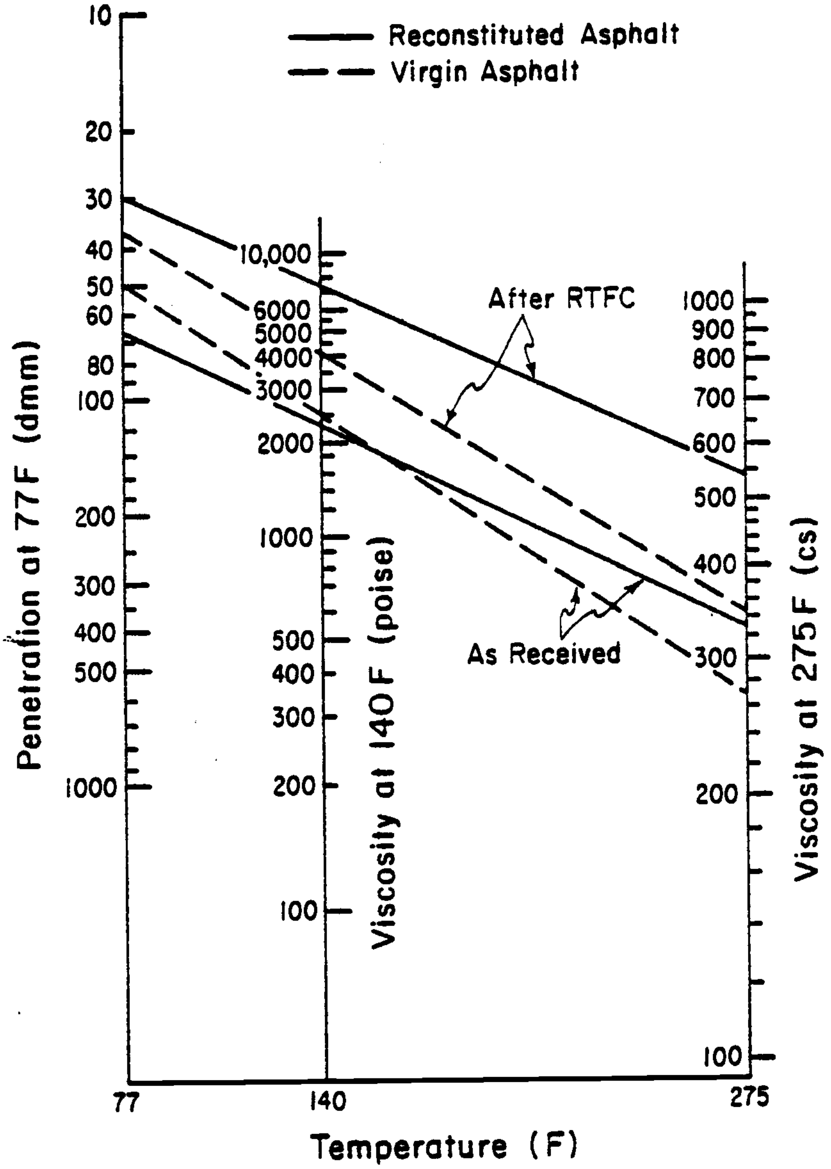


FIGURE 7. Modified Softening Diagram for Penetration and Viscosity Relationships

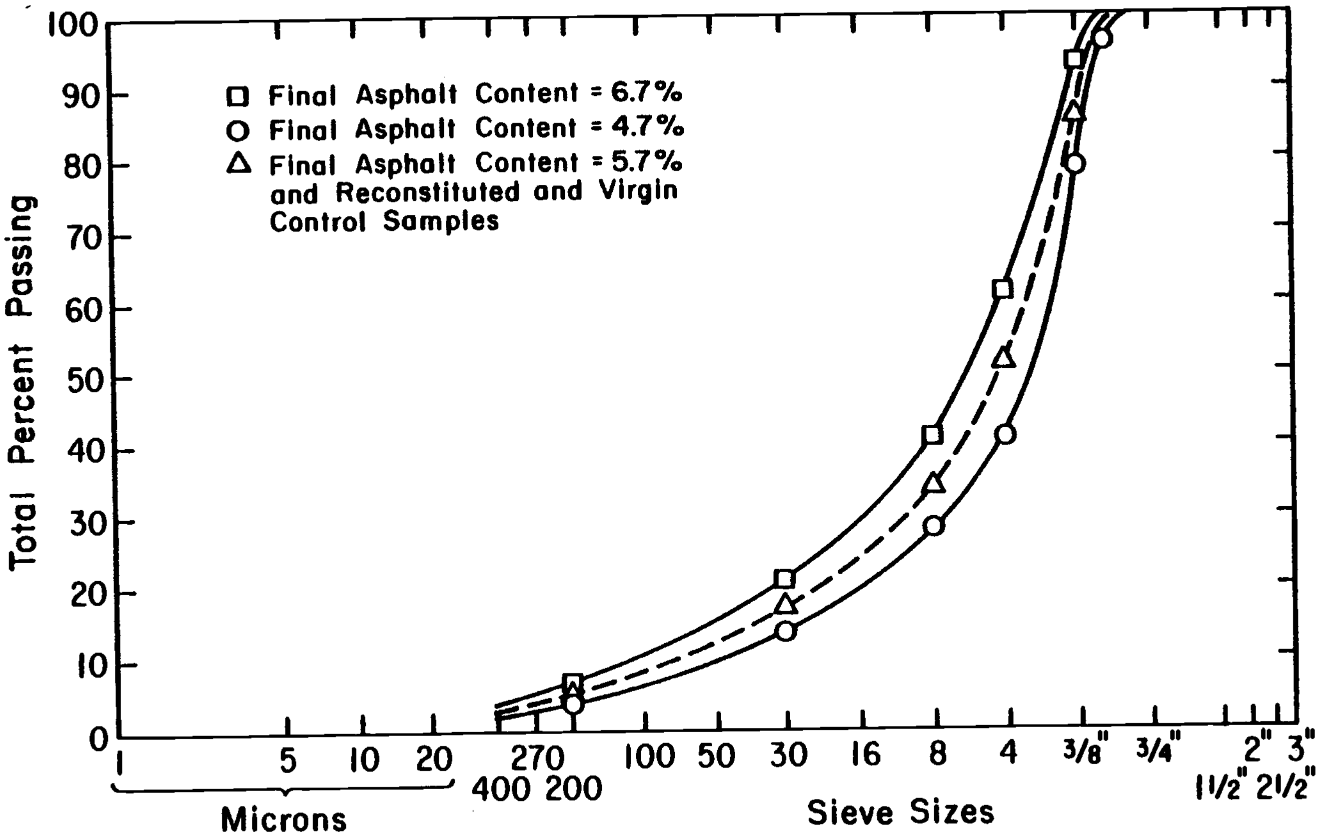


FIGURE 8. Final Calculated Aggregate Gradations for Mix Design Samples

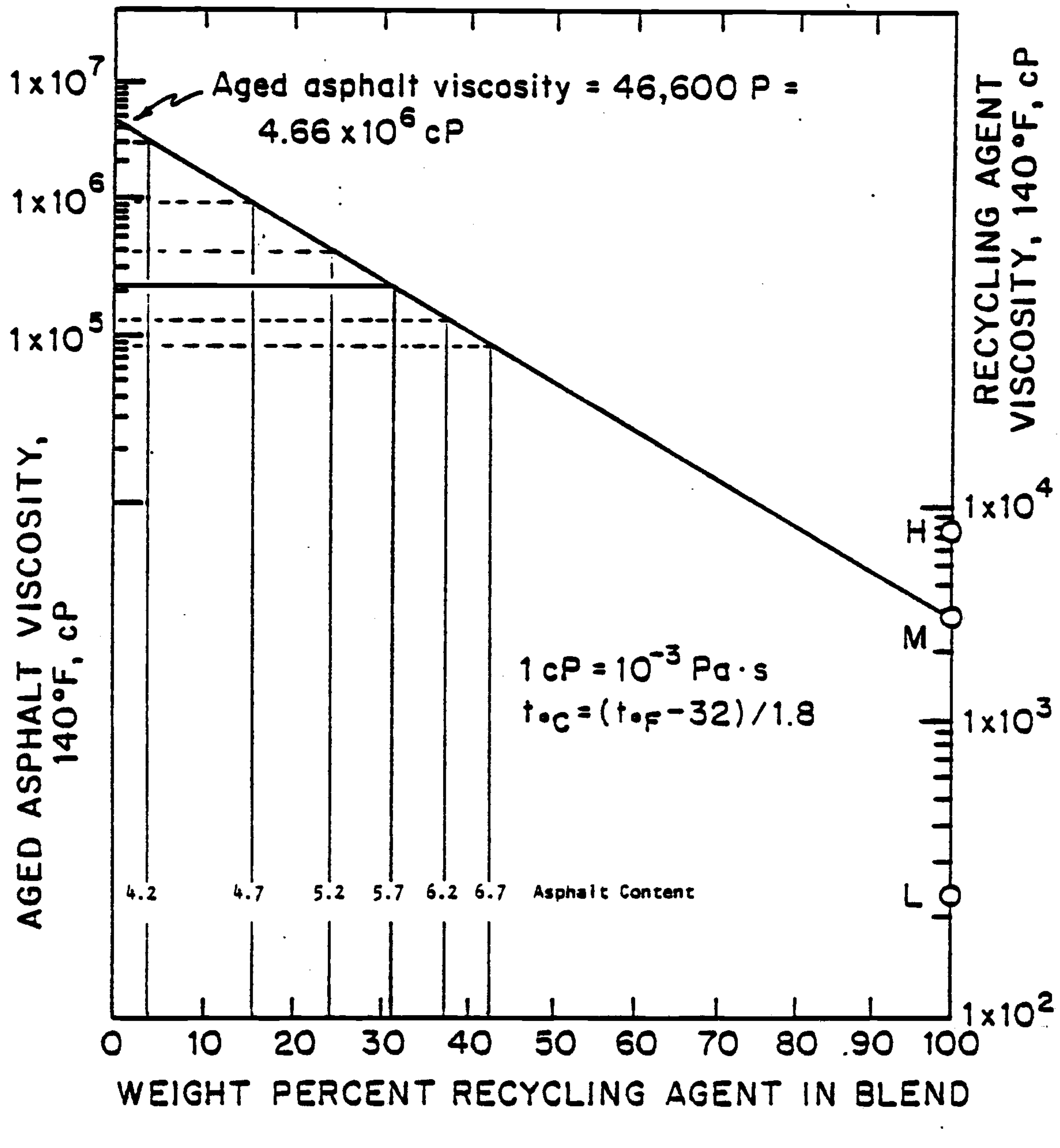


FIGURE 9. Nomograph for Viscosity - Comparison of Asphalt Contents

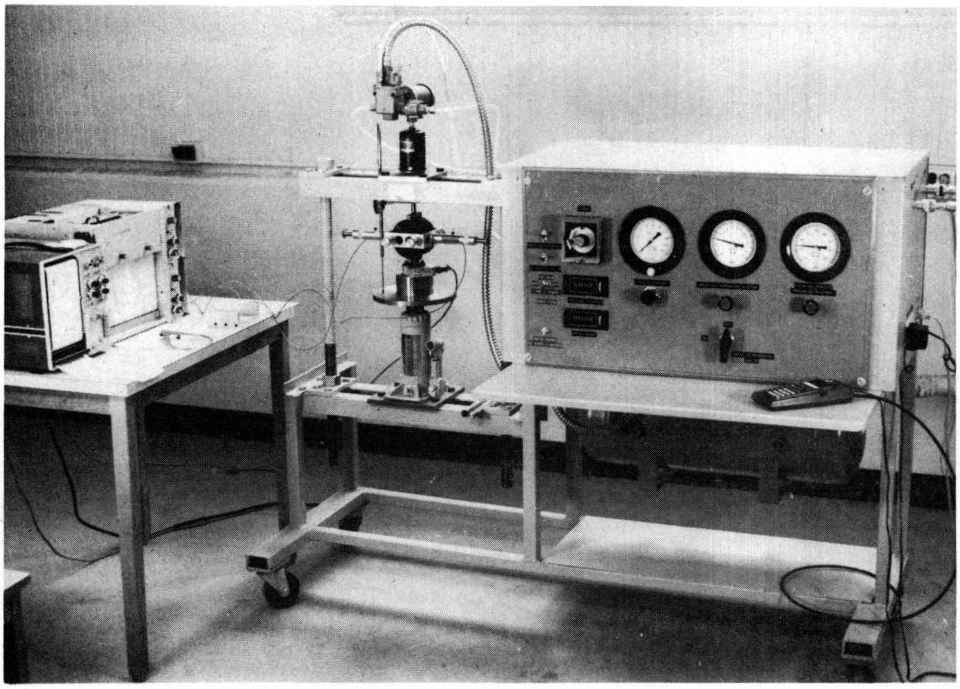


FIGURE 10a. Equipment Developed for Dynamic Testing

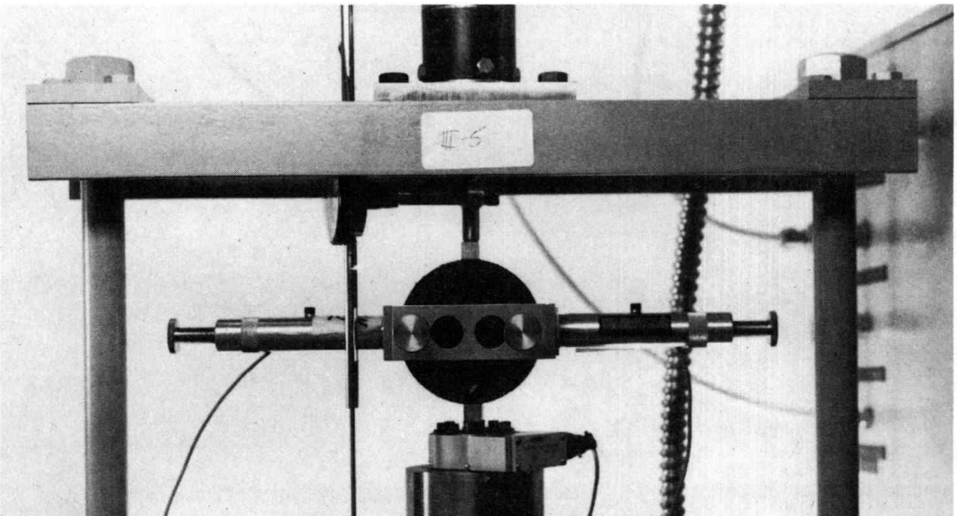


FIGURE 10b. Resilient Modulus Testing Configuration

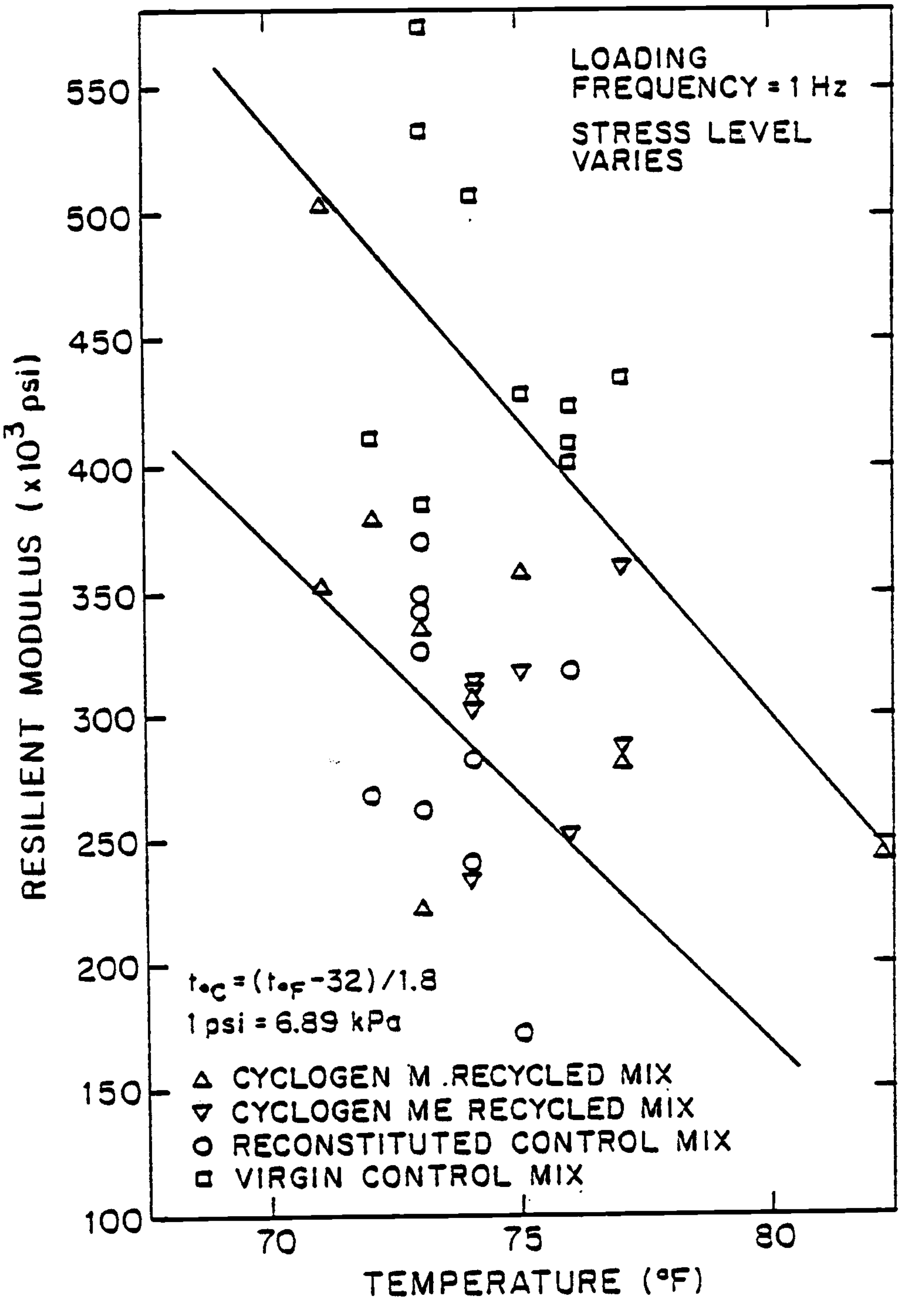


FIGURE 11. Variation of Resilient Modulus with Temperature

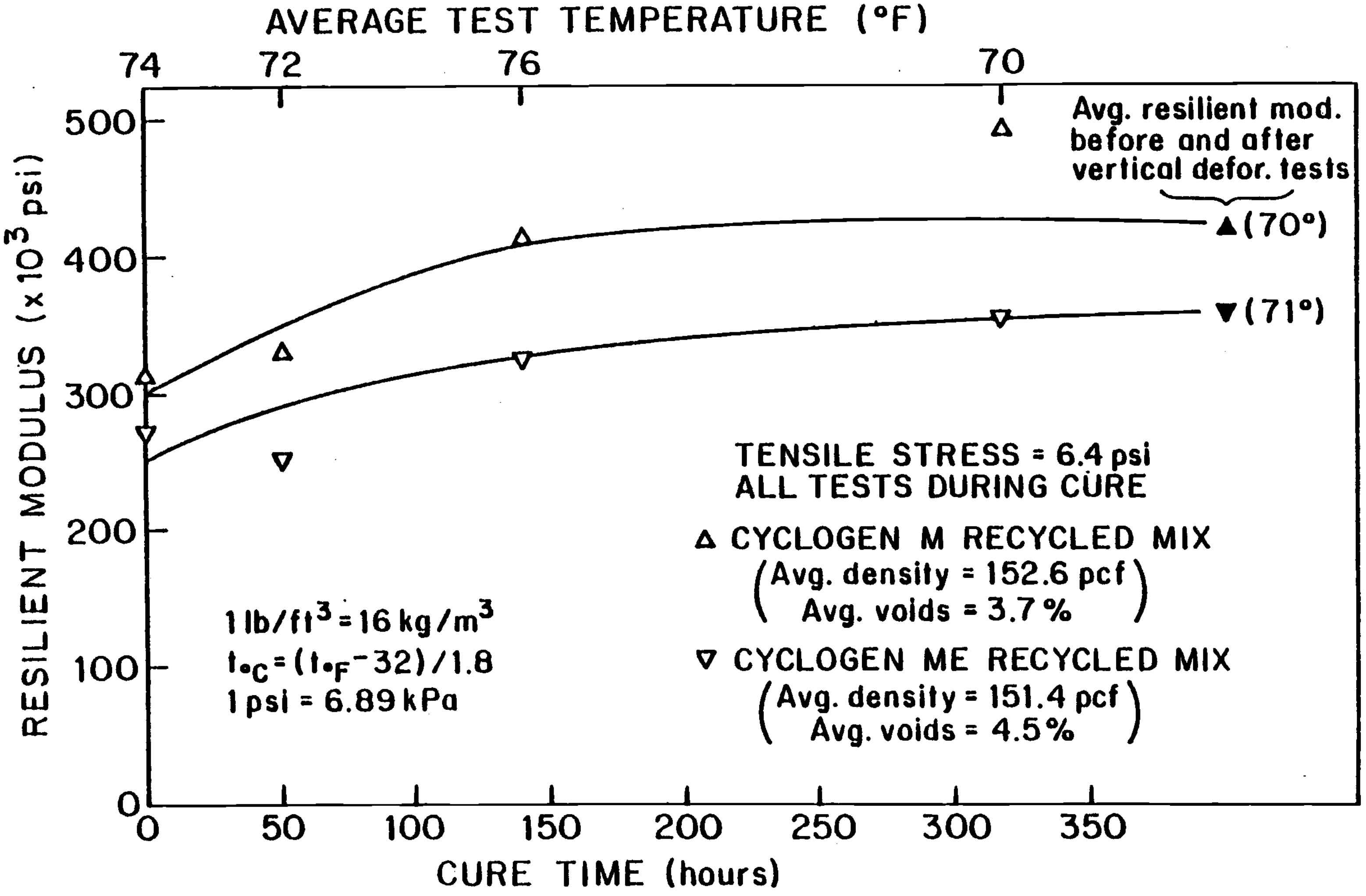
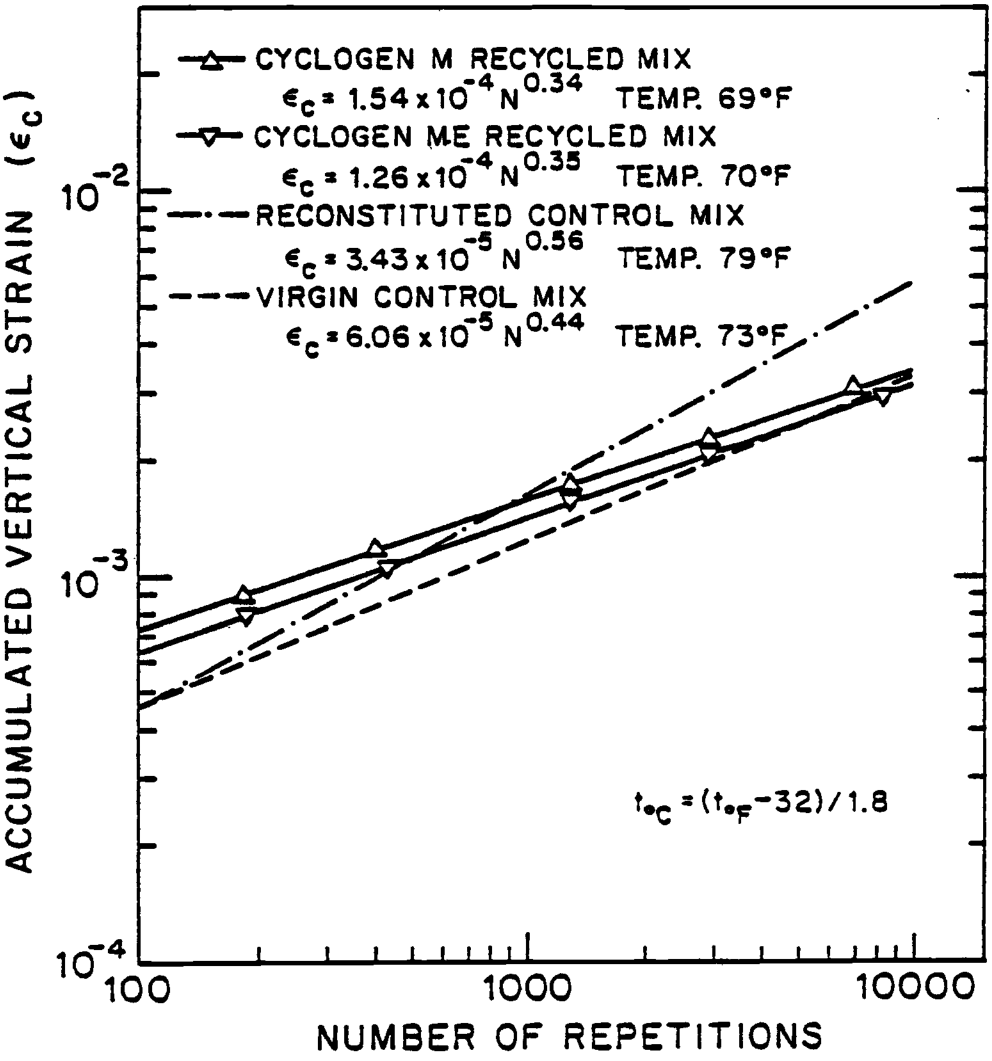
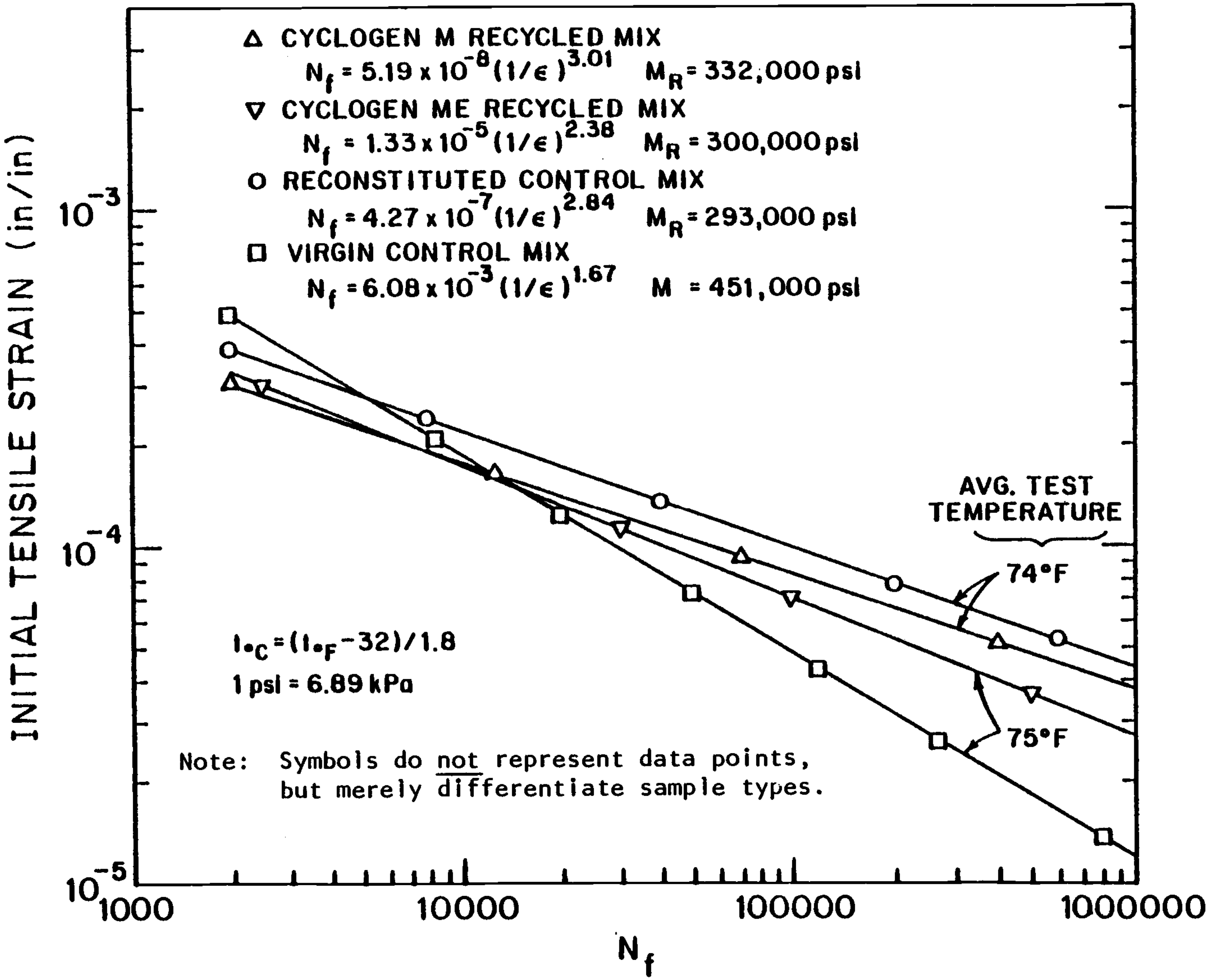


FIGURE 12. Modulus Changes in Recycled Mixes During 140 F Oven Cure



Note: Symbols do not represent data points, but merely differentiate between sample types.

FIGURE 13. Permanent Vertical Deformation During Repeated Loading



Note: Symbols do not represent data points, but merely differentiate sample types.

FIGURE 14. Fatigue Test Results

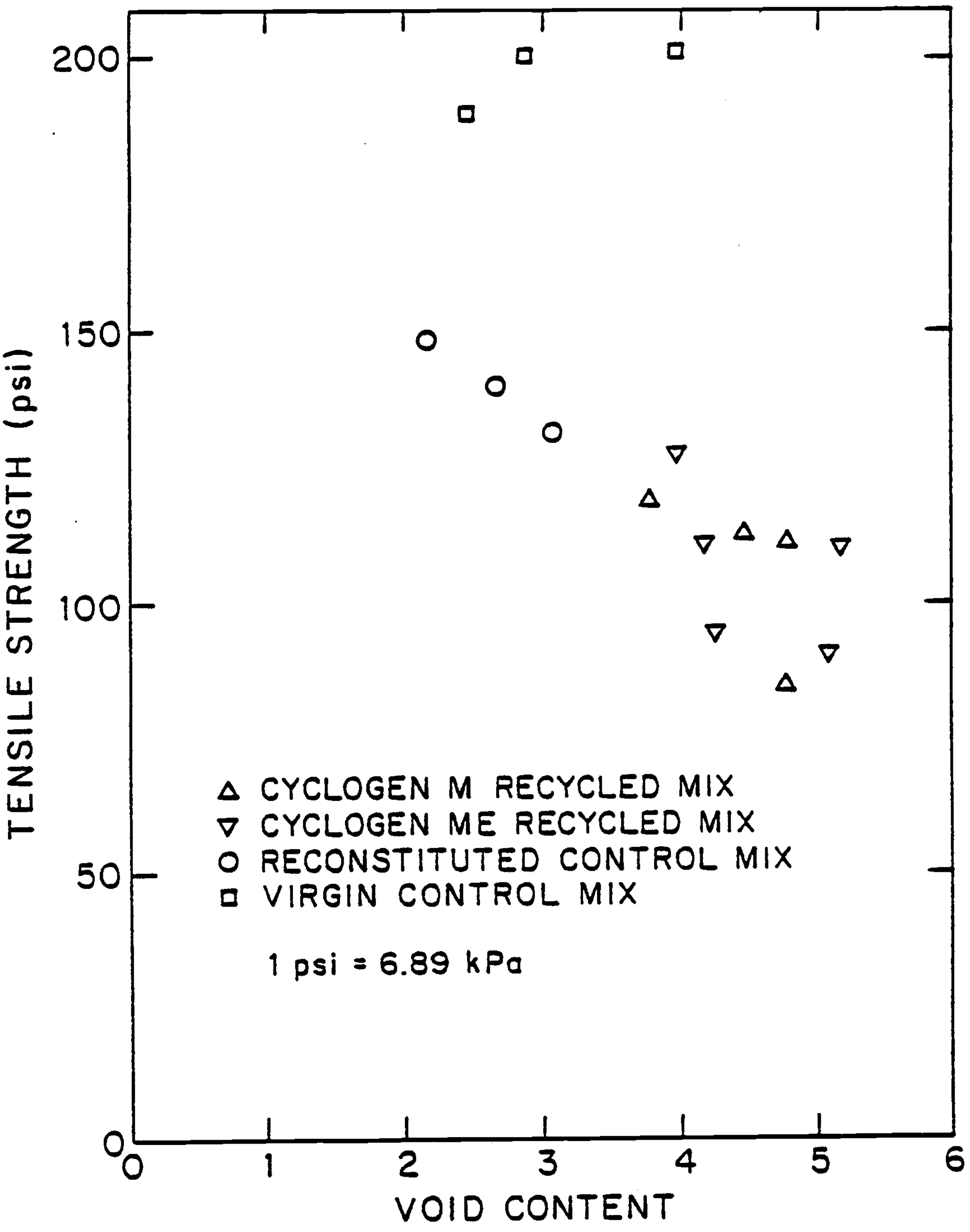


FIGURE 15. Effect of Void Content on Tensile Strength