Mechanistic Characterization of Superpave Asphalt Mixes in Costa Rica

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ABSTRACT. *This paper presents an investigation of the dynamic modulus, fatigue properties, and static creep of ten different Superpave mixes used in Costa Rica. The mechanistic properties were compared with empirical properties and also with equivalent Marshall Mix designs. The effect of the volumetric properties on the mechanistic and empirical properties was investigated. It was found that resilient modulus has a high correlation with Indirect Tensile strength yet it is not a good estimator for dynamic modulus. Effective binder content was found to correlate with the fatigue resistance. Asphalt Pavement Analyser (APA) results are highly influenced by the air voids of the specimens, whereas the benefits of using gap-graded gradations (e.g., SMA) is not reflected by the APA results. The paper shows that the tensile strength ratio (AASHTO T183 test) is highly sensitive to gradation and it fails to quantify moisture effects.*

KEYWORDS: *mechanistic properties, Superpave hot mix asphalt,*

1. Introduction

The state of practice in pavement design in many parts of the world, including Latin America is based on empirical methodologies. Many agencies have relied (and some are still relying) on the AASHTO 1993 pavement design guide. However, progress in research is moving towards adoption of mechanistic – empirical (ME) design methodologies as punctuated by the completion of the National Cooperative Highway Research Program (NCHRP) Project 1-37A which is now under evaluation. These new pavement design methodologies, among other things require a shift on how asphalt materials are characterized. Notably, the resilient modulus (Mr) – the key strength parameter in AASHTO 1993 is replaced with the dynamic modulus (E*) in the NCHRP 1-37A ME pavement design guide.

To prepare the pavement design industry in Costa Rica, a study was proposed to investigate the new protocols for mechanistic characterization of asphalt mixtures, and to understand their relationship with the existing empirical tests, as well as, the effects of volumetric properties on the mechanistic and empirical properties. Another motivation also included the need to quantify how typical gradations and volumetric properties influence the mix characterization test protocols. The move from the Marshal to Superpave mix design method also has brought a need to evaluate other mix characterization protocols such as the rutting potential measured by Asphalt Pavement Analyser (APA). The key research question for agencies that are getting started in this transition process is, are the test protocols consistent? Do they always identify good gradations, good aggregates sources, etc? With this in mind, the study undertook to understand the sensitivity of the APA test to variations on the asphalt content and the sensitivity of the moisture sensitivity test (AASHTO T-183) to mix gradations.

2. Objective

This paper investigates mechanistic properties of dense graded asphalt mixes typically used in Costa Rica. The aim was investigate the dynamic modulus, fatigue properties, and static creep of ten different Superpave mixture gradations that are representative of those used in the construction of asphalt base layers for flexible pavements in Costa Rica. The paper also aimed at comparing mechanistic mixture properties with empirical properties such as rutting potential (APA) and resilient modulus. The effect of the volumetric properties on the mechanistic and empirical mixture properties was also investigated.

3. Material Characterization

3.1 Mineral Aggregates

One of the goal of this study was to investigate the sensitivity of various test protocols and the effects of volumetric properties on such test results as dynamic modulus, resilient modulus, APA, fatigue performance, etc. For that matter, we studied one source of aggregate in eastern Costa Rica, an alluvium rock of igneous origin extracted from river beds in the Region of Guápiles. The course aggregate typically has a bulk and apparent specific gravity of 2.65 and 2.77, respectively, and absorption of about 1.7%. The fine aggregate, also riverbed sand, has bulk and apparent specific gravity typically of about 2.58 and 2.75, respectively, and absorption of 2.5%.

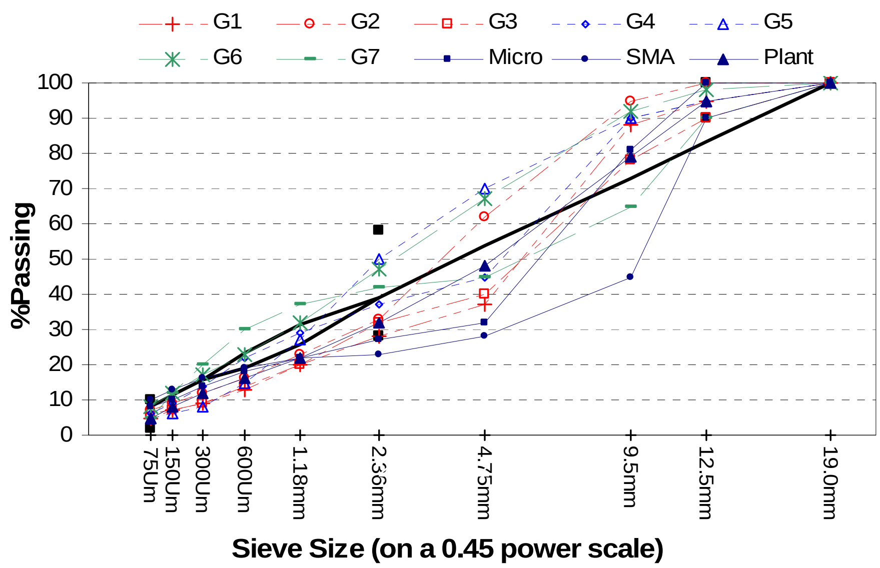
3.2 Selection of Aggregate Gradations

Table 1 and Figure 1 show the aggregate gradations that were investigated in this study. Eight of these gradations meet all the Superpave requirements for dense graded mixtures, one gradation is gap-graded and the last one is an SMA gradation. As seen from Table 1 (and Figure 1) of the eight dense-graded Superpave gradations, three passes below the so called restricted zone, two above and two through the restricted zone. The dense-graded gradations are labelled G1 through G7, except one of them which is labelled “Plant.” The “Plant” gradation was obtained as an average from sampling at several plants in Costa Rica. It is worth noting that the “Plant” gradation passes below the restricted zone, and is sort of the median of all the gradations investigated in this study. All the gradation are of maximum size of 19-mm, except G2 and “Micro” with maximum size of 12.5-mm. The gap graded gradation, labelled “Micro” has 68% retained on the 4.75-mm sieve size and would be typically used for open graded friction course (OGFC) mixes.

TABLE 1. *Summary of Aggregate Gradations Investigated in Percent Passing*

Sieve (mm)	Below Restricted Zone			In Restricted Zone		Above Restricted Zone		Micro	SMA	Plant
	G1	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**	**G10**
19.0	100	100	100	100	100	100	100	100	100	100
12.5	95	100	90	95	95	98	90	100	90	95
9.50	88	95	78	90	90	92	65	81	45	79
4.75	37	62	40	45	70	67	45	32	28	48
2.36	28	33	32	37	50	47	42	27	23	32
1.18	20	23	20	29	27	32	37	22	22	22
0.600	13	16	14	22	15	23	30	18	19	16
0.300	9	12	9	14	8	17	20	14	16	12
0.150	7	9	7	9	6	12	12	10	13	8
0.075	5	7	6	6	5	8	5	8	10	5

FIGURE 1. *Summary of aggregate gradations investigated*



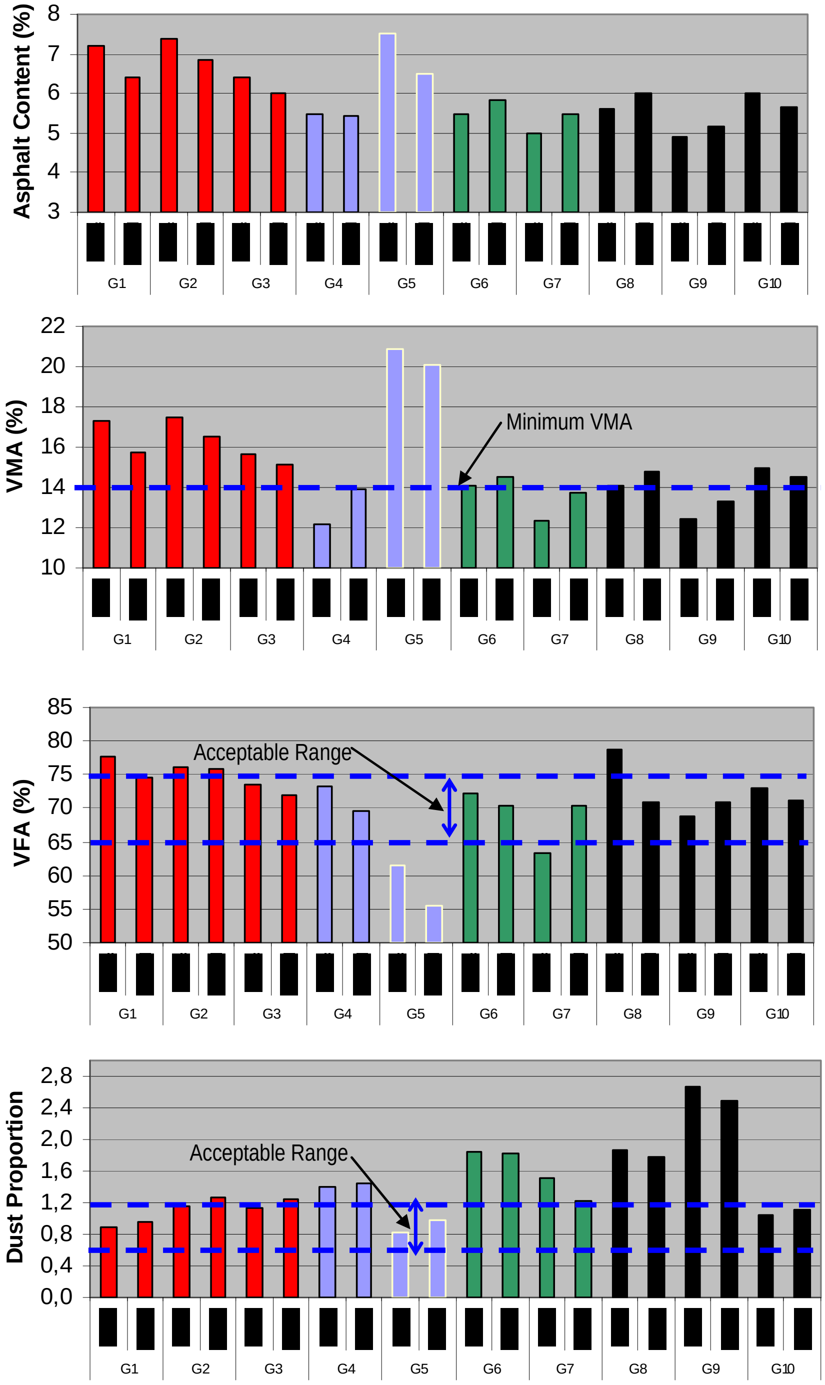
3.3 Asphalt Binder

We investigated the asphalt binder that is in most common use in Costa Rica for paving works. Since polymer modified asphalt is not available commercially within Costa Rica, the binder was modified in the laboratory with 1.5% EGA (Etilen glicidil acrilato) polymer. The polymer modification was achieved in the laboratory by mixing at high temperature while stirring the right amount of virgin binder with the polymer thereby making the polymer form a three-dimensional "network" with the asphalt molecules. The unmodified binder had a viscosity of about 3429 Poises to 60°C and of 5472 Poises after modifying. The unmodified binder would classify as a PG 64-19, according to the SUPERPAVE methodology for performance grading. After modifying with the polymer, the binder was tested and graded as PG 76-10.

3.4 Mix Volumetric Properties

Using the study aggregate and binder, mix designs were carried out for each gradation using both Superpave and Marshall Methods. Test briquettes of 150-mm diameter were compacted in the gyratory compactor while 101-mm diameter briquettes were prepared by the Marshall hammer. Volumetric properties were tested on four test specimens to determine the mean volumetric properties. Figure 2 shows a summary of the volumetric properties for the ten aggregate gradations. The optimum binder content in both Marshall and Superpave was defined at 4% air voids. This is a common practice in Costa Rica to design all mixes based on the 4% air voids criterion. As seen in the figure, the optimum binder content varies from just below 5% to just over 7.4%. As noted by others in the literature, for the gradations passing below the restricted zone, the optimum binder content tends to be higher for Superpave than Marshall Mix designs. Whereas, for gradations through or above the restricted zone, we observe the contrary – Marshall mixes having higher binder content compared to Superpave mixes. The “Plant” and “Micro” gradations behave like the later, while the SMA mirrors the former.

FIGURE 2. *Effect of aggregate gradation and mix type on volumetric properties*



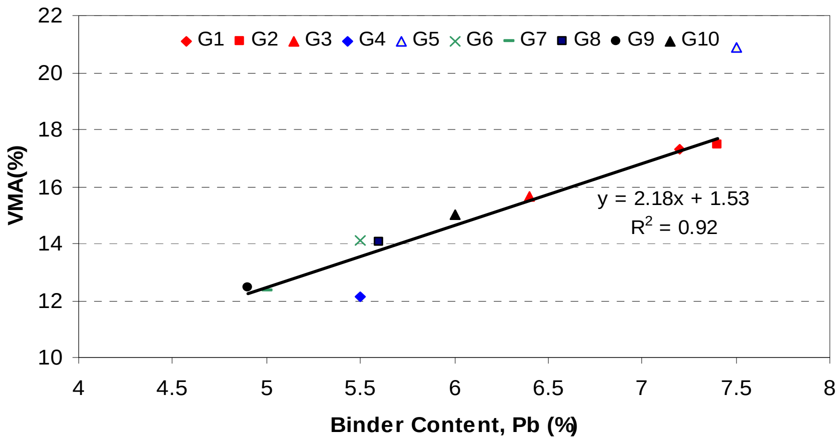
Again as shown in the figure, voids filled with asphalt (VFA) vary from 55% to about 78%. Voids in the mineral aggregate (VMA) vary from 12.1% to 17.4%. However, one gradation, G5 seems to have an unusually high VMA and was considered a bad gradation for comparison with others in all subsequent tests. It is worth noting that the mix design for the G5 mix gradation had problems meeting the 4% air voids criterion for both Marshall and Superpave. For that reason, it is not prudent to draw conclusions based on this mix. What is interesting is that, generally speaking, the gradations that pass below the restricted zone tend to require higher asphalt contents compared to the other gradations in the study. Consequently, it was much easier to meeting minimum VMA for the gradations that pass below the restricted zone. VMA for the three gradations passing below the restricted zone ranged from 15.2% to 17.4% while for the seven gradations passing through or above the restricted zone ranged from 12.1% to 15.0%.

Again, as is well known from the Marshall and Hveem mix design literature, there is a close correlation between VMA and binder content of the mix. Equation [1] is typically used to determine VMA. Figure 3 shows a plot of VMA versus the mix optimum binder content for all the ten gradations in the study. As expected from Equation [1] the relationship is linear with an R^2 of 92%. Almost all the mixes in the figure were Superpave and had air voids of 4% except G8 with 8%. A second group of mixes designed at 5% air voids plotted approximately linear with an R^2 of 55% both for Superpave and Marshall design methods. However, this is still an interesting observation since the VMA vs. binder content presented here is not for only one mix gradation; rather it is for 10 very different mix gradations. This finding is significant especially given recent new evidence revisiting the linkage between VMA and permanent deformation (rutting) of in-place asphalt concrete pavements (Christensen et al. 2005). The new rutting models are likely to generate further interest on the interaction between VMA and other mix design factors after the publication of NCHRP Projects 9-25 and 9-31 expected soon.

$$VMA = 100 - \left(\frac{G_{mb} P_s}{G_{sb}} \right) \qquad [1]$$

where, VMA = voids in mineral aggregate, G_{sb} = bulk specific gravity of combined aggregates, G_{mb} = bulk specific gravity of compacted briquette, and P_s=100-P_b = percent by weight of aggregates in the mix.

FIGURE 3. *Correlation of voids in the mineral aggregate with binder content*



3.5 Moisture Susceptibility Test

The presence of moisture within the asphalt concrete layer may have critical impact on the durability of the hot mix asphalt pavement. Moisture susceptibility failure or stripping occurs as loss of strength and durability due to the presence of moisture at the binder-aggregate interface. This phenomenon is known to occur only in specific aggregate type – asphalt binder type pair. It is therefore assumed to result from the specific surface chemistry of the aggregate and its interaction with the asphalt binder used. With this premise, it is often deemed sufficient to test a given aggregate type – asphalt binder type pair once for moisture damage susceptibility. If the test results pass, then it is assumed that the given aggregate does not have a stripping problem.

In this study, all the ten mix gradations are from one type of aggregate. The intent for carrying out the moisture sensitivity test on all the mix gradations types was to determine if the test is consistent or repeatable over a given aggregate type.

The modified Lottman Test recommended by Superpave (AASHTO T 283) was evaluated. Specimens were prepared according to the AASHTO TP 4. Eight 150-mm diameter Superpave briquettes were made for each mix type with target air voids of between 6 and 8%. Four briquettes from the eight were assigned to the control group, while the remaining four briquettes were assigned to the treated group. Using the Excel Solver, the assignment was done so as to minimize differences in air voids between the two groups. The treated group was conditioned by saturating them under vacuum to achieve between 55 and 80% saturation. Subsequently, the samples were placed for 24 hours in a water bath at 60°C. Then the specimens were placed in a water bath at 25°C for 2 hours to bring them to testing temperature. Both the control and treated groups were tested at 25°C by Indirect Tensile Strength (splitting test) at a loading rate of 0.85 mm/s. The test results were compared as tensile strength ratio given by [2]:

$$TSR = \frac{S_t}{S_c} \qquad [2]$$

Where, *TSR* is the tensile strength ratio, S_t is the mean strength of the treated group (conditioned), and S_c is the mean strength of the control group (unconditioned).

Figure 4a shows the result of the moisture susceptibility test for all the ten mix types. Contrary to our expectations, the tensile strength ratio (TSR) varies widely from one mix type to the next, ranging from low of 70% to high of 101%. This was not expected since the whole study we tested one source of aggregate with the same asphalt binder. It was therefore assumed that since moisture damage susceptibility is an issue of the interaction between the aggregate surface and binder chemistry, then the TSR results would be very comparable irrespective of mix gradation types. Figure 4b shows the relationship between dust proportion and the moisture sensitivity test. It is also interesting to note that the binder content does not seem to have an effect on the moisture damage susceptibility test (Figure 4c). The mastic does not seem to influence the TSR test as it would be expected. Again, contrary to expectations, the open graded mix types (SMA, "Micro" and "Plant") seem to perform better generally compared to the other gradations. Next, the gradations passing below the restricted zone show marginally higher TSR than those passing through or above. However, the TSR does not have any correlation with the material passing either the 600 μm or 300 μm. Although the findings are limited in scope, they raise an important issue worth of further research.

FIGURE 4(a). *Consistency of the moisture sensitivity test for the same aggregate*

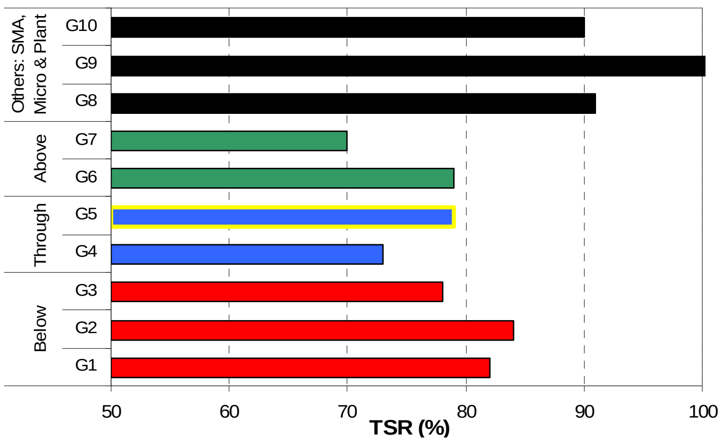


FIGURE 4 (b). *Effect of dust proportion on the moisture sensitivity test*

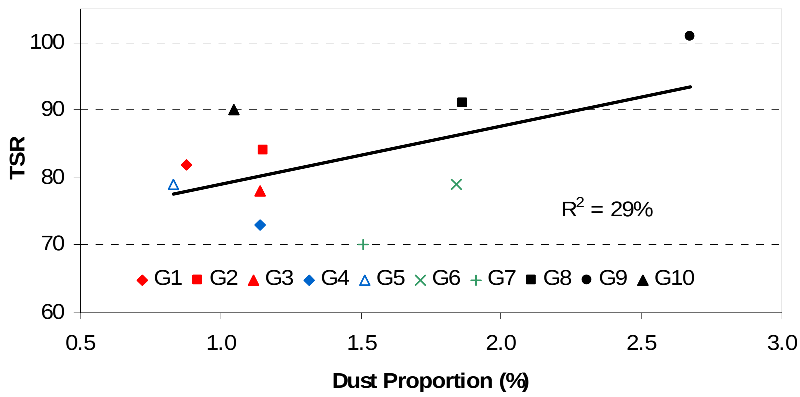
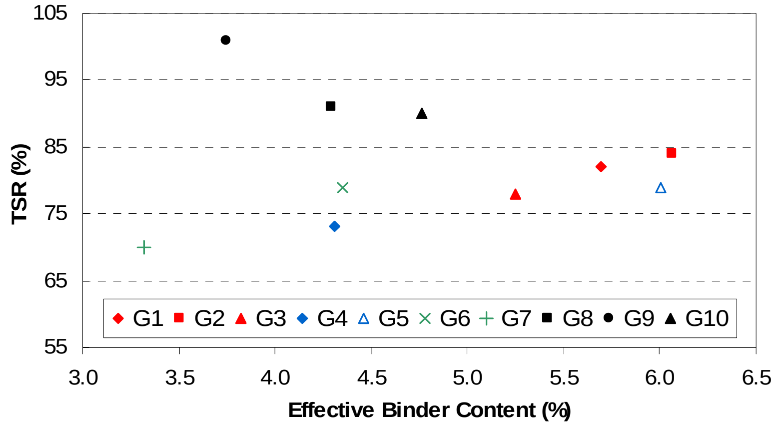


FIGURE 4 (c). *Effect of binder content on the moisture sensitivity test*



4. Evaluation of Rutting Potential of Mixtures

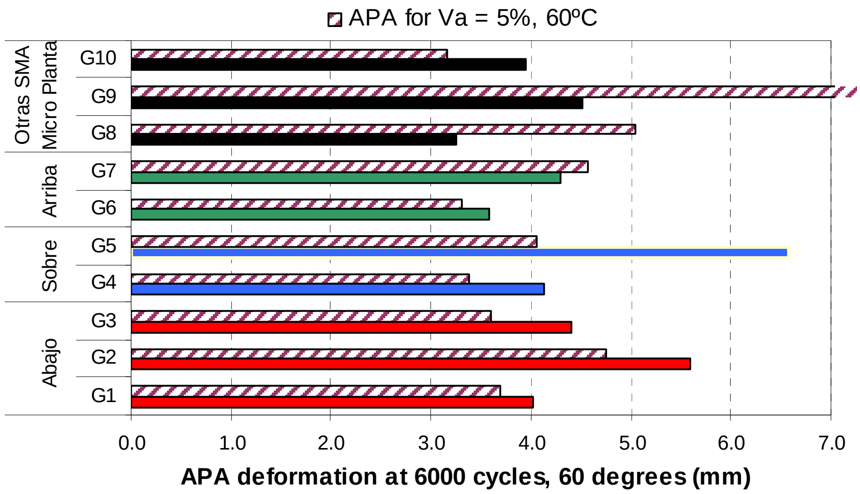
4.1 Permanent Deformation Performance by the Asphalt Pavement Analyser

Evaluation of mix performance with respect to permanent deformation was carried out using the Asphalt Pavement Analyser (APA) according to the AASHTO Test Protocol TP 63-03. The specimens were produced by in the Pine Instrument's Superpave Gyratory Compactor (SGC) according to AASHTO T-312. The mix design was performed according to the Superpave method using two levels of design air voids, 4 and 5%. For each mix type six briquettes of 150-mm diameter by 75±3 mm height were compacted to about 7±1% air voids. In other words, the mix design criterion for the purposes of optimum binder content was the normal 4% air voids, but the compaction effort was selected to achieve 7% air voids. This is slight variation from the AASHTO TP-63 in that specimens are normally compacted at the design number of gyration (N_{des}) and subsequently saw cut to a 75-mm height. The briquettes were preheated to the test temperature for six hour before testing them in the APA. The permanent deformation (or rutting potential) testing was done at 60°C for all the mix types; instead of the binder PG grade high temperature as required in the AASHTO TP-63. The APA was run at with 690 kPa (100-psi) hose pressure and 445 N (100-lb) load to 8000 cycles.

Figure 5 presents the comparison of the APA results of all the mix types for the two levels of air voids. It is interesting to note that contrary to expectations, the gap graded mixtures – "Micro" (G8) and SMA (G9) – did not out perform the other mix types in resistance to permanent deformation. In this study, the SMA and the "Micro" mix types had 72% and 68%, retained on the 4.75 mm sieve, respectively. The discussion in some of the literature has suggested that SMA mixes would achieve much better stone-to-stone contact and therefore perform better in permanent deformation.

As seen from Figure 5, the APA test results seem to be sensitive to the design air voids of the mix. Note this effect is confounded with binder content. When we change the design air voids from 4% to 5% the optimum asphalt content tends to reduce. Less asphalt content is associated with less rutting as we observe in Figure 5. This argument holds for most of the mix gradations except the gap graded mix types (SMA and Micro). The effect appears to be reversed and more pronounced for the gap graded mix types (SMA or Micro) where changing the design air voids from 4 to 5% seems to increase the observed rut depth at 8000 cycles by over 55%. This effect could not however be tested statistically because of the small sample size, but is worth further investigation.

FIGURE 5. *Sensitivity of the rutting potential (APA results) to compaction level*



4.2 Permanent Deformation Testing by Static Creep

Both the uniaxial (unconfined creep) or triaxial (confined creep) tests, either in the static mode (single loading and unloading cycle) or dynamic mode (repeated loading and unloading cycles) have been used to estimate the tendency of hot mixed asphalt to failure by permanent deformation under traffic loading (Brown et al. 2001). The literature presents extensive studies on the unconfined creep test (the simple creep test) to try and determine its correlation with observed in-place rutting (Van de Loo, 1974 & 1976). Several studies related to the NCHRP Project 9-19 to develop Simple Performance Test for Superpave reported that the flow time (*Ft*), determined from the triaxial static creep test, was observed to have a high correlation with in-place rutting (Witczak et al, 2002).

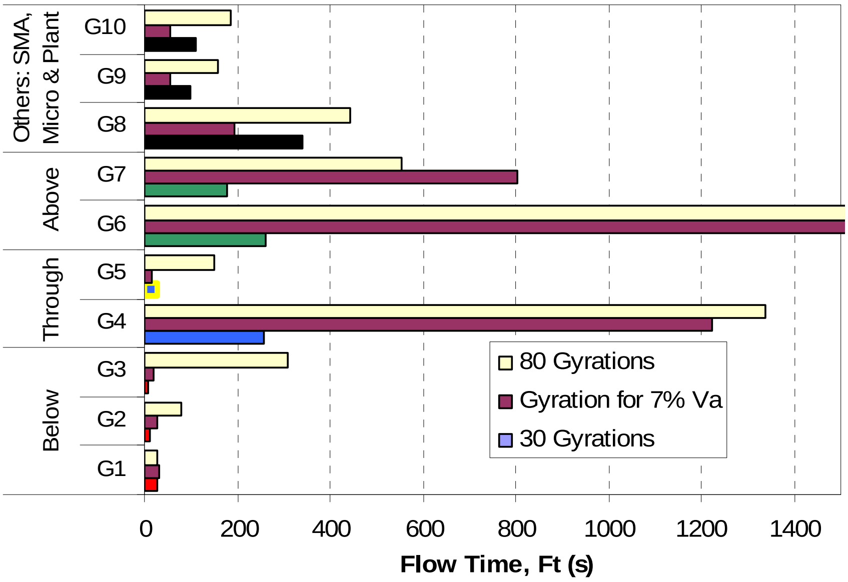
With this current interest in the literature on the static creep test as a mix simple performance test for permanent deformation, the study evaluated the ten mix types using the NCHRP 465 protocol. The mix designs were carried out using Superpave method at 4% design air voids, similar to those for APA testing. The specimens were compacted at design number of gyration (N_{des}) in the Pine Instrument's Superpave Gyratory Compactor (SGC). In this case, for each mix type, three briquettes of 150-mm in diameter by 170 mm height were compacted to at different number gyrations. The creep test coupons were obtained by sawing the top and bottom and coring each briquette to a final size of 100 mm diameter by 150 mm height. The creep test was carried out at the recommended 55°C (130°F) temperature and a loading stress of 207 kPa (30 psi). These test parameters were selected because they were reported to have the highest correlation with observed in-place rutting from the MnROAD, WesTrack and FHWA-ALF facility (Witczak et. al. 2002). The static test is carried out by applying the constant stress to the specimen until it starts to undergo tertiary deformation.

From the analysis of the test data, primarily the axial strain – time data, the flow time (F_t) is calculated as the time corresponding to the minimum rate of change of axial strain (NCHRP 513). The numerical work is done automatically by the test software supplied with the Universal Testing Machine (UTM) made by Industrial Process Controls, Inc. (IPC) (which was also used in the NCHRP 465).

Figure 6 summarizes the results from the creep test. As seen from the figure, the flow time is significantly dependent on the compaction level (number of gyrations) within a given mix type. The observed flow time also varies significantly from one mix to the other. Mix designated G6 was observed to have unusually high flow time of over 3160 and 3473 seconds for high (80) and intermediate number of gyrations (45 to 65), respectively. Interestingly, the flow time of 260-s for 30 gyrations was comparable to other mix types. Also, it is interesting to note that Mix G4 also had relatively high flow time (over 1200 s) for high and intermediate numbers of gyrations, but relatively comparable flow time for 30 gyrations. Of the three levels of compaction, compaction at 30 gyrations seems to produce lowest variation in the flow times over the ten mix types. The flow time for 30 gyrations ranged from 8 to 342-s, whereas for 80 gyrations the range was 29 to 3162-s. Mix gradations passing below the restricted zone G1, G2 and G3 tended to have the lowest range and variation of flow times with compaction level. Mix gradations passing through and above the restricted zone (G4, G6 and G7) seem to have relatively high flow times and also higher variation with the level of compaction (number of gyrations). It was surprising to note that the "Plant" mix had flow time – range and variability within a given compaction level – very comparable to the SMA Mix.

As expected, an attempt to correlate the flow time with the APA results produced very low coefficient of correlation. Needless to say that the comparison is not in any way conclusive, but it adds to the existing discussions about the adequacy of the APA test result as a predictor for in-place rutting.

FIGURE 6. *Summary of the static creep test from the study*



5. Load Resistance and Fatigue Characterization

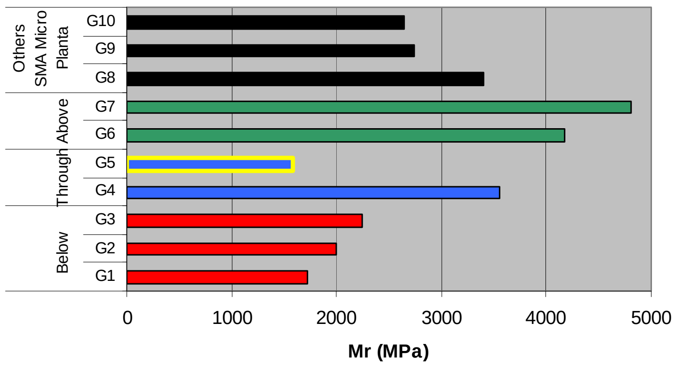
5.1 Resilient Modulus Test

The resilient modulus test is the primary load resistance characterization method for hot-mix asphalt in the 1993 AASHTO pavement design guide. The resilient modulus test, also called the repeated indirect splitting test, is relatively simple and can be conducted on both lab compacted or cored samples. It is therefore by far the most common method of strength characterization in use in many existing empirical design methods. The motivation for carrying resilient modulus testing in this study was to determine if there is any correlation with the more complex and time consuming dynamic modulus test recommended in the new NCHRP 1-37A mechanistic-empirical design guide.

The test is performed by loading the cylindrical test briquette through a diametral plane. The test set-up induces tensile stress distributed almost uniformly along the loaded diameter. The repeated loading sequence is of haversine waveform with 0.1 s load time followed by 0.9 s a resting time. The deformations along and perpendicular to the load axis are recorded by using a set of LVDTs mounted at the center of the specimen.

For each mix type, four Superpave briquettes of 150-mm diameter by 75-mm height were compacted with a target of 7 The optimum content of asphalt in both cases Marshall a Superpave were define as 4% air voids. % air voids. One specimen for each mix was used to determine the maximum (failure) load in the static Indirect Tensile Test mode. The remaining three briquettes were tested for resilient modulus. Figure 7 shows the summary of the resilient modulus tests for the ten mix types at 25ºC. Resilient modulus ranges from about 1580 to 4170 MPa, with mix gradations passing below the restricted zone exhibiting lowest values, while mix types passing above the restricted zone exhibit the highest values. It is interesting to note that the gap graded mix gradations, including SMA, recorded mid range modulus values of about 2740 to 3400 MPa.

FIGURE 7. *Summary of the resilient modulus results*



5.2 Dynamic Modulus

The dynamic modulus testing has recently become important to the pavement industry especially since the new NCHRP Project 1-37A mechanistic – empirical design guide became available for evaluation. One of the goals for our study was to obtain a good data base of dynamic modulus for typical hot mix asphalts in Costa Rica for future implementations of the M-E pavement design guide. In other words, LANAMME initiated the study with the goal of understanding typical values of dynamic modulus in Costa Rica, relationship with mix design factors and estimating typical variability in the dynamic modulus data. It was important to evaluate if and how the mix properties, such as volumetrics, binder content, air voids, etc. impact on the dynamic modulus.

The test specimens were prepared based on the protocol "Preparing and determining the density of hot mix asphalt specimens by means of the Superpave Gyratory Compactor (AASHTO T 312). This compaction procedure is the recommended method for dynamic modulus testing according to AASHTO TP62 or ASTM D3497. Three specimens were prepared and tested for each mix type. For a given mix, the test specimens were compacted at three different levels, 30 gyrations, target 7% air voids, and at 80 gyrations. The low and high compaction effort was selected (as in the fatigue test presented subsequently) to correspond to N_{des} for low and high design traffic typically expected in Costa Rica. The goal was to evaluate if compaction effort has an effect on dynamic modulus. In this case, we estimated the amount of material need to compact the specimen at N_{des} to achieve 170-mm height after compaction. After the bulk (and maximum) specific gravity determination, the 150-mm diameter briquette is cored to extract a cored and saw cut at both ends to obtain a 100-mm and 150-mm high test coupon.

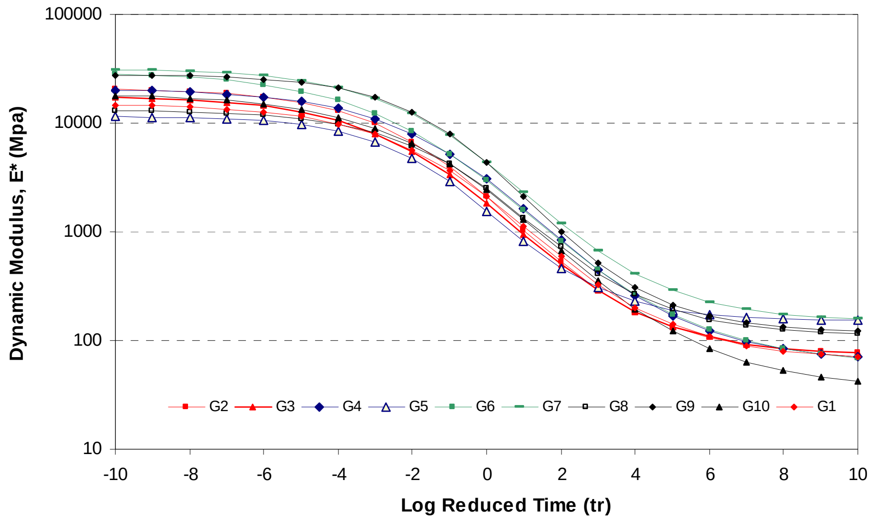
The dynamic modulus testing was carried out according to the test protocol AASHTO TP62-03. The test coupons were first conditioned to a constant temperature before running the dynamic modulus test. Following closely the TP62 protocol, testing was started at the lowest temperature. Testing at the lowest temperature – highest frequency first was also beneficial in protecting the integrity of the specimens. The conditioning times were overnight and 12 hours for -5°C and 5°C, respectively. After testing at 5°C, we would condition at 20°C again overnight, followed by 6 hours condition each before testing at 40°C and 50°C. In this study, the dynamic modulus test was carried at 5 target temperatures and 6 frequencies, such that for each temperature of -5, 5, 20, 40 and 55ºC we did frequency sweeps of 25, 10, 5, 1, 0.5 and 0.1 Hz. At a given test temperature, a continuous uniaxial sinusoidal compressive stress was applied at a given frequency to an unconfined cylindrical test coupon. It is worth pointing out that the temperature actually recorded during a test was always different from the target temperature. This recorded temperature was used in the analysis. Also, the test stress used varied at each test temperature as suggested in the protocol AASHTO TP 62-03. The applied test stress varied slightly in the range 1400 – 2800 kPa for -5°C, 700 – 1400 kPa for 5°C, 350 – 700 kPa for 20°C, 140 – 250 kPa for 35°C and 35 – 70 kPa for 55°C. The actual stress used was recorded by the equipment and used in the analysis.

The stress – strain relationship for a linear viscoelastic HMA specimen, is defined by a complex number called the complex modulus (E^*). The dynamic modulus is defined as the absolute value of the complex modulus $|E^*|$, that is, the ratio of the maximum (peak) dynamic stress (σ_0) to the peak recoverable axial strain (ε_o), as outlined in the protocol. The protocol specifies the number of loading cycles to apply at each frequency 200 cycles for 25 and 10 Hz, 100 cycles at 5 Hz, 20 cycles at 1 Hz and 15 cycles at 0.5 and 0.1 Hz.

Figure 8 presents the master curve at 20ºC reference temperature of the ten mix types investigated. The master curve plots the dynamic modulus in log scale versus the reduced time by superimposing the effect of loading time on temperature. We see from the figure that the ten typical mix gradations in Costa Rica exhibit very similar time – temperature susceptibility pattern. This was expected since the ten mix types are from the same binder grade and same aggregate type. Also as expected, mixes with higher binder content are associated with reduced dynamic modulus. The figure shows slight spread of the dynamic modulus at higher reduced time. This we speculate to be caused by increased experimental errors typically observed at low load frequencies and high test temperatures.

As noted before, the dynamic modulus data has not tangible correlation with the resilient modulus. However, statistical analysis on the data from all the mixes demonstrated that the mix design factors – gradation, effective binder content, air voids, as well as load frequency, binder viscosity, test temperature – all seem to have significant effect on the dynamic modulus as reported by Andrei (1999).

FIGURE 8. *Master curve of dynamic modulus of the ten gradations*



In an attempt to compare dynamic modulus to resilient modulus, dynamic modulus values were extracted from the Master curve to correspond to the test conditions of resilient modulus. Given that resilient modulus is tested at 10 Hz at 25ºC, dynamic modulus corresponding to 10 Hz and 25C were read from the Master curve. The correlation results between the resilient modulus values with dynamic modulus showed very poor fit (*see* Figure 9). It was therefore observed that resilient modulus is not always a good estimator for dynamic modulus. This suggests that Level 1 pavement design in the NCHRP 1-37a MEPDG cannot reliably be based on resilient modulus test results without needing some data from dynamic modulus test results. What we find interesting is that the resilient modulus results were highly correlated with the indirect tensile strength (splitting test) results. As seen in Figure 9, the coefficient of correlation, R^2 of 93% is significant given that the data if from ten different mix gradations.

FIGURE 8. *Correlation between dynamic modulus and resilient modulus at 10 Hz and 25 ºC*

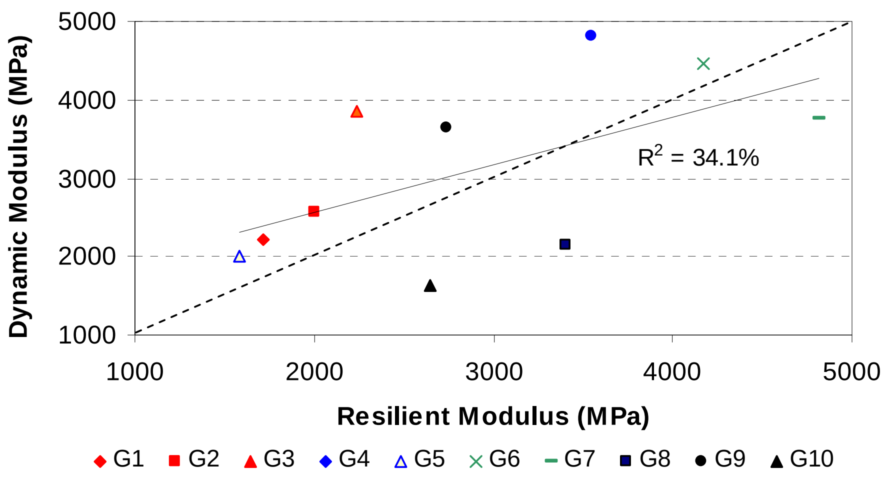
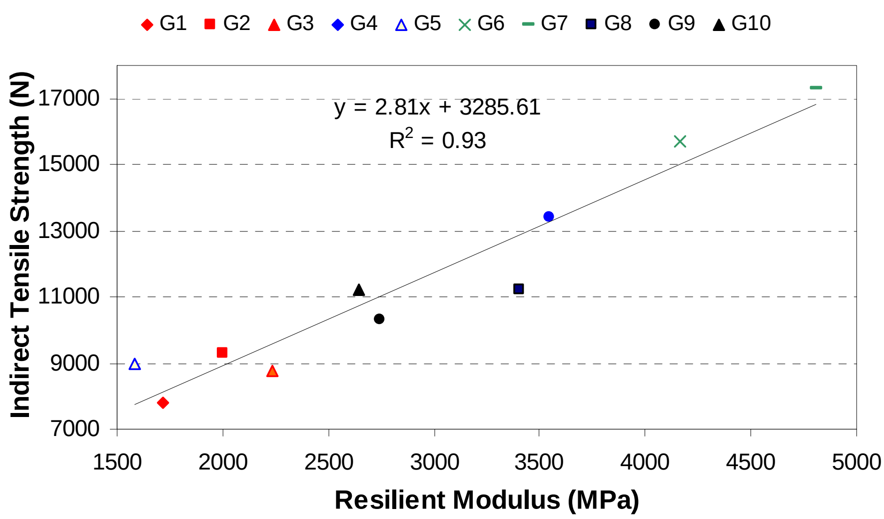


FIGURE 10. *Correlation between resilient modulus and indirect tensile test*



5.3 Beam Fatigue Test

Four fatigue beam test specimens were produced for each of the ten mix gradations by compacting them in the Cooper Technology Roller Compactor (Model CRT-RC2S) according to ASTM D3202. This kneading compactor is capable of rolling a 305 mm wide by 380 mm long and 50 to 100 mm thickness slab specimens, with an option to apply vibration. The pressure level and number of passes of the kneading compact was selected by trial and error process to achieve the target air voids of 8%. This target air voids level was selected since it compared to compaction level of in-place new pavements. For our study gradation, a total of eight passes, two each at 172, 276, 345 and 414 kPa were able to achieve the target compaction in most cases. However, given the variety of mixture types, the resulting air voids ranged from a low of 5.7% to 12.2% with a mean of 9.7%.

The beam fatigue test was carried out according to the AASHTO TP8. The 400 mm by 400 mm slab specimens were saw cut into 50 mm x 63 mm x 380 mm test coupons for the fatigue beam test. Four replicates of test coupons saw cut from one slab were tested for each mixture. The test coupons were brought to an equilibrium temperature of 20±0.5°C by conditioning them in a temperature controlled chamber for 2 hours before the test. One beam specimen was tested at each level of controlled strain (350, 450, 550 and 650 με) and 10 Hz frequency. Fatigue tests at low strain levels are preferred however they tend to be associated with low precision due to equipment resolution. An analysis of typical pavement structures in Costa Rica showed that strains up to 700 με are not uncommon. The initial stiffness was designated as stiffness after the first 50 cycles. The test was continued until stiffness reduced to 50% of initial stiffness, as recommended by many test protocols.

Table 2, Figures 11 and 12 present the test results of beam fatigue testing. In Figure 11, the test strain is plotted against the number of load repetitions to failure. It is seen that the test strain – number of cycles to failure relationship is almost linear in the semi-log scale for most of the mixes investigated. (The coefficient of determination (R^2) ranged between 79% and 99%.) For a given test strain level, the performance in fatigue (number of load repetitions to failure) seems to be a linear function of the binder content of the mix. As shown in Figure 11 (based on the 450-με test strain), the fatigue performance increases with effective binder content. Beyond this dominant factor, the large variability of the results suggests that there are many other factors that may affect fatigue performance, such as mix stiffness, aggregate gradation, etc. Air voids did not seem to be an important factor in the fatigue performance.

It was observed that at a given test strain level, the between mix types fatigue performance has a wide range – up to an order or two of magnitude. For a given mix type, the lab fatigue performance decreases almost linearly with test strain level; the change in the number load repetitions from 650 με to 350 με test strain is typically an order of magnitude. It is worth noting that the SMA Mix (Gradation G9) has the lowest fatigue performance at all test strain levels. The best fatigue performance was observed from the group of mix gradations G1, G2 and G3 – all of which are dense graded and passes below the restricted zone.

TABLE 2. *Summary of Beam Fatigue Performance Results at 10 Hz*

Mix Type	Effective Binder (%)	Air Voids (%)	Test Strain Level (microstrain)			
			650	550	450	350
G1	5.7	8.4	64,890	136,850	875,820	2,591,770
G2	6.1	10.0	118,700	375,670	1,275,560	3,561,970
G3	5.3	12.2	73,230	201,000	307,000	1,701,180
G4	4.3	5.7	23,200	24,920	144,740	1,020,710
G5	6.0	15.2	167,020	320,790	373,610	1,338,590
G6	4.4	11.0	8,860	6,820	73,270	314,740
G7	3.3	8.4	21,480	10,920	137,690	668,350
G8	4.3	8.7	9,280	51,590	115,290	578,280
G9	3.7	7.0	7,740	20,220	31,790	111,630
G10	4.8	10.2	51,810	53,270	302,450	1,001,860

FIGURE 11. *Plastic strain versus number of load cycles from the beam fatigue test*

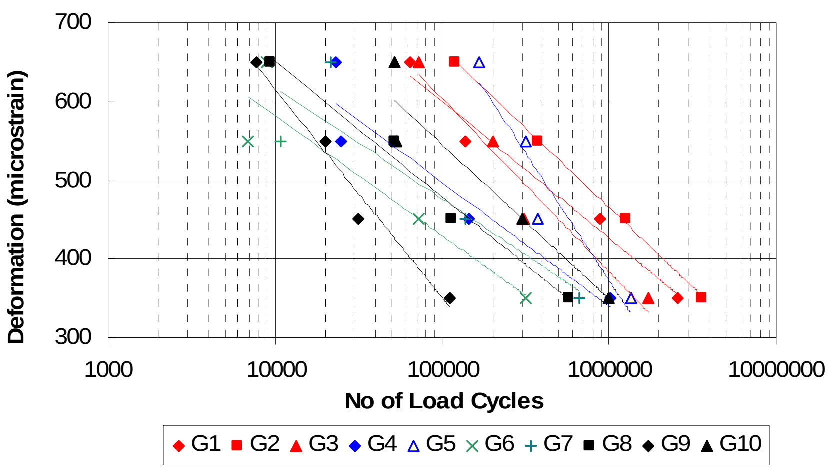
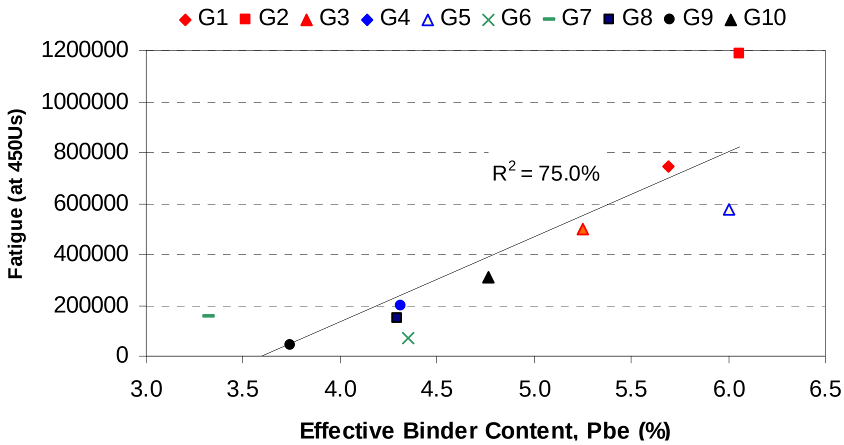
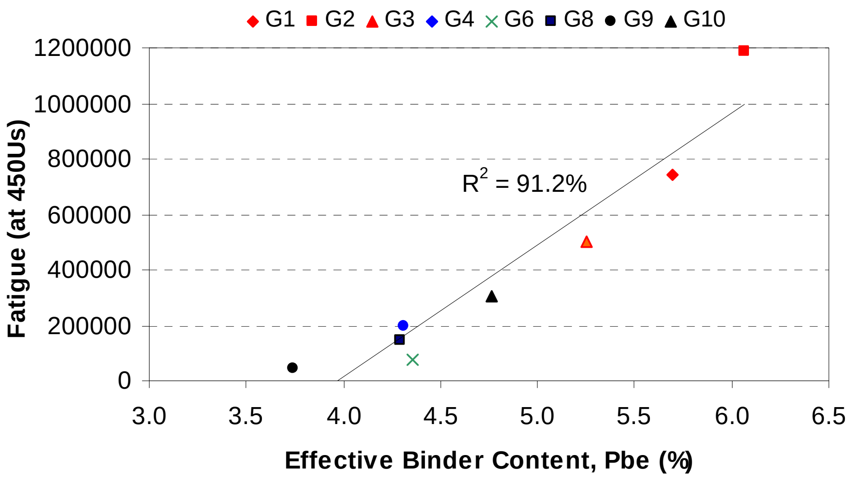


FIGURE 12. *Correlation between fatigue at 450$\mu\varepsilon$ and effective binder content*
(a) All ten aggregate gradations



(b) Aggregate gradations G5 and G10 removed



6. Conclusions

Based on this investigation of 10 different typical gradations, aggregate and binder used in Costa Rica, it was concluded that resilient modulus is not a good estimator for dynamic modulus. As suspected, there is a very poor correlation between resilient modulus and dynamic modulus. It was interesting to find that resilient modulus has a high correlation with Indirect Tensile strength of the mixtures investigated. The study also shows that effective binder content is strongly correlated with the fatigue resistance of mixtures as measured in the laboratory by the NCHRP 465 protocol, i.e., flow time. It was found out that APA results are highly influenced by the air voids of the specimens, whereas the benefits of using gap-graded gradations such as SMA could not be captured by the rutting potential measured by APA. Also, it was interesting to demonstrate that the APA results do not correlate with the flow time data – the NCHRP 465 recommended simple performance test for rutting. The results also demonstrate that the tensile strength ratio (TSR) recommended by the AASHTO T183 test is highly sensitive to the gradation used to the extent it fails to identify moisture effect on the aggregate – asphalt bond.

7. Acknowledgement

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