DETERMINATION OF THE PG BINDER GRADE TO USE IN A RAP MIX

Final Report

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Jack E Stephens
James Mahoney
Cory Dippold

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16. Abstract

The use of Recycled Asphalt Pavement (RAP) in new Hot Mix Asphalt (HMA) has become routine in the past few years. This practice is spurred by the increased amounts of pavement being milled off prior to overlaying. Using RAP has economical and environmental benefits. The drawback to using RAP in pavements is determining the correct virgin binder grade to add to the asphalt mixture. This problem has been accentuated by using the Superpave System for determining the asphalt binder grade.

This asphalt binder in RAP is typically much stiffer than the binder grade required by the Superpave System. Determining the correct virgin binder to use in the HMA is critical to ensure that the pavement will be durable enough to last for its' anticipated service life. The current methods of determining the correct virgin binder assumes complete blending of the RAP binder and the virgin binder which does not occur. The simple physical testing procedure presented in this paper does not require the Superpave binder test equipment could be carried out at the mix plant.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F
-40 0 40 80 120 180 200
-40 -20 0 20 40 60 80 100
°C 37 °C

PREFACE

This is the final report on JHRAC Project 99-1 entitled " Determination of the PG Binder to Use in RAP Mix". The Connecticut Department of Transportation materials specialists have been concerned with the degree of blending between RAP binder and virgin binder which occurs in RAP bituminous concrete mixes. Complete blending may not occur as the virgin binder can't reach the RAP binder in the center of small RAP clods if the clods are not completely broken up. Grading of binder recovered from the RAP mix is misleading as the recovery results in complete blending. The small clods essentially act as aggregate particles and the blended films over the aggregate and clod surfaces determines the mix character and durability. The emphasis of this project became the determination of the effective grading of the binder holding the mix together.

This work was sponsored by the Joint Highway Research Advisory Council at the University of Connecticut. This council was founded some 40 years ago to carry out studies of interest to both ConnDOT and UConn researchers.

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CHAPTER 1.0

INTRODUCTION

1.1 PROBLEM STATEMENT

The use of Recycled Asphalt Pavement (RAP) in hot mix asphalt (HMA) has become standard practice throughout the HMA industry. RAP is generated when old pavements are either milled prior to overlaying them or when the entire pavement structure is removed prior to total reconstruction. Milling of old pavements has become a very common method of surface preparation prior to overlaying. Because milling has become so commonplace, great quantities of RAP are generated each year. This is not such a bad thing since RAP is the most widely recycled material in the world today. The reasons for such wide spread include both economic and environmental. For HMA producers, the use of RAP reduces the amount of virgin aggregates and virgin binders that they must purchase. The environmental reasons for its wide spread use include the reduction of use of petroleum products as well as avoiding the practice of landfilling the RAP.

One problem that has recently surfaced with the advent of the Superpave technology is the selection of the proper virgin binder to use in HMA mixes that contain RAP. The Superpave system goes to great lengths to ensure that the binder used in virgin mixes matches the anticipated service temperatures for the pavement. The problem arises with the addition of the RAP. The binder in the RAP is considerably harder than the virgin binder. This poses the question of how much blending occurs, if any, between the RAP binder and the virgin binder. The amount of this blending may greatly affect the properties of the binder in the finished pavement. This may cause the binder in the finished pavement to not meet the required Superpave binder properties for the anticipated service temperatures.

The Expert Task Group for Bituminous mixtures has made several recommendations regarding the use of RAP in HMA mixes. Some of these recommendations do not take in account the properties of the RAP binder since there is no testing of it. These recommendations include ignoring the existence of RAP in mixes that contain small amounts of RAP (less than 15%). The recommendation for mixes containing moderate amounts of RAP (15-25%) was to drop the PG grade by one level for both the high and low service temperatures or to use a blending chart. And for mixes containing high amounts of RAP (more than 25%) the recommendation was to use blending charts. The method of using blending charts to graphically determine the Superpave Performance Grade (PG grade) of placed pavements has several problems associated with it. These problems include the timely and expensive process of extracting, recovering and PG grading the binder in the RAP. Also, the blending charts are usually only used to predict the high service temperature for the finished pavement. These charts are therefore assuming the binders will completely mix during the HMA production. Assuming complete blending of the RAP binder with the virgin binder is problematic because of the method by which RAP is introduced into the mixer. RAP is generally added to overheated virgin aggregates. The idea is that the heat will be transferred to the RAP and the RAP binder will become completely fluid to allow complete blending in the short period of time the materials are in the mixer. This heat transfer problem is further complicated by any moisture that is present in the RAP. An additional problem with the blending charts is that although they are used to ensure the binder in the finished pavement will be stiff enough to resist rutting after construction, the blending charts are not generally used to check the low service temperature properties of the binder in the finished pavement. This low service temperature may be the larger problem for the northern states where thermal cracking is a substantial problem. The binder in the RAP is most likely to have the greatest detrimental effect on the low service temperature since the RAP binder has aged and lost its flexibility at low temperatures.

An additional method that has surfaced for determining the effective PG grade of the binder in the finished pavement is to extract and recover the binder from the RAP. This binder is then blended with the virgin binder at the proportions each binder will be present in the finished pavement. The PG grade for the composite binder is then determined. This method does assume that there is complete blending of the two binders, it does give an indication of the properties at the lower service temperatures. This does not adequately characterize the material properties at the lower temperature but it is an improvement over the blending charts because the effective PG grade would then be somewhere between the composite PG grade and the PG grade of the virgin binder.

The best solution to this problem would be the development of a test method that would measure the effective PG grade of the mix based upon the blending that occurs under real mixing conditions. Ultimately, the development of a test method that could be performed by HMA plants that did not require Superpave binder testing equipment would save time and reduce the cost associated with using RAP.

1.2 INTENT OF RESEARCH

The first phase of this research was to establish the amount of blending, if any, that occurs when RAP is used in HMA. This was carried a step further by determining the amount of preheating of the RAP that was needed to produce a homogeneous binder throughout the HMA mix. The second phase of this research was aimed at the development of testing procedure that could be used to determine the effective PG grade of the binder in the finished pavement.

CHAPTER 2

BINDER BLENDING IN A RAP MIX

2.1 BLENDING IN A RAP MIX MUST BE DETERMINED USING THE TOTAL MIX

Many different methods were attempted to distinguish between the RAP binder and the virgin binder added to the HMA mix. The intent of these methods were to test the RAP and virgin binder prior to mixing and then to isolate portions of the mix from which to recover the binder and test it. The concept behind this procedure was that the films of binder on coarse aggregates would be more likely to blend with the virgin aggregates than the asphalt located in lumps of fine aggregates. To test this theory, samples of RAP mix were secured from two Connecticut hot-mix plants. An additional mix containing only virgin materials was also collected. For each mix, a portion was lightly heated in an oven until it could be spread one stone thick in a flat pan. After cooling, the material was put in a five gallon mixer with ten 1 ½ inch steel ball bearings and agitated for 4 minutes, breaking the sheet of material into binder coated aggregate pieces, small lumps, and fines. The material was then sieved separating it into coarser than ¼ inch and finer than ¼ inch. The coarser material was then hand sorted into aggregate pieces and lumps. To see if the binder blending was the same for each portion, the binder was recovered from each part of the mix and PG graded. The original goal of this work was to be able to back-calculate the amount of blending occurring by comparing the blended binder with each of the components that it comprises.

2.2 RESULTS OF TESTING MIX FRACTIONS

The assumption was that the binder recovered from the coarse aggregate fraction would be similar to the virgin binder; the binder recovered from the lumps would be approximately the RAP binder and the binder recovered from the loose fine aggregate would be a blend of RAP and virgin binder. The Dynamic Shear Rheometer (DSR) value G*/sin(d) was expected to be greatest for the binder recovered from the lumps and lowest for that from the coarse aggregate. The expected DSR value for the binder recovered from the loose fine aggregate would fall between the other two values. Table 1, Appendix I, lists the results. The measured DSR values from neither RAP mix followed the expected pattern. In fact, there appeared to be no pattern. Mix #1 exhibited the lowest DSR values for the binder recovered from the coarse aggregate but the DSR values for the binder recovered from the lumps and loose fine aggregate were reversed from the anticipated outcome. Mix #2 exhibited the highest DSR value for the binder recovered from the coarse aggregate and the lowest value for the binder recovered from the loose fine aggregate. A third mix was tested in this manner, but it contained only virgin materials. The results of this testing were expected to show little or no difference between each recovered binder fraction. The measured DSR values for each fraction showed large differences between each recovered fraction. The DSR values for the portions of the virgin mix are in a different order from both of the RAP mixes. The thin layers of binder on the aggregate should have the greatest exposure during hot mixing and therefore harden the most but the test results show the binder in the lumps as stiffest.

The results of these fractionation tests indicate that the degree of blending cannot readily be found by sorting the material. Additional work on this method as well as the original plan of having the University of Connecticut Materials Science Institute, apply molecular level measurements to the fractions, were both abandoned at this point.

2.3 EFFECT OF RAP HEATING TIME

The degree to which the RAP binder blends with the virgin binder is related to the degree to which the RAP is heated during mixing. In the event that the RAP acts as a "black aggregate" and does not contribute binder to the mix, the different preheating times for the RAP should have very little to no effect on the mix.

To verify that the RAP binder has an effect on the overall binder and to try to establish the amount of time required to preheat the RAP to achieve complete blending, eleven laboratory mixes were made all with the same aggregate, RAP and binder. The difference between the molded samples was the length of time the RAP was preheated before being added in the mixer to the new hot aggregate and binder. The RAP preheat time ranged from zero to five hundred forty minutes. At the long heating times, the RAP lumps should have been heated clear through and broken down during mixing making for complete blending. All eleven mixes had 15% RAP which had been dried prior to any mixing to avoid problems associated with the moisture content of the RAP changing. A twelfth mix was made with the same aggregate as the RAP mixes but 100 percent virgin binder in a quantity equal to the sum of the percent virgin plus the percent RAP binder in the eleven RAP mixes. To avoid variance in the aggregate, 85% was virgin aggregate and 15 % reclaimed aggregate from the same RAP source used to produce the RAP mixes. Reclaiming of the RAP aggregate was done in the ignition oven.

The amount of material used to fabricate the specimens was adjusted so that the 150 mm diameter compacted specimens were approximately 110 mm tall. The specimens were compacted using a Superpave gyratory compactor. Standard compaction factors of 1.25 degree gyratory angle, 600 kPa pressure and 125 cycles were used for all of the specimens generated. Six specimens were made for each of the twelve mixes.

After molding, the specimens were extruded from the molds and cooled to room temperature. Prior to testing, the specimens were conditioned at 36C and then tested at 36C. Three specimens were tested in unconfined compression and three in indirect tension. Tables 2a and 2b, Appendix I, list the results. There is some variation from specimen to specimen within a set of three. Tables 2a and 2b, Appendix I also list the standard deviation for set of three. Figure 1, Appendix II, is a plot of the averages at different preheat times. Using 15 percent RAP, with no preheating, increased both compression and tension strengths of the mix by approximately one third when compared to the virgin mix using the same virgin binder. This increase of strength with no preheating indicates that some blending occurs immediately upon adding the RAP to the mix. Preheating did increase both strengths further. The increase at one minute was significant but only minor increases occurred from one to fifteen minutes with a slow increase thereafter. It is then reasonable to hypothesize that more complete binder blending occurs in a HMA mix containing RAP if the RAP during mixing reaches a temperature that softens the RAP binder allowing intimate blending.

CHAPTER 3

ESTIMATION OF EFFECTIVE BINDER GRADE IN RAP MIXES

3.1 STATEMENT OF PROBLEM

The results of the determination of the amount of time required for RAP binders to blend completely indicated that physical strength tests could produce a method for determining the effective PG grade of the binder in a HMA mix that contains RAP. Figure 1, shows the results of the unconfined compression test and the indirect tension test for the different pre-heat times.

The shapes of the curves were virtually identical which indicates that as the unconfined compressed strength of the material increases, the indirect tension strength also increases in a similar proportion. Based upon that relationship, it was decided that for the development of a test procedure to determine the effective PG grade the indirect tension test would be utilized. This was decided upon for two reasons. The first reason for this was that it was felt that tension would provide a slightly better indication of the binder's characteristics than compression. The second and more practical reason for choosing indirect tension testing is that the amount of force required to test the specimens would be considerably less, therefore reducing the strength requirements for the equipment needed to perform this testing.

3.2 TEST PROCEDURE

Samples of aggregate, binder and RAP were obtained from a Connecticut mix plant. An aggregate structure was chosen and maintained throughout each testing series. Table 3.2 shows the different combinations of RAP and virgin binders used.

Table 3.2 – Combinations of Virgin binder and RAP used

Number of specimens	Virgin Binder Added	RAP or Reclaimed Aggregate
6	64-28	15% RAP
6	64-28	15% Reclaimed Aggregate
6	58-34	15% RAP
6	58-34	15% Reclaimed Aggregate

The goal of making these mixes was to maintain a same aggregate structure in each specimen while varying the grade of the binder present in the mix. Non-modified stretch grade binders were intentionally chosen for this process to ensure that their true PG grade would not differ substantially from their AASHTO MP-1 PG grade. Compaction of all specimens was performed at an angle of gyration of 1.25 degrees, a pressure of 600 kPa, and 125 cycles.

Using the ignition oven, the binder content of the RAP was determined and a quantity of RAP aggregate recovered. The virgin aggregate consisted of ½" crushed trap rock, 3/8" crushed trap rock, manufactured trap rock sand and natural sand. Half of the mixes as shown in Table 3.2 contained 15% RAP and half contained 15% reclaimed RAP aggregate making the aggregate gradation identical for all samples. Six samples were made of each type so that three could be tested at each of two different temperatures. The virgin materials and reclaimed RAP aggregate were batched and after heating at 158° C for at least 2 hours were mixed. For the 15% RAP mixes, the unheated RAP was added to the hot materials in the mixer. Mixing lasted for one minute. The mixes was scraped into clean pans and placed in a 153° C oven for 1 hour. The mix removed from the oven and stirred before being returned to the oven for a second hour of curing. All specimen were molded in preheated molds using the gyratory compactor for 125 cycles at 1.25 degrees and 600 kPa. After removal from the mold, each sample was allowed to stand at room temperature for at least 12 hours before being temperature conditioned for the indirect tension test.

The intent was, through the use of 15% reclaimed RAP aggregate in the virgin mixes, was for all specimen to have identical gradations. The virgin binder content added was adjusted so that all had the same total binder content.

Indirect tension tests were performed on the specimens using a 6 inch Lottman Breaking Head at two temperatures, 3° C and 28° C, and loaded at a rate of 250 lbs/sec. Tables 3a and b, Appendix I list the specimen data and the indirect tension load for each combination of binders and RAP.

Figure 2a and 2b, Appendix II were generated from the data contained in Table 3. Figure 2a was created by first plotting the average indirect tensile load at 28^0 C against the high end of the PG grade for the specimens that contained only virgin binder. A linear relationship is then assumed between the virgin specimen average tensile loads and a straight line is passed between the two points. Next a horizontal line is drawn at the average indirect tensile load of the specimens containing RAP which intersects with the straight line drawn between the average indirect tensile strengths for the specimens containing all virgin binder. At the intersection of these two lines, a vertical line is projected down until it intersects with the x-axis. The point where the vertical projection meets the x-axis is then the effective high end PG grade for that combination of RAP and virgin binder. Figure 2b is generated using a similar technique except the low end values are substituted for the high end values and the average indirect tensile loads at 3^0 C are used.

Figure 2a shows the effective high end PG grade for the specimens containing a virgin PG 58-34 and 15% RAP was 63.0^0 C. As the PG grading system defined by AASHTO MP-1 is defined by 6 degree intervals, this would still be classified as a material with a high end PG 58 grade. The specimens that contained the virgin PG 64-28 binder and 15% RAP yielded an effective PG grade for the mix of 66.9^0 C. Again as the PG grading system is defined by AASHTO MP-1 this would still be classified as a material with a high end PG 64 grade. Using Figure 2b, the effective low end PG grade for the specimens containing the PG 58-34 virgin binder and 15% RAP is -32.7^0 C. According to AASHTO MP-1 this would be a low end PG -28^0 C. The effective low end PG grade for the specimens containing the PG 64-28 virgin binder and 15% RAP is -27.9^0 C. According to AASHTO MP-1, this would be a low end PG-22^0 C. In both cases tested for the low end PG grade, the values did not differ greatly from the virgin binder added.

3.3 INVESTIGATION OF THE EFFECT OF TESTING TEMPERATURE

Recognizing that the test temperatures were substantially different from the Superpave high and low end service temperatures, the testing procedure was repeated with the specimens conditioned to 34^0 C and -18^0 C. The results are listed in Tables 4a and b, Appendix I and are graphed in Figures 3a and b, Appendix II. Table 3.3 shows the results of changing the conditioning temperatures compared to the original conditioning temperatures.

Table 3.3 Effect of Changing Conditioning Temperature

Virgin Binder Added	% RAP Added	Effective PG value			
		Conditioning Temperature			
		28^0 C	34^0 C	3^0 C	-18^0 C
		High End PG Value		Low End PG Value	
58-34	15	63.0	62.3	-32.7	-32.5
64-28	15	66.9	65.7	-27.9	-26.5

The results indicate that changing the test conditioning temperature does not appear to have a significant effect on the effective PG grade determined for the mix.

3.4 EFFECT OF PERCENT RAP ON BINDER BLENDING

Another variable that might effect the interpretation of test results is the percent RAP in the mix. To evaluate this effect tests were performed at 28^0 C and 3^0 C with 25 percent RAP. The aggregate structure for these tests were maintained as close to the previously used aggregate structure as possible. The RAP and virgin binders used for this were the same as used in the previous testing. The total asphalt contents for both the 15% and 25% RAP mixes were held constant by adjusting the amount of virgin binder added to compensate for the asphalt content of the RAP. Tables 5a and b Appendix I list the data and Figures 4a and b, Appendix II graph the determination of the effective PG grades.

Table 3.4 compares the results of adding 25% and 15% RAP when conditioning the specimens at 28^0 C and 3^0 C.

Table 3.4 Effect of Percentage of RAP

Virgin Binder Added	% RAP Added	Effective PG Grade	
58-34	15%	63.0	-32.7
58-34	25%	65.7	-32.0
64-28	15%	66.9	-27.9
64-28	25%	71.0	-26.5

It can be seen that the increase in RAP added to the mix did in fact cause the anticipated change in the effective PG grade of the binder. Both the high and low end values of the PG grade did increase. This change is anticipated because of the additional RAP binder tends to increase the hardness of the combined binders. This indicates that the test is sensitive enough to detect changes in the effective PG grade.

3.5 EFFECT OF AGGREGATE SOURCE ON BINDER BLENDING

To ensure that the results obtained were not dependent upon the source of the aggregates, an additional set of samples were prepared using aggregates from a completely different source. The RAP and binders were the same as what was used in the prior testing. These specimens were again made using either 15% RAP or 15% reclaimed RAP aggregate. The intent of these specimens was that if the results were truly being derived by the combined RAP and virgin binder, the effective PG grade for the same virgin binder and RAP should be independent of the aggregate used if all other things are held constant. Due to a shortage of virgin binder, only specimens that were to be conditioned at 3^0 C were fabricated. The low end PG values were deemed to be the critical factor in this process since the addition of RAP tends to degrade the low temperature properties and the addition of RAP tends to enhance the high end properties of asphalt binders. Table 3.5 summarizes the detailed data of Tables 6, Appendix I and Figures 5, Appendix II.

Table 3.5 shows the results of the alternate aggregate source compared to the baseline aggregate results discussed earlier.

Table 3.5 Effect of Changing Material Source

Virgin Binder Added	% RAP Added	Effective Low End PG Value – Baseline Aggregate Structure	Effective Low End PG Value – Alternate Aggregate Structure
58-34	15	-32.7	-32.8
64-28	15	-27.9	-27.0

As can be seen in Table 3.5, changing the aggregate structure has very little effect on the effective PG grade for the specimens. The results of this test indicate the results of this test procedure appear to be independent of the aggregates used in the mix.

3.6 TESTING HMA PLANT PRODUCED MATERIAL

In order to attempt to validate this procedure, aggregates, binder, RAP and a HMA plant produced Superpave mix containing 10% RAP and PG 64-28, were secured. These materials were combined to produce a mix with the same aggregate characteristics as the HMA plant produced Superpave mix that contained 10% RAP. The laboratory made mixes used virgin binders with PG grades of either PG 64-28 or PG 70-22. The RAP was slowly dried so as to eliminate problems associated changing moisture contents. Specimens were created by either adding 10% RAP or 10% reclaimed RAP aggregate to the mixes. Six of specimens were fabricated from each of the following: PG 64-28 with 10% RAP; PG 64-28 with 10% reclaimed RAP aggregate; PG 70-22 with 10% RAP; PG 70-22 with 10% reclaimed RAP aggregate and the plant produced HMA with 10% RAP.

These specimens were conditioned at 25^0 C and 3^0 C and tested using the indirect tension test method. The results are presented as Table 7a and b, Appendix I and grafted in Figure 6a and b, Appendix II. Table 3.6 summarizes the results of this testing.

Table 3.6 Difference of Effective Binder Grade as Measured on Lab or Plant Mix

Mix Tested	% RAP	Effective PG Grade
Laboratory Mix	10%	67.7-26.2
Plant Mix	10%	69.3-24.7

The RAP binder was also extracted and recovered using the Abson Recovery method. This recovered binder was then blended with the virgin PG 64-28 binder in the proportions as they would be in the finished pavement. The blend of recovered and virgin binder was then tested using the Superpave binder testing methods outlined in AASHTO MP-1. The results of this testing can be seen in Table 8, Appendix I. The PG grade of this laboratory blended material was PG 64-28. The low end value of the PG grade was slightly below the –22 and so barely placed it within the specification value for a –28. This result is contrary to the anticipated result that the completely blended binder produced by the laboratory blending should be the stiffest of all the PG grades determined for this material. The fact that the plant mixed material PG values are higher than the laboratory mixed material does not come as a surprise as the HMA plant mixing process is much harsher than the laboratory process and the plant mix had to be reheated for the laboratory molding of specimens.

These results indicate that there is a need to further correlate the results obtained in the laboratory with results obtained with materials produced by HMA plants. These results only represent a single set of tests performed on HMA plant material.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

As the degree of blending that occurs in HMA mixes that contain RAP is not known, tests of completely blended binders may be misleading. The development of a quick and economical test for the estimation of the effective binder grade is necessary. The limited results available at this time indicate that the indirect tension test can fill this need. The indirect tension test is a relatively quick test to perform that yields anticipated results. The use of the test will provide a realistic estimate of the character of the binder in HMA mixes containing RAP.

One assumption that needs to addressed is that the indirect tension test assumes that all asphalt binders with the same PG grades have the same characteristics. Using neat stretch grade binders tends to limit these differences, but there may always be a minor degree of variability in the test results because of these differences.

4.2 RECOMMENDATIONS

Since the testing for this study was carried out on only one set of materials, further testing on a broader range of materials should be carried out. The results of this test may be affected by material property variations that were not present in this study. This would be especially true for HMA plant produced materials. The heating and mixing operations that occur at HMA plants are difficult, if not impossible, to reproduce under laboratory conditions. Because of this, an effort should be made to correlate the laboratory results of this test with results obtained from HMA plants. Additional testing should be carried out using RAPs with binders of varying degrees of hardness as well as percentage of RAP used. A series should also be undertaken that compares results of specimens molded at the plant without additional heating to those transported to the laboratory and reheated for molding.

Additional research work should be performed on using this test to examine the interaction of modified virgin binders with RAP. The use of RAP in low percentages will probably not produce any problems. The problem of using higher percentages of RAP in conjunction with modified virgin binders may produce an undesirable reaction between the modified virgin binder and the RAP binder. This negative reaction may greatly affect the effective PG grade of the finished pavement. This type of problem is likely to become more common as the use of modified PG binders increases. The most severe problem with the blending of modified binders and RAP would be when a RAP containing a modified binder is combined with a modified virgin binder. Many times the mixing of modified binders creates an even larger problem because of interaction between the modifiers. This situation is further complicated by the fact that the process of recovering asphalts does not always capture the modifying agents: compatibility tests between recovered modified asphalt binders and virgin modified binders may indicate whether a problem exists. A quick physical test that provides an estimate of the effective PG grade of the mix would indicate a compatibility problem between the RAP binder and the virgin binder being added before any materials were actually placed. Permitting adjustments for better performance.

APPENDIX I

TABLES

Table 1 DSR Results on Binder from Portions of Virgin and RAP Mixes
Agg piecies > 1/4", Fines < 1/4", Lump > 1/4", Tot Entire Mix

Sample ID	% of Mix by weight	G*/sin(d) (kpa)	Average	Standard Deviation	Standard Deviation % of Avg.
Plant #1, 15% RAP Mix					
P1Agg1	32	3.11	3.038	0.072	2.4
P1Agg2		2.966			
P1Fines1	45	8.299	8.328	0.029	0.3
P1Fines2		8.357			
P1Lump1	22	6.292	6.449	0.157	2.4
P1Lump2		6.605			
Tot1Mix1	100	4.484	4.504	0.019	0.4
Tot1Mix1		4.523			
Plant #2, 15% RAP Mix					
P2Agg1	35	3.998	3.944	0.054	1.4
P2Agg2		3.889			
P2Fines1	32.5	1.606	1.657	0.051	3.0
P2Fines2		1.707			
P2Lump1	32.5	2.82	2.89	0.07	2.4
P2Lump2		2.96			
Virgin Mix, no RAP					
VAgg1	39	4.662	4.455	0.208	4.7
VAgg2		4.247			
VFines1	30	6.294	6.743	0.449	6.7
VFines2		7.192			
VLump1	31	7.872	8.034	0.162	2.0
VLump2		8.195			

TABLE 2a UNCONFINED COMPRESSION TEST, VARIOUS PRE-HEAT TIMES, 15% RAP					
Sample	RAP Pre-heat Time (min)	Max Load Pounds	Average Load Pounds	Standard Deviation	Standard Deviation % avg Load
1-9	540	18130	18100	36	0.20
2-9	540	18120			
3-9	540	18050			
4-6	360	18430	18510	599	3.23
5-6	360	17820			
6-6	360	19280			
7-4	240	17310	17900	417	2.33
8-4	240	18180			
9-4	240	18210			
10-2	120	16290	15707	474	3.02
11-2	120	15700			
12-2	120	15130			
13-1	60	14480	15193	517	3.40
14-1	60	15410			
15-1	60	15690			
16-30	30	16260	15957	267	1.67
17-30	30	16000			
18-30	30	15610			
19-15	15	14980	13880	990	7.13
20-15	15	12580			
21-15	15	14080			
22-7	7	14450	14387	119	0.83
23-7	7	14490			
24-7	7	14220			
25-3	3	15160	14907	476	3.19
26-3	3	15320			
27-3	3	14240			
28-1	1	14500	14247	662	4.64
29-1	1	13340			
30-1	1	14900			
31-0	0	14890	14613	210	1.44
32-0	0	14380			
33-0	0	14570			
34-V	N/A	11170	10967	368	3.36
35-V	N/A	11280			
36-V	N/A	10450			

Notes: 85% virgin aggregate evenly divided between 1/2:, 3/8", Natural sand and manufactured sand.
All molded samples were 15 cm in diameter and 11.1mm in heigth.
All had 15% RAP and 5.1% binder.
All were tested at 36C.
The 28-Virgin was 15% RAP Agg, 85% new Agg and 100% new binder

TABLE 2b INDIRECT TENSION TEST, VARIOUS PRE-HEAT TIMES, 15% RAP					
Sample	RAP Pre-heat Time (min)	Max Load Pounds	Average Load Pounds	Standard Deviation	Standard Deviation % Avg Load
1-4	240	6960	6890	51	0.74
2-4	240	6840			
3-4	240	6870			
4-2	120	6920	6617	219	3.31
5-2	120	6520			
6-2	120	6410			
7-1	60	6230	6180	131	2.13
8-1	60	6310			
9-1	60	6000			
10-30	30	6180	5823	256	4.40
11-30	30	5590			
12-30	30	5700			
13-15	15	5190	5343	336	6.30
14-15	15	5810			
15-15	15	5030			
16-7	7	5430	5817	274	4.71
17-7	7	5990			
18-7	7	6030			
19-3	3	5690	5277	606	11.48
20-3	3	5720			
21-3	3	4420			
22-1	1	5580	5410	148	2.73
23-1	1	5430			
24-1	1	5220			
25-0	0	4860	4647	211	4.53
26-0	0	4360			
27-0	0	4720			
28-Virgin	N/A	3600			

Notes: 85% virgin aggregate evenly divided between 1/2:, 3/8", Natural sand and manufactured sand.
All molded samples were 15 cm in diameter and 11.1mm in diameter.
All had 15% RAP and 5.1% binder.
All were tested at 36C.
The 28-Virgin was 15% RAP Agg, 85% new agg and 100% new binder

Table 3a Indirect Tension Test, Different Binders, 15% RAP Binder Grade 64-28 or 58-34, Tested at 28C						
Sample	Binder	15% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation As % of Avg Load
1 2 3	64-28 64-28 64-28	Yes Yes Yes	4110 4090 3430	3877	316	8.15
7 8 9	64-28 64-28 64-28	no no no	3060 3110 2980	3050	54	1.76
13 14 15	58-34 58-34 58-34	Yes Yes Yes	2780 2840 2690	2770	62	2.23
19 20 21	58-34 58-34 58-34	no no no	1360 1290 1360	1337	33	2.47

Table 3b Indirect Tension Test, Different Binders, 15% RAP Binder Grade 64-28 or 58-34, Tested at 3C						
Sample	Binder	15% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation As % of Avg Load
4 5 6	64-28 64-28 64-28	Yes Yes Yes	17950 17400 16050	17133	798	4.66
10 11 12	64-28 64-28 64-28	No No No	16880 16090 17700	16890	657	3.89
16 17 18	58-34 58-34 58-34	Yes Yes Yes	9230 9560 9270	9230 9560 9353	147	1.57
22 23 24	58-34 58-34 58-34	No No No	6660 7060 6510	6743	232	3.44

Table 4a Indirect Tension Test, Different Binders, 15% RAP Binder Grade 64-28 or 58-34, Tested at 34C						
Sample	Binder	15% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation As % of Avg Load
R7 R8 R9	64-28 64-28 64-28	Yes Yes Yes	3070 3480 3200	3250	171	5.26
V10 V11 V12	64-28 64-28 64-28	No No No	2770 2890 2680	2780	86	3.09
R2 R4 R6	58-34 58-34 58-34	Yes Yes Yes	2390 2510 2070	2323	186	7.99
V1 V3 V5	58-34 58-34 58-34	no no no	1250 1070 1030	1117	96	8.57

Table 4b Indirect Tension Test, Different Binders, 15% RAP Binder Grade 64-28 or 58-34, Tested at -18C						
Sample	Binder	15% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation As % of Avg Load
V7 V8 V10	64-28 64-28 64-28	Yes Yes Yes	31580 27960 29900	29813	1479	4.96
R9 R11 R12	64-28 64-28 64-28	No No No	32170 31920 32420	32170	204	0.63
R3 R5 R6	58-34 58-34 58-34	Yes Yes Yes	22410 23880 23300	23197	605	2.61
V1 V2 V4	58-34 58-34 58-34	No No No	21640 19910 21480	21010	781	3.72

Table 5a Indirect Tension Test, Different Binders, 25% RAP, at 28C

Binder Grade 64-28 or 58-34, Tested at 28C

Sample	Binder	25% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation as % of Avg Load
R2 R4 R6	64-28 64-28 64-28	Yes Yes Yes	4260 4520 4860	4547	246	5.4
V1 V3 V5	64-28 64-28 64-28	no no no	3010 2970 3280	3087	138	4.5
R2 R4 R6	58-34 58-34 58-34	Yes Yes Yes	3250 3860 3260	3457	285	8.3
V1 V3 C11	58-34 58-34 58-34	no no no	1920 1690 1860	1823	97	5.3

Table 5b Indirect Tension Test, Different Binders, 25% RAP, at 3C

Binder Grade 64-28 or 58-34, Tested at 3C

Sample	Binder	25% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation as % of Avg Load
R7 R8 R9	64-28 64-28 64-28	Yes Yes Yes	18300 18490 18170	18320	131	0.7
V10 V11 V12	64-28 64-28 64-28	No No No	16260 15760 16260	16093	236	1.5
R5 R7 R9	58-34 58-34 58-34	Yes Yes Yes	10560 10380 10360	10433	90	0.9
V8 V10 V12	58-34 58-34 58-34	No No No	7560 7450 7730	7580	115	1.5

Table 6 Indirect Tension Test, Different Source, 15% RAP

	Sample	Binder Grade	Load Max Pounds	Average Load	Standard Deviation
25C Test Temperature					
	1 Virgin	64-28	2260	2310	50
	2 Virgin	64-28	2360		
	3 Virgin	70-22	2870	2955	85
	4 Virgin	70-22	3040		
	5 RAP Plt	64-28	2840	2900	60
	6 RAP Plt	64-28	2960		
	7 RAP Lab	64-28	2650	2715	65
	8 RAP Lab	64-28	2780		
3C Test Temperature					
	9 Virgin	64-28	9040	9010	30
	10 Virgin	64-28	8980		
	11 Virgin	70-22	14530	14265	265
	12 Virgin	70-22	14000		
	13 RAP Plt	64-28	12130	11940	190
	14 RAP Plt	64-28	11750		
	15 RAP Lab	64-28	10680	10645	35
	16 RAP Lab	64-28	10610		

TABLE 7a: HMA PLANT MATERIAL VERSUS LAB MIX: INDIRECT TENSION High End Determination: Samples Tested at +25 C The RAP mixes contained 10% RAP The Virgin mixes contained 10% RAP aggregate P indicates Plant, L indicates Lab						
Sample	Binder	10% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation as % of Avg Load
1 Virgin	64-28	No	2260			
2 Virgin	64-28	No	2360	2310	50	2.2
3 Virgin	70-22	No	2870			
4 Virgin	70-22	No	3040	2955	85	2.9
5 RAP P	64-28	Yes	2840			
6 RAP P	64-28	Yes	2960	2900	60	2.1
7 RAP L	64-28	Yes	2650			
8 RAP L	64-28	Yes	2780	2715	65	2.4

TABLE 7b: HMA PLANT MATERIAL VERSUS LAB MIX: INDIRECT TENSION Low End Determination: Samples Tested at +3 C The RAP mixes contained 10% RAP The Virgin mixes contained 10% RAP aggregate P indicates Plant, L indicates Lab						
Sample	Binder	10% RAP	Max Load pounds	Average Max Load Pounds	Standard Deviation	Standard Deviation as % of Avg Load
9 Virgin	64-28	No	9040			
10 Virgin	64-28	No	8980	9010	30	0.3
11 Virgin	70-22	No	14530			
12 Virgin	70-22	No	14000	14265	265	1.9
13 RAP P	64-28	Yes	12130			
14 RAP P	64-28	Yes	11750	11940	190	1.6
15 RAP L	64-28	Yes	10680			
16 RAP L	64-28	Yes	10610	10610	35	0.3

TABLE 8: DSR & BBR VALUES FOR 10% RAP MIXTURE

11.7% Recovered RAP binder and 88.3% Virgin 64-28

DSR after Rolling Thin Film Oven	Test Temperature 64 C			
	Blend		PG64-28 Spec	Grade Met
G*/sin(delta), kPa	5.140		>2.2	64
G*	4.987			
Delta	74.71			
Rotational Viscosity after RTFO	Test Temperature 135 C			
	Blend		PG64-28 Spec	Grade Met
Viscosity, cp	990.0		<3,000	64
Mass Loss/Gain	-0.535		<1%	
DSR after Pressure Aging Vessel	Test Temperature +22 C			
	Blend		PG64-28 Spec	Grade Met
G*sin(delta), kPa	2131		<5,000	-28
G*	3090			
Delta	43.60			
BBR	Test Temperature -18 C			
	Blend		PG64-28 Spec	Grade Met
Beam 1, Stiffness, Mpa	198			
m - value	0.303			
Beam 2, Stiffness, Mpa	194			
m - value	0.299			
Average, Mpa	196		<300	-28
Average, m - value	0.301		>0.300	-28

APPENDIX II

FIGURES

Figure 1 - RAP Preheat Time Before Mixing
Comparison of Unconfined Compression and Indirect Tension

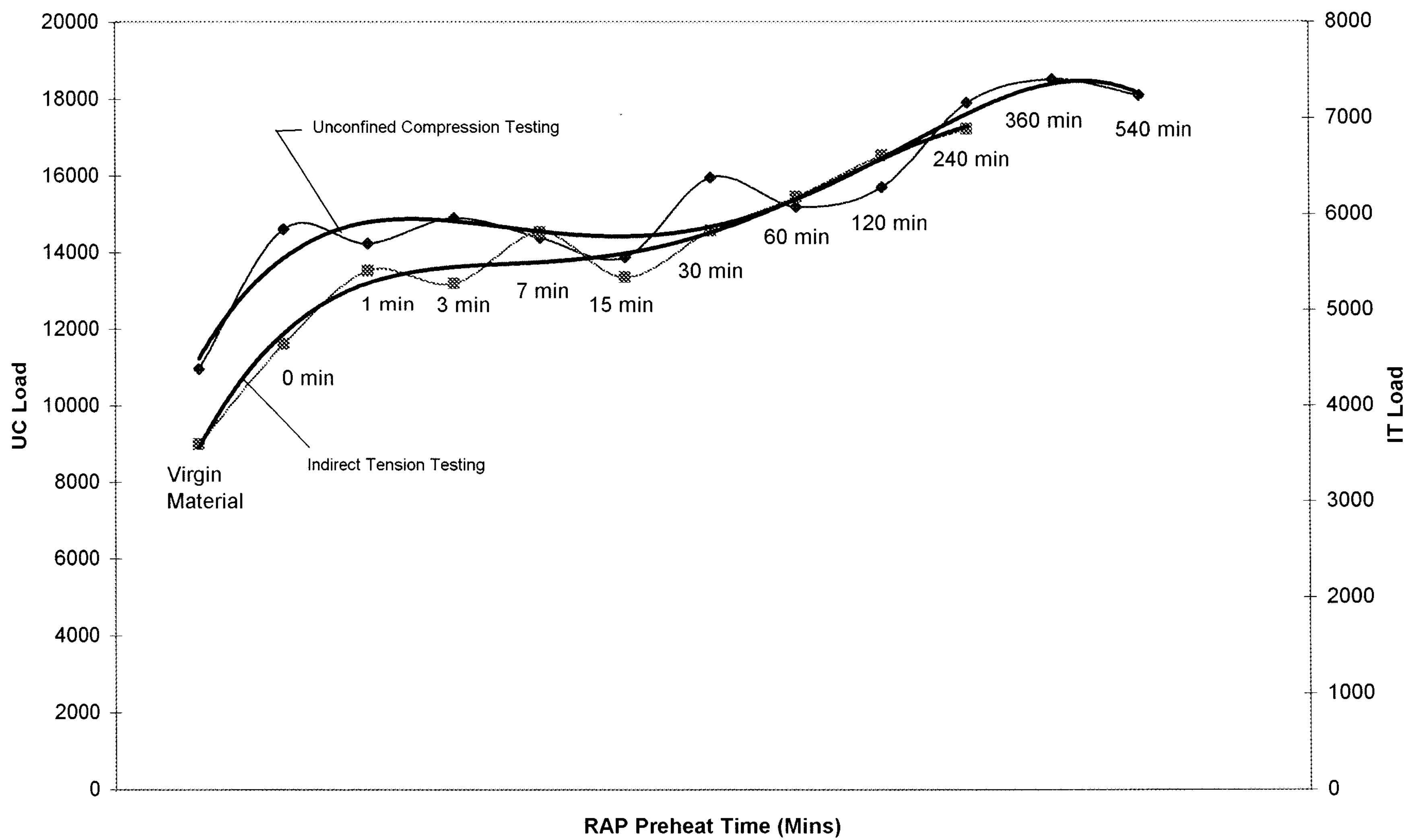

Figure 2a - Baseline Samples: Indirect Tension
High End Determination: 15% RAP

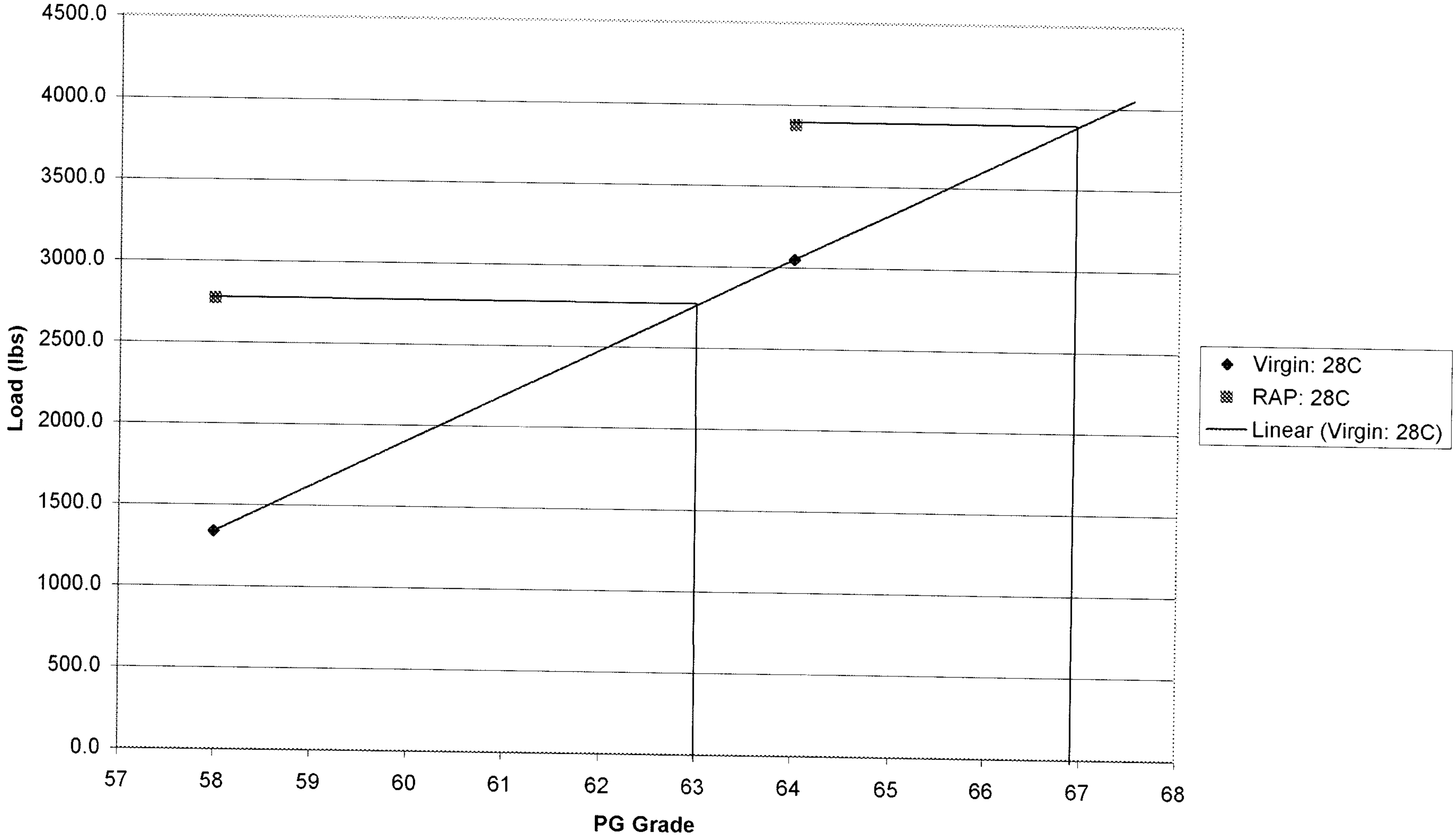

Figure 2b - Baseline Samples: Indirect Tension
Low End Determination: 15% RAP

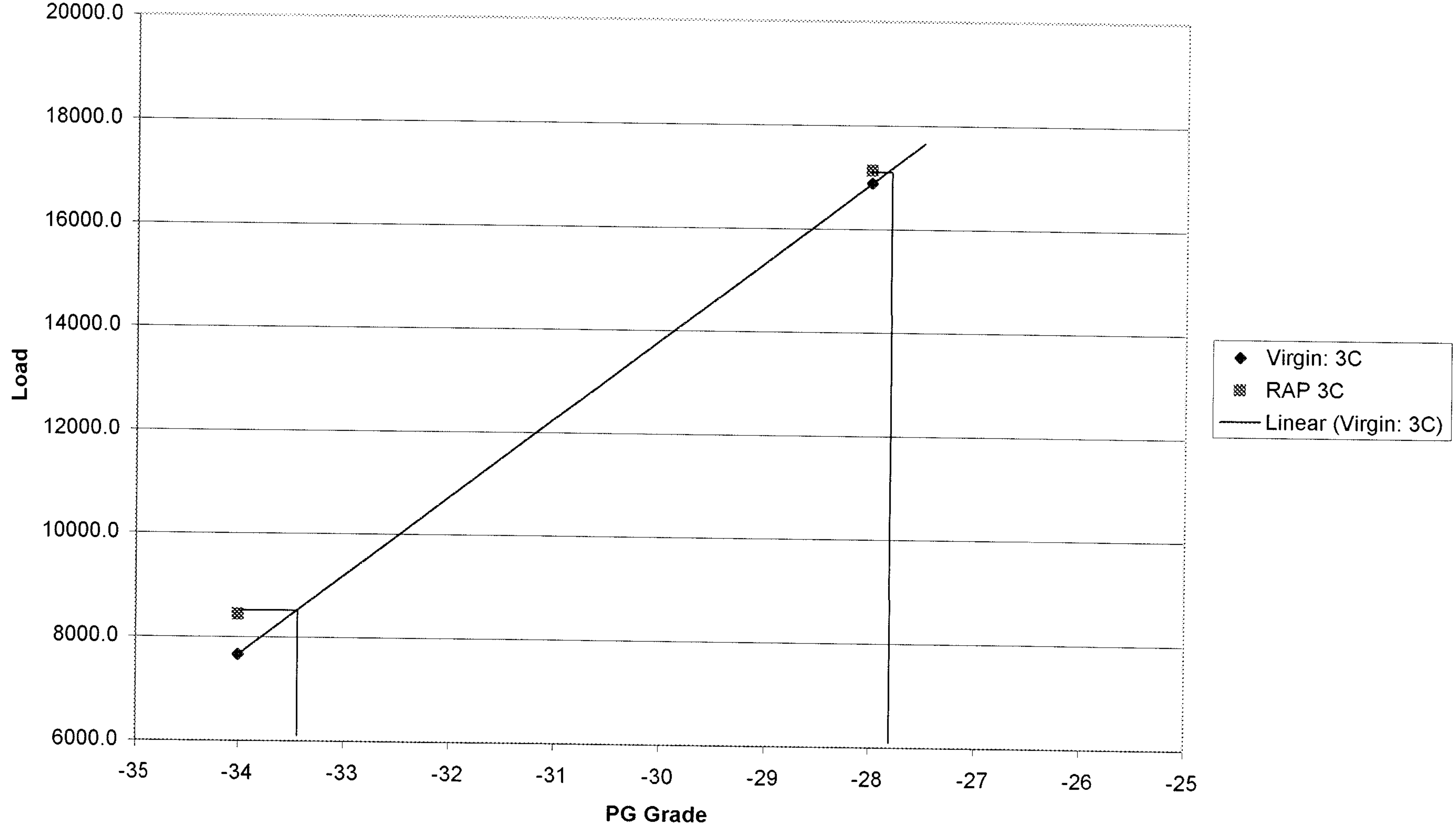

Figure 3a - Baseline Samples: Indirect Tension
Hight End Determination 34C: 15% RAP

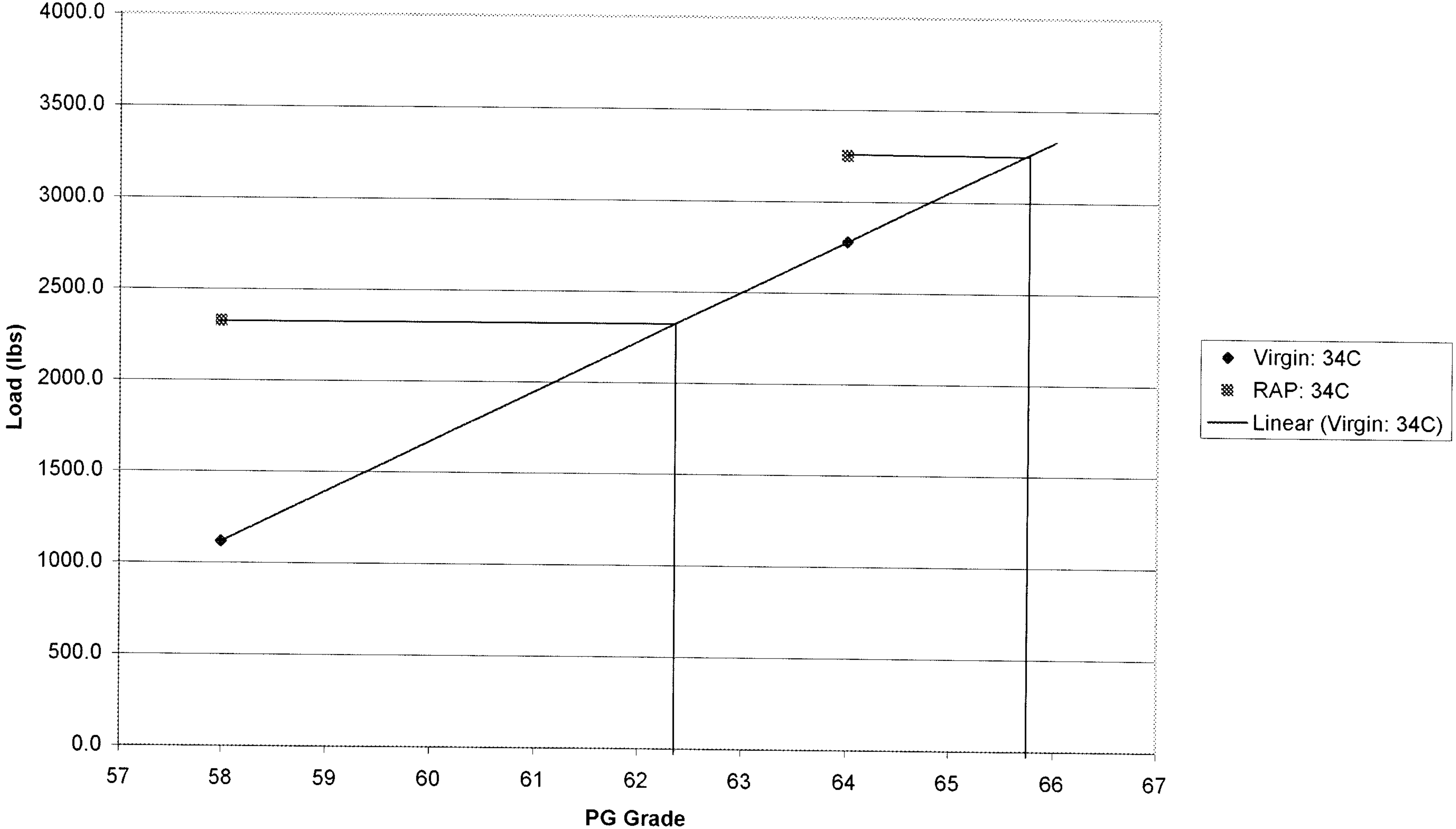

Figure 3b - Baseline Samples: Indirect Tension
Low End Determination -18C: 15% RAP

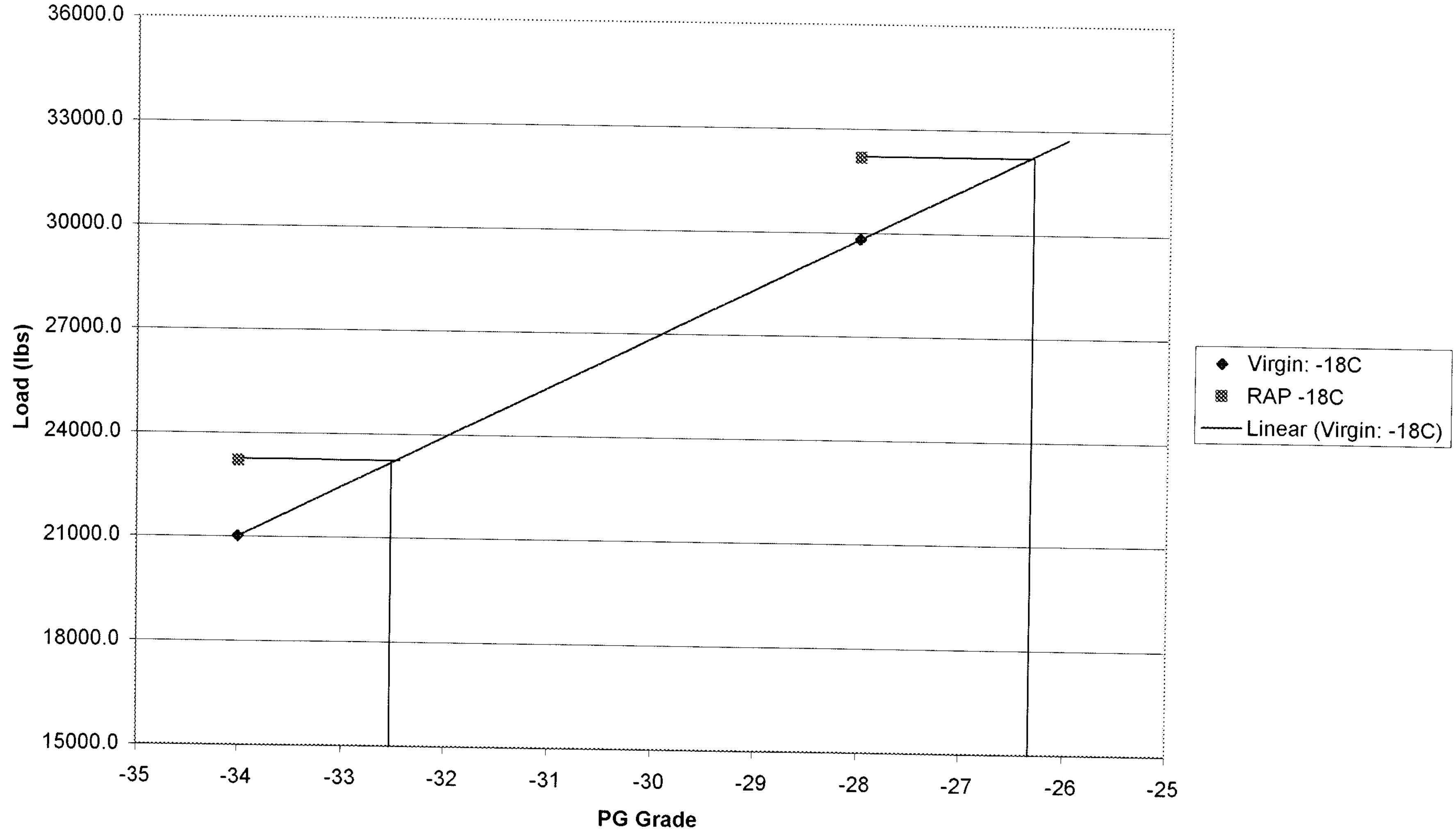

Figure 4a - Increased RAP Content: Indirect Tension
High End Determination: 25% RAP

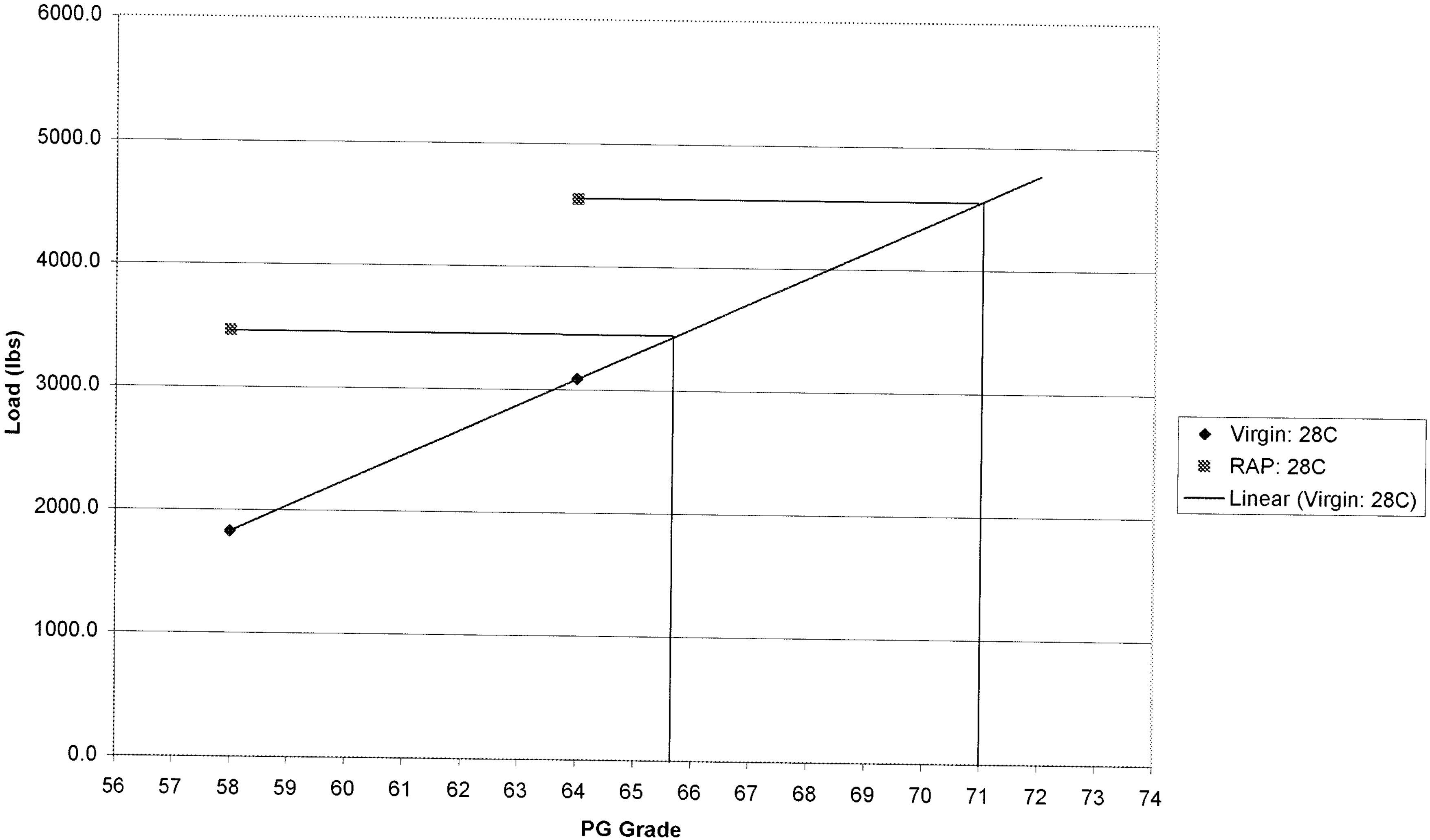

Figure 4b - Increased RAP Content: Indirect Tension

Low End Value: 25% RAP

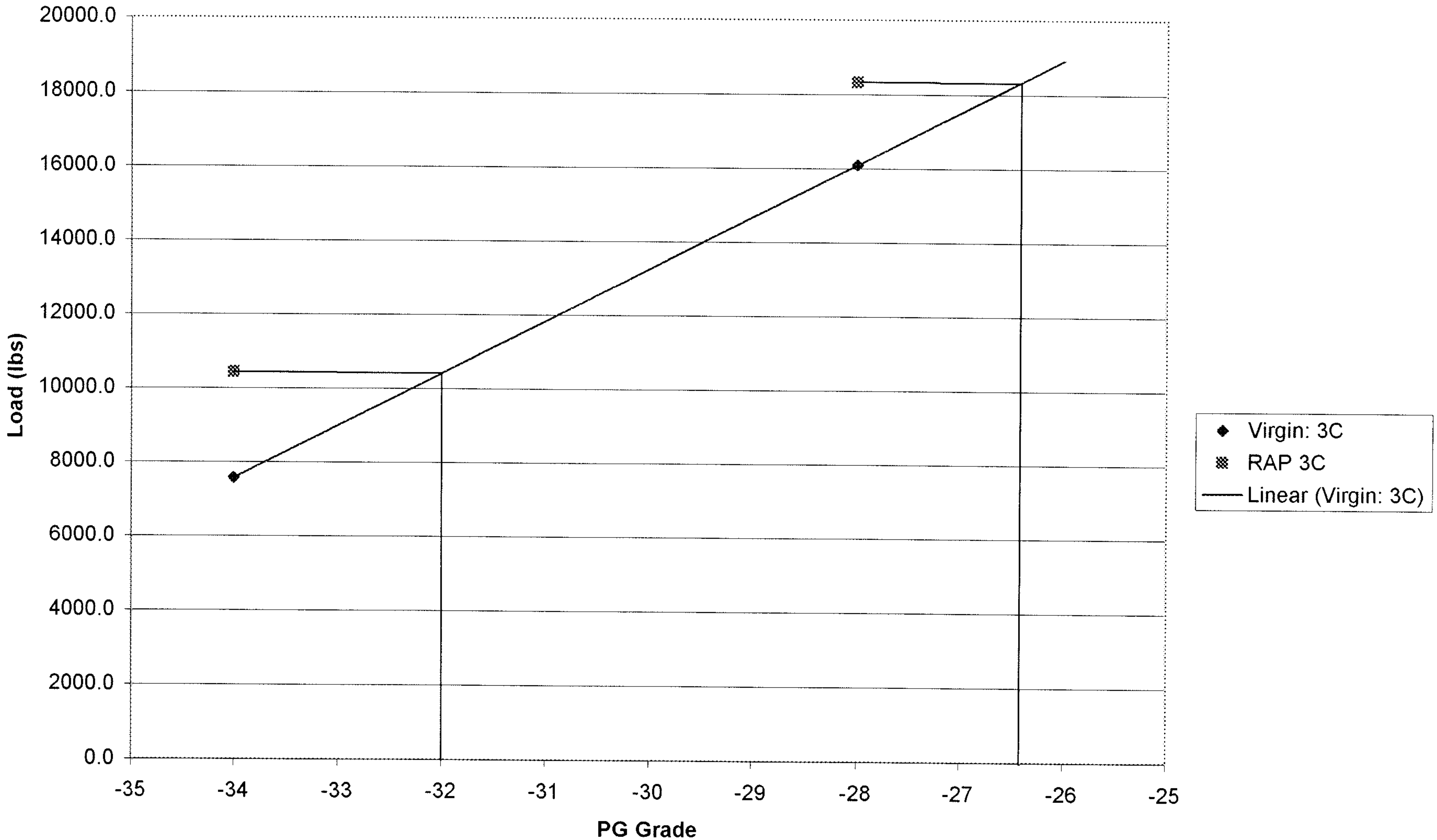

Figure 5 - Altered Aggregate Structure: Indirect Tension
Low End Determination: 15% RAP

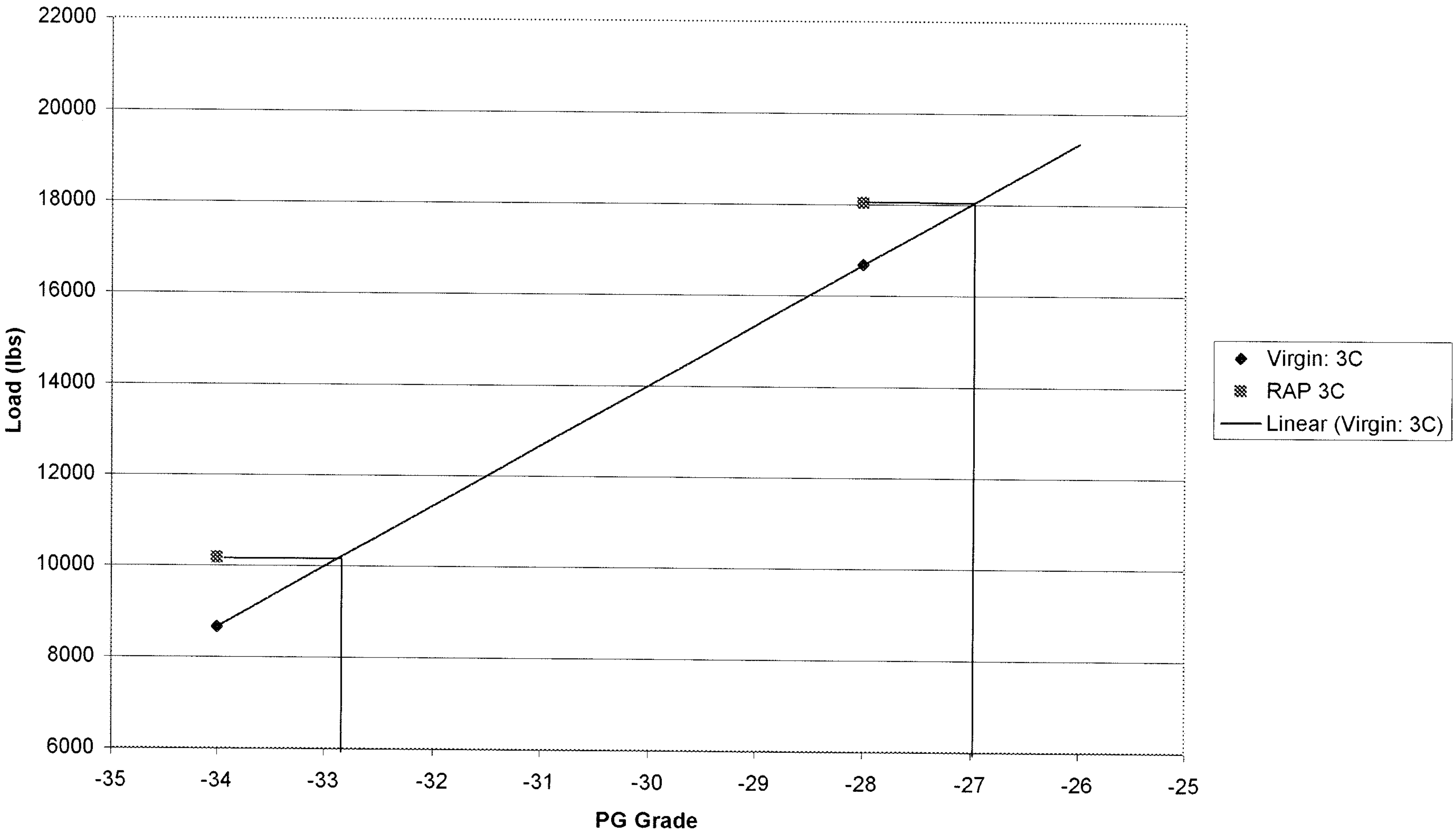

Figure 6a - HMA Plant Material: Indirect Tension Test
High End Determination: Samples Tested At 25 C

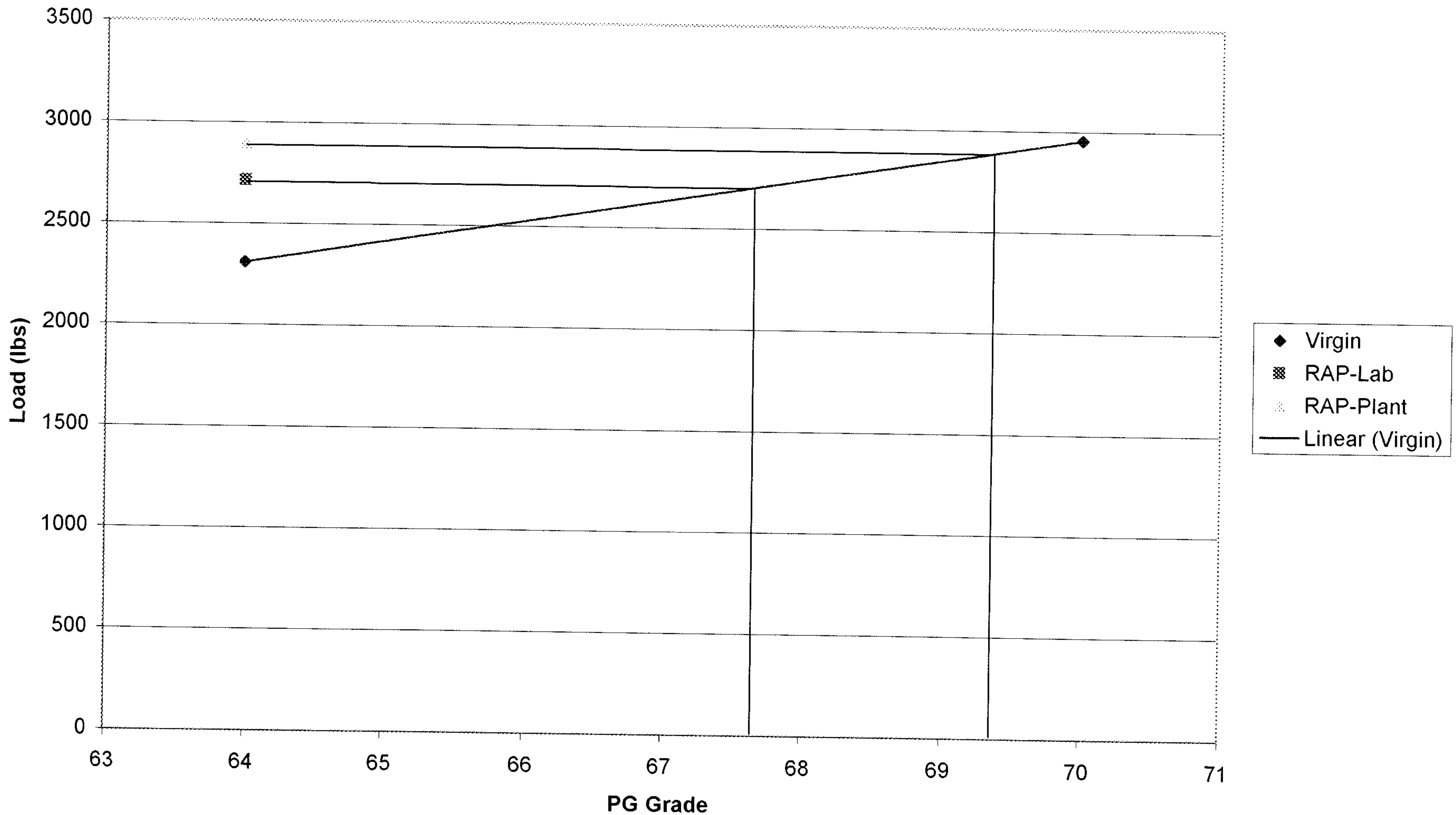

Figure 6b - HMA Plant Material: Indirect Tension Test
Low End Determination: Samples Tested At 3 C