NON-CONTACT ULTRASONIC CHARACTERIZATION OF HOT MIX ASPHALT (HMA)

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Abstract: In this study, non-contact ultrasound technology is successfully utilized to characterize hot mix asphalt (HMA) used in roadway construction. HMA is a heterogeneous mixture of asphalt binder, stone aggregates, fines (sand) and mineral additives. Specifications require that HMA have 3% to 5% air voids by volume. Mechanical properties of HMA depend upon the binder type, the sizes and gradations of the aggregates and the sands, the type of mineral additives, and the proportions by weight of each of the component of the mix and the percentage of air voids. Mechanical properties such as rutting resistance of HMA beam specimens (75mm x 75mm x 300mm) are routinely tested for quality control and compliance to project specifications. These tests are slow and labor intensive. They require specialized equipment and technicians. A suite of beam specimens for different HMA mixes was tested using the NCA 1000 system. The NCA 1000 measures time of flight, thickness, velocity, and integrated response (area underneath transmitted or reflected signals in dB) of the material. Preliminary data indicate that these measurements could potentially be correlated to a property of HMA, in this case density relative to the particular design. The application of non-contact ultrasound to HMA characterization could revolutionize the HMA quality control process for roadway construction projects

Introduction: An important aspect to road construction is contractor quality control (QC) and owner quality assurance (QA). One of the construction materials that necessitate an extensive amount of testing is asphalt concrete that is used for road pavements. The QA/QC testing of asphalt concrete production is a time consuming and costly process. The lack of timeliness of a test result could make the difference between a product remaining on the project or having it removed after placement. For example, in order to determine the percent asphalt cement in production, a sample must be either chemically extracted to separate the aggregate from the asphalt cement or have it burned off for a weight difference. This may take up to three hours to perform the test at which time the asphalt concrete plant is producing about 250 metric tons per hour. This would yield about 900 lineal meters of a traffic lane width of pavement before a test result would be known. There would be a great benefit for the application of a rapid testing method during the production and placement phase of the construction.

The purpose of this study was to try a new non-contact ultrasonic technique for detection of mix component changes along with correlations to a known property of the material. The development and use of this test method, which would reduce the delay time as compared to conventional testing, would translate into a significant cost savings.

New ultrasound GMP^{tm} non-contact transducers are introduced and applied to the testing of the laboratory prepared asphalt specimens. The specimens were fabricated with varying gradation and asphalt cement proportions. The analysis consists of a statistical review of the data to detect changes in the sample test values for correlation to the known material property.

Results: The testing revealed, as indicated in Table 1, a very close correlation of the Integrated Response (IR_m) value of the asphalt concrete samples with the Bulk Specific Gravity (BSG) when checked as individual sets however no correlation for all of the values collectively. This would indicate that there is a property related to both the BSG and the IR_m that would need to be isolated in a further study. The two non-correlating results, sample set 4.8% -8 Dev may be a result of one of the samples in the set not fabricated correctly. Sample 4.8% -8 Dev was very coarse and rough textured; this would have created a high scatter of the signal.

Table 1 - Ultrasound Correlation Results

Set	R-sq Correlation of IRm to Bulk SG
5.0% 0 Dev	0.992
5.3% 0 Dev	0.904
5.0% +8 Dev	0.756
5.3% +8 Dev	0.841
5.6% +8 Dev	0.966
4.5% -8 Dev	0.991
4.8% -8 Dev	0.293
5.1% -8 Dev	0.993
4.7% 0 Dev	0.977
ALL data points	0.189

Table 2- Ultrasound Testing

SAMPLE ID	BULK DEN	TYPE	MEAN	SD	AIR MEAN	AIR SD	IRM	POOLED SD
5.0% 0 Dev	2.255	IR	-10.29	0.476	74.81	0.0653	-85.11	0.481
5.0% 0 Dev	2.301	IR	-6.48	0.362	75.00	0.0335	-81.49	0.364
5.0% 0 Dev	2.342	IR	-4.04	0.233	75.09	0.1570	-79.13	0.281
5.3% 0 Dev	2.331	IR	-9.76	0.471	74.84	0.0653	-84.61	0.476
5.3% 0 Dev	2.340	IR	-5.77	0.307	74.78	0.0653	-80.55	0.314
5.3% 0 Dev	2.347	IR	-5.13	0.270	74.72	0.0653	-79.85	0.277
5.0% +8 Dev	2.265	IR	-4.99	0.283	74.45	0.0622	-79.44	0.290
5.0% +8 Dev	2.259	IR	-5.25	0.590	75.00	0.0214	-80.25	0.590
5.0% +8 Dev	2.395	IR	-5.96	0.372	75.24	0.0335	-81.20	0.373
5.3% +8 Dev	2.364	IR	-7.08	0.317	75.00	0.0653	-82.08	0.323
5.3% +8 Dev	2.338	IR	-5.30	0.351	74.65	0.0653	-79.96	0.357
5.3% +8 Dev	2.340	IR	-6.00	0.211	74.93	0.0653	-80.94	0.221
5.6% +8 Dev	2.397	IR	-4.55	0.239	74.90	0.0653	-79.46	0.248
5.6% +8 Dev	2.253	IR	-5.28	0.372	74.92	0.0214	-80.20	0.372
5.6% +8 Dev	2.421	IR	-1.21	0.174	74.69	0.0653	-75.90	0.186
4.5% -8 Dev	2.319	IR	-7.28	0.323	74.68	0.0214	-81.97	0.324
4.5% -8 Dev	2.320	IR	-7.12	0.353	74.75	0.0653	-81.87	0.359
4.5% -8 Dev	2.326	IR	-4.69	0.251	74.87	0.0653	-79.56	0.260
4.8% -8 Dev	2.319	IR	-11.39	0.551	74.89	0.0335	-86.28	0.552
4.8% -8 Dev	2.357	IR	-8.79	0.378	74.97	0.0653	-83.76	0.384
4.8% -8 Dev	2.340	IR	-6.37	0.303	74.76	0.0214	-81.13	0.304
5.1% -8 Dev	2.342	IR	-6.62	0.487	75.08	0.0793	-81.70	0.493
5.1% -8 Dev	2.347	IR	-8.85	0.499	75.16	0.0793	-84.01	0.505
5.1% -8 Dev	2.339	IR	-4.71	0.249	75.12	0.0335	-79.83	0.252
4.7% 0 Dev	2.332	IR	-6.52	0.306	74.84	0.0214	-81.36	0.307
4.7% 0 Dev	2.379	IR	-2.37	0.205	74.23	0.0622	-76.60	0.214
4.7% 0 Dev	2.408	IR	-0.74	0.200	74.34	0.0622	-75.08	0.209

Discussion: Asphalt Concrete Material: Asphalt Concrete aggregate is the granular material used in asphalt concrete mixtures, which make up about 90 to 95 percent of the mixture weight and provides the primary load bearing uniqueness of the mix. As a result, the quality and physical properties of the aggregates are a significant factor in the pavement performance (1).

Aggregate: Aggregates are produced through a crushing process into various sizes ranging from 37.5 mm diameter down to a measurable size of 0.075 mm diameter. The best type of shape is angular (cubical) in order to provide the maximum resistance to shear.

Asphalt Cement: Asphalt grade and characteristics are critical to the performance of the asphalt pavement. Asphalt is waste product from refinery processing of crude oil sometimes called the "bottom of the barrel" that is very viscous with the characteristic of having a viscosity that varies with temperature. The properties depend on the refinery operations and the composition crude source. The Grade(s) of asphalt cement used in hot-mix paving are selected based on climatic conditions and on past performance.

Mix design: The asphalt concrete mixes are designed to meet the necessary criteria based on type of roadway, traffic volumes, intended use, and the seasons. The design method for this research was the Marshall method due to its use by Clark County, Nevada.

Non-Contact Ultrasound: The predominant method of introducing wave propagation into a sample is by placing the transducer onto the material using a coupling medium such as a gel. This technique is a contact mode for which the use in construction inspection or testing is very tedious. Non-contact modes of transducer placement are more practical and the method employed in this study (Figure 1). The type of Non-contact transducer utilized was the new generation GMP^{tm} from The Ultran Group, which is a new piezoelectric material, characterized by the highest possible thickness mode-coupling coefficient. The analysis of the signal was performed with the ultrasonic non-contact analyzer NCA 1000 system, Figure 2 that is based upon the synthesis of a computer-generated chirp with transducer characteristics and advanced signal processing. In general, transducers are designed to produce longitudinal waves (2). This wave depends only on the elastic properties of the material thus they are appropriate for the use in laboratory and field construction material testing.

The study focus was on the use of the processed Integrated Response (IR), which is the attenuation value of the area underneath the signal wave measured in decibels (3). IR_m can be used to measure the amount of ultrasonic energy transmitted (transmissivity) or reflected (reflectivity) from a test material. Using the Equation 1:

Equation 1

$$\mathbf{IR_m = IR_c - IR_a}$$

IR_m is the amount of ultrasonic energy transmitted in the test material, IR_c is the ultrasound transmission through air and the material (between the transmitting and receiving transducers), and IR_a is the amount of ultrasound energy transmitted only through air. IR_c and IR_a are directly measured by the NCA 1000. The IR_m value for the material was then correlated to the Bulk Specific Gravity.

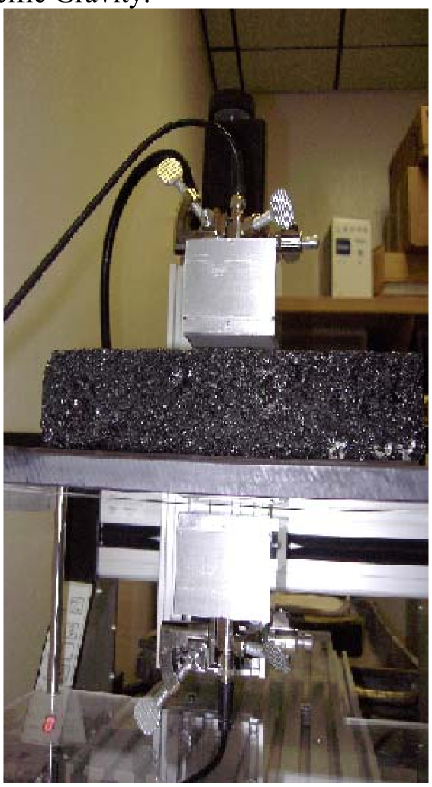

Figure 1- Non-contact mode

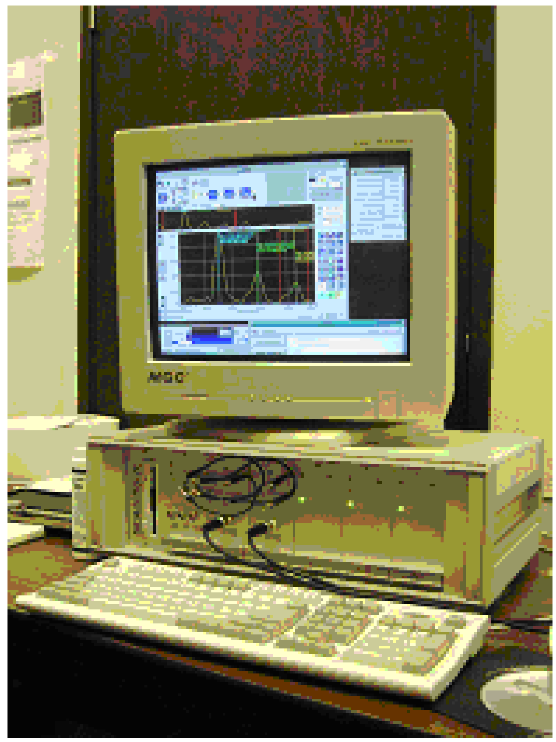

Figure 2- NCU-1000 display

<u>Lab Processing Procedure</u>: The Materials were processed and a mix design determined for the Clark County type 2 coarse specification ranges, Table 3, targeting the mid-range of the specification, which is labeled as the "zero point". The samples were fabricated in sets of three 75 mm x 75 mm x 300 mm beams compacted using a laboratory vibratory device (Figure 3). These samples were varied in gradation and asphalt cement content. The gradation was varied on the 2.6 mm size sieve from the mix design baseline by minus eight percent to plus eight percent. The asphalt cement was also varied from 4.5 percent to 5.6 percent for the same design. The samples were identified (Table 2 column one) and denoted as percent asphalt cement content and the percent deviation from the zero point gradation on the 2.6mm sieve, as exampled in Table 4.

Table 3- Zero point gradation target

Sieve Size	Type 2 Coarse % Passing
1"	100
¾"	84-97
½"	66-82
3/8"	56-72
No. 4	35-50
No. 8	23-38
No. 50	5-19
No. 200	2-7

Table 4- sample Identification Example

Sample number	Definition
4.8% -8 Dev	4.8% asphalt cement -8% Deviation from the 2.6mm sieve as compared to the original mix design gradation.

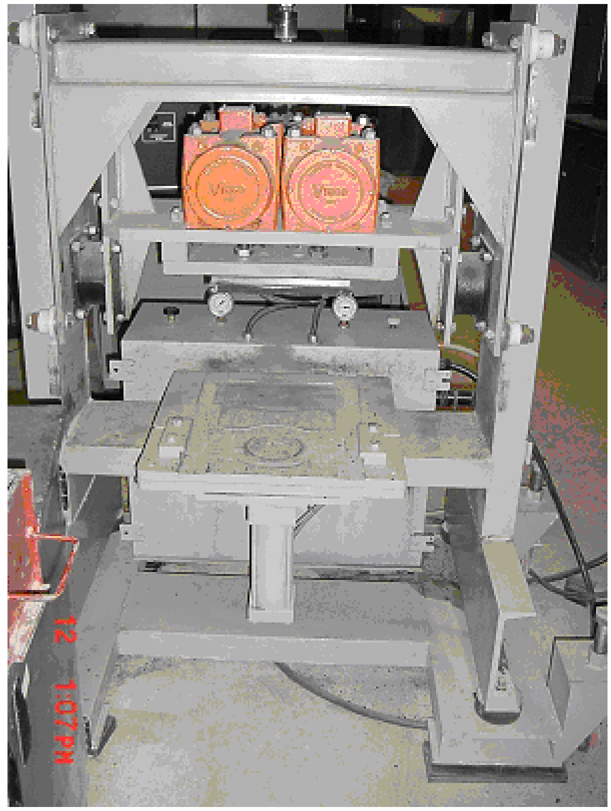

Figure 3- Vibratory beam compactor

Ultrasound Testing: The transducers were checked for a parallel face with the use of a round bubble level and plumb line for the relative orientation. The signal was set for the transducer parameters, Table 5, and visually checked on the computer screen for maximum peak amplitude by adjusting the transducers slightly.

The Chirp signal duration specifications for these transducers can range from 500 µs to 1200 µs. The best visual signal was at 650 µs, which was the setting for all of the testing. Various power amplitude settings were tried for a maximum stable signal with minimum noise. The amplitude was set a 90 percent due to some of the samples texture issues. The signal was then checked for both low (Chirp A) and high (Chirp B) frequency visual uniformity on both ends of the Chirp, Figure 4, and set at 20% and 50% respectively.

The coarser the asphalt concrete, the more detrimental was the affect on the Ultrasound signal. In each case of high scatter, a signal was detected, however the standard deviation of the result was at times high. Through trial and error, it was found that the best method to achieve a consistent standard deviation less than 0.5 db was to use water based medical gel applied to the surface of the sample while maintaining the air gap distance from the sample of about 25mm.

The IR_m, which is the integrated response of the material (area under the processed signal curve), is determined from the IR_c and IR_a, which are the material plus air and the air column only, respectively. The determination of the IR_a is simply the recording of the signal in air, Figure 5 with no sample between the transducers then acquiring a signal with the sample (IR_c), Figure 6. The NCA-1000 has a Quality Control (QC) module that records and generates statistical means and standard deviations of the measurements.

During the trial period for setup of the signal, it is possible to set the amount of signal that will be averaged for which the QC module will use for a record. It was found through the trial that a signal average of 20 was able to reduce the standard deviation to a minimum. The QC module also allows for the averaging of the pulse shots before recording and through trial and is the default on the equipment, was set at 20. Thus the signal shot is an average of 20 readings then 20 each of these readings are detected and averaged for a record on the QC module yielding a mean and standard deviation with n = 20.

Table 5- Transducer parameters

Frequency	112 KHz
Bandwidth	36 KHz
Duration	650 µs
Amplitude	90%
Chirp A	20%
Chirp B	50%

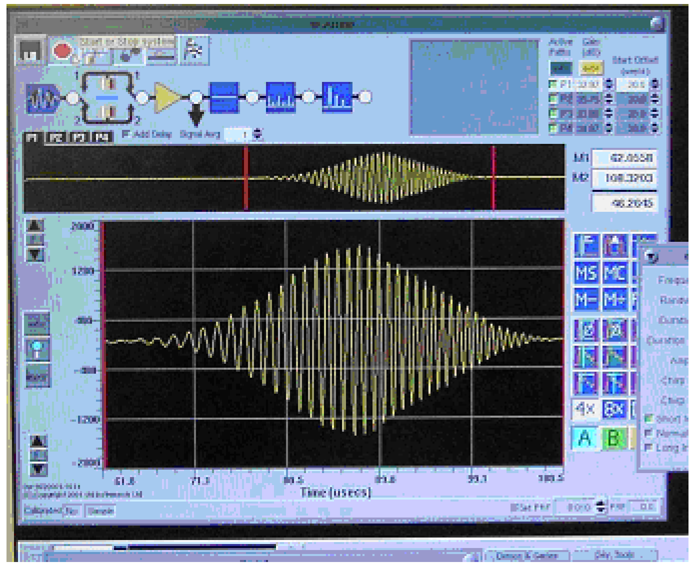

Figure 4- Chirp signal

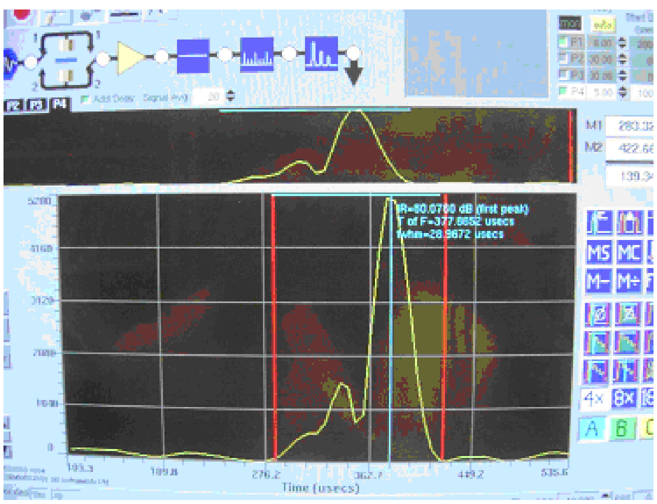

Figure 5- Air Column Signal. IR_a

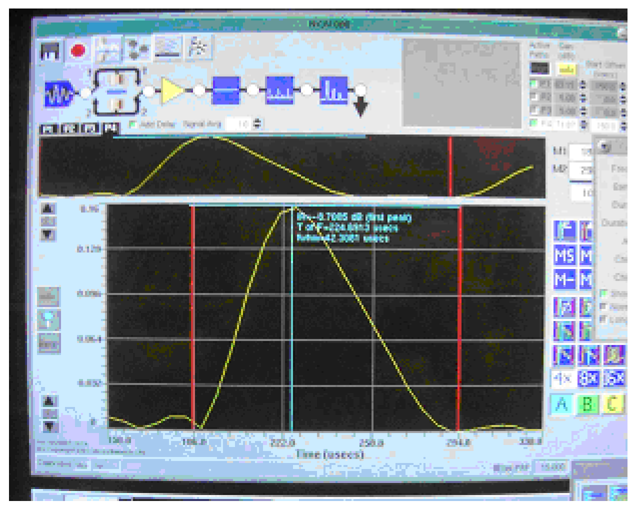

Figure 6- Material and Air Signal. IR_c

During the testing, it was found that the individual sample sets were correlated between the IR_m and the Bulk Specific Gravity (BSG) with R-square values ranging from 0.293 to 0.992 with 7 out of the 9 sets that were above an R-square of 0.70 as demonstrated in Figures 7a and 7b. These high R-square values represent an outstanding achievement for an air-gap non-contact mode. There is no concrete explanation as to why two sets were poorly correlated. However the set “4.8% -8 Dev” was very coarse texture and the key point is that all of the samples in that set contained visual rock pockets. This would have created a much higher attenuation due to the air voids in these pockets.

While the individual sets correlated, a plot of all of the individual samples did not (Figure 8). This would indicate that there is a material property that is tied to both IR_m.

The individual samples were then reduced to using only those that represented a set that had a R-square value above 0.90, Figure 9. The overall correlation is better but not significant. The next plot, Figure 10, is the averaged sets with a R-square value greater than 0.900.

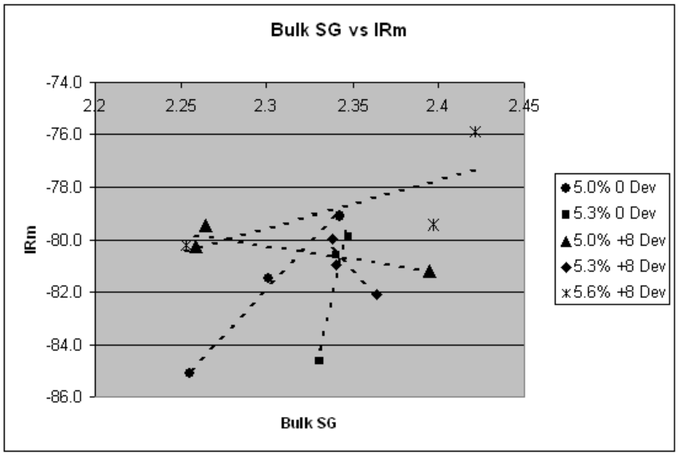

Figure 7a Correlated by sets

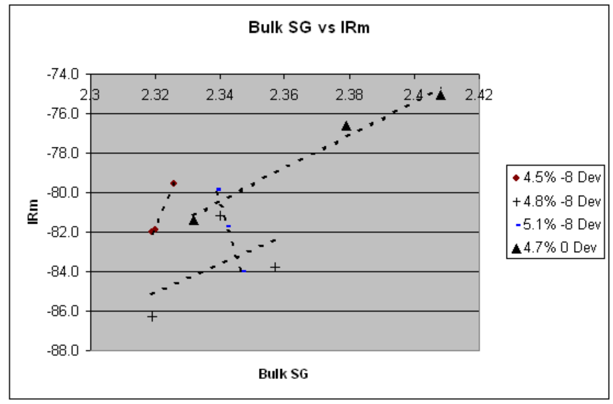

Figure 7b- Correlated by sets

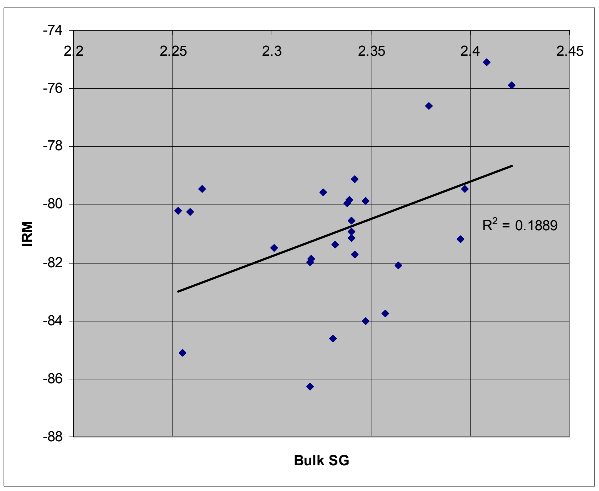

Figure 8- Plot of all of the individual samples

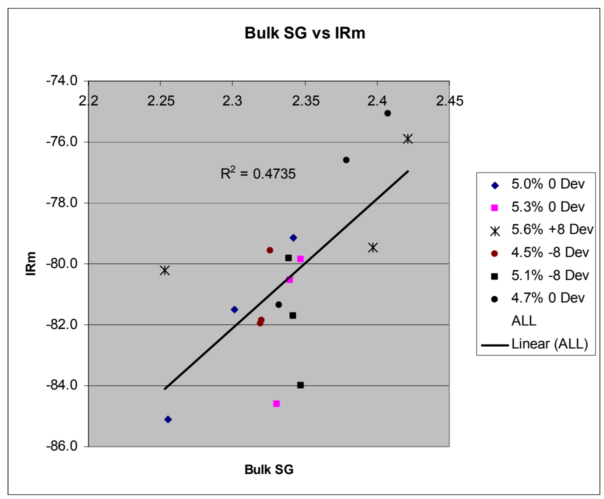

Figure 9- Demonstrating individual samples where the sets had a R-square value above .900

It is interesting to consider that possibly there are two curves in Figure 10, the two data sets below the line plot may represent another linear segment for which there are not enough data sets. However, as demonstrated in Figure 11, there did not appear to be any logical break for another curve set. In this case, a contour of the data would be more appropriate as demonstrated in Figure 12.

Conclusions: The study consisted of fabricating asphalt concrete samples at various gradation and asphalt cement content for the determining a correlation of the bulk density with an acoustical value, in this case, the Integrated Response IR_m. It was found that:

1. There was no correlation when comparing all of the sample data as one population
2. When correlating the samples within a set, there is a strong correlation for 7 out of 9 sets

The successful detection of a strong acoustical signal through asphalt concrete and the strong correlation with a material property with the use of the new non-contact transducers established a baseline for further in-depth study.

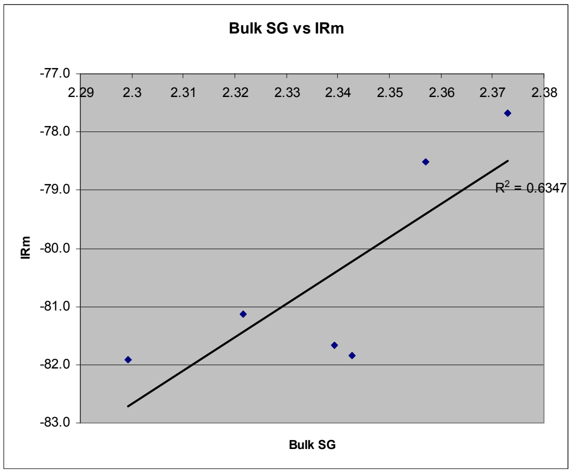

Figure 10- Plot of average sample sets with R-square greater than 0.90.

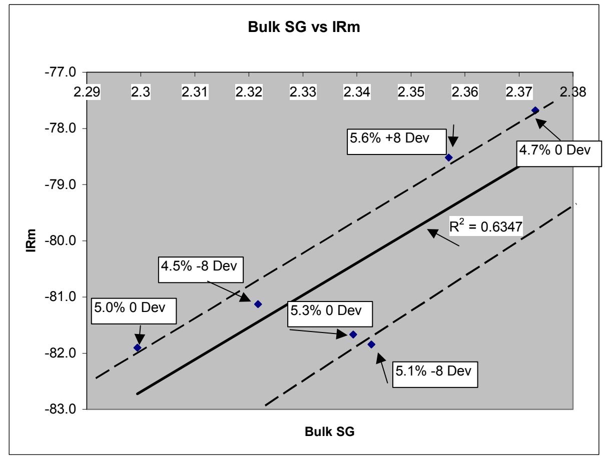

Figure 11- Demonstrating the possible multi-curve set

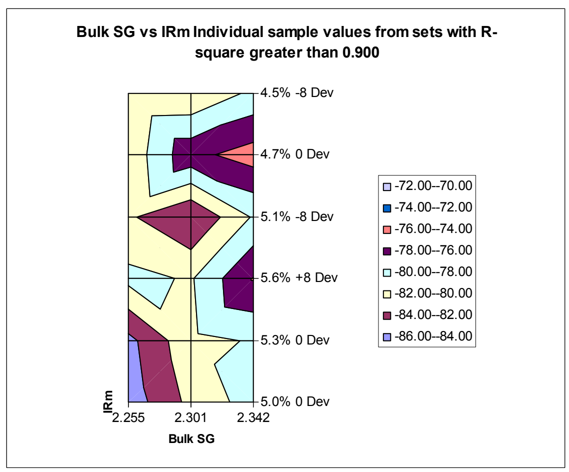

Figure 12- Contour plot of individual sample values from sets with R-square greater than 0.900

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