Reviewing the Testing Protocol for Density Cores Collected from CTDOT during the 2012 and 2013 Construction Seasons

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Disclaimer

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Standard Conversions

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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16. Abstract

Density of cores that are cut from the roadway following compaction on new pavements in CT is used as a quality indicator. This density needs to be determined accurately as it impacts payment. Cores need to contain material from the placed surface without mix adhering to underlying layers in order to be determined accurately. In addition, when cut cores do not have a smooth bottom surface, density may not be able to be determined accurately. More than 1,100 cores from the 2012 and 2013 construction season were collected and analyzed to determine what level of surface relief (or texture depth) would affect accurate measurement, and thus require saw cutting. It was determined that when more than 4.5 mm of surface relief exists on the bottom of a core it should be saw cut to a planar condition to avoid density measurement errors. A gauge was developed at the University of Connecticut to measure texture depth when it is not readily evident that it is greater than 4.5 mm. Recommendations include saw cutting core bottoms to remove underlying material attached to the pavement to be tested, as well as when surface relief is in excess of 4.5 mm. It is further recommended that cores containing less than 4.5 mm of surface relief and having no underlying material attached be measured in their existing condition because there is no benefit gained when saw cutting these cores.

17. Key Words

Hot-mix asphalt pavement, core density, pavement density

18. Distribution Statement
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Introduction and Background Summary

The achievement of proper density during placement of Hot-Mix Asphalt (HMA) is one of the most important aspects of constructing a pavement that will provide a long service life. In recent years, the Connecticut Department of Transportation (CTDOT) has modified their construction specifications to measure the in-place density of HMA pavements at the time of construction by cutting cores and measuring the density of the cores as a basis for payment. Previously, in-place density was measured by CTDOT primarily through the use of nuclear density gauges.

During the process of cutting the cores, the cores for the layer being tested may separate cleanly from the layers below. In other cases, the pavement may have to be cut (cored) well into the underlying layers and broken off in order to remove it from the core hole. In these cases the materials from the underlying layers must be removed before the wearing surface can be tested for density. The use of a chisel to remove the unwanted layers often produces a smooth surface on the bottom side of the core to be tested. In other cases however, the unwanted layer does not separate cleanly, which leaves a very uneven surface on the bottom of the core. This can result from either the wearing surface breaking unevenly or a portion of the underlying paving course remaining on the bottom side of the core.

Some have expressed concern about the potential impact to core integrity when using a hammer and chisel to separate the layers of the cores. An alternative method for removing the unwanted layers is to use a diamond saw to cut between the layers. From previous experimentation conducted by the CAP Lab, the use of a diamond saw to remove the unwanted material will result in a clean separation of layers leaving only the material intended to be measured.

CTDOT uses a vacuum sealing device (as described by AASHTO T331 [1]) for the standard method of testing cores for density. This method uses a soft plastic bag and a vacuum to seal the plastic bag to the core. This method is desirable as it is the most reproducible when compared to the alternative practice of density measurement (AASHTO T166 [2]) where the core is submerged in water and then its saturated surface dry weight is determined. Experience has proven some difficulty with AASHTO T166 for cores with higher air void contents as the length of time taken to dry the specimen to saturated surface dry will allow the water to drain out of the pore spaces, and therefore alter the results. However, there can also be issues with using the vacuum sealing method. Given that the test method assumption is that the surfaces of the cores are relatively smooth, when the chiseling method produces an uneven surface, the density measured can be impacted. It is stated in the AASHTO designation [1] "*Specimen ends or planar edges may require sawing if the bag does not conform to the specimen in a uniform manner*."

Problem Statement

The separation of the unwanted layers from the cores being tested is necessary to accurately measure the density of the layer being tested. In some cases, this separation leaves a very irregular surface during extraction or while removing underlying material with a chisel. The intention of this research was to determine the effect of surface relief on cores that do not have a relatively smooth surface when separated. This research was also intended to produce a recommendation as to the maximum amount of relief that will not have a significant impact on the accuracy of the measured density.

In anticipation of this research, the CAP Lab collected approximately 700 cores from CTDOT during the 2012 construction season. These cores were collected on random days during the construction season and included mat and joint cores from both HMA and Warm Mix Asphalt (WMA) projects. CTDOT forwarded the density testing results for all of these cores to the research team. Several of the cores collected in 2012 were collected at the end of the season and may or may not have been tested by CTDOT.

Objectives

The objectives of the research were to determine the effects of surface relief on the bottom side of a core after splitting the unwanted layers from the core, producing a methodology for measuring the relief on the bottom side of the core, as well as developing a recommendation on the maximum amount of relief that can be allowed to remain on the core without affecting the resultant measured density. In addition, this research sought to examine the effect of taking thin slices (each slice approximately the width of a diamond saw blade) from the bottom of cut cores by measuring density before and after each cut.

Work Plan

The work items associated with this research were:

- Performing a survey of the handling of cut cores within Departments of Transportation in the northeast region. The specific information sought was whether they have smoothness requirements for the bottom of cores and how they remove unwanted material from cores prior to density measurements.
- Collection from CTDOT of cores used for acceptance. The research team requested cores from the CTDOT testing facility to use for analysis of surface irregularity, underlying material and density measurements. The cores were picked up by CAP Lab personnel on random days throughout the 2012 and 2013 construction seasons.
- The collected cores were sorted into surface mat and paving joint cores, and these cores were analyzed in an effort to determine if either of those groups was more prone to having irregular surfaces and therefore in need of being handled differently.
- All of the cores were examined to see if there appeared to be underlying material still attached when they were received from CTDOT. The number and percentage of cores with underlying material on them was recorded

- The cores were categorized as having separated cleanly (i.e. having a thorough separation of material at the interface of the wearing surface and the underlying material) or not.
- Finally, the research team investigated a methodology for quantifying the level of relief or surface irregularity on the bottom of those cores that did not separate cleanly. Once this methodology was developed, the research team determined the maximum allowable amount of surface relief on the bottom of cores before saw cutting becomes necessary for density measurement purposes. This was followed by cutting cores with the most uneven surfaces to remove the "highest" peaks by shaving approximately one saw blade width from the core. Then, the Corelok® (vacuum seal) procedure, which conforms to the standards in the vacuum seal procedure [1] discussed previously, was used to determine how much this changed the bulk specific gravity of the cores. Finally, the amount of the reduced surface relief remaining was measured. This was indicative of the threshold amount of relief present at the bottom of the core that will not affect density.

Review of Regional Specifications

Rhode Island Department of Transportation (RIDOT)

RIDOT supplemental specification [3] indicates that roads not designated as with "Pay Adjustments" will be measured using either a nuclear density gauge or in-place cores. For the roads that are designated as with "Pay Adjustments" compaction levels are to be measured using in-place cores. The specification further states that any cores that are not taken under the direction of the engineer and witnessed by the engineer, will not be used for acceptance. The cores are to be extracted following rolling and prior to opening the section to traffic. The engineer takes immediate possession of the cores upon extraction and retains them for a minimum of four weeks after the results are reported to the contractor. Cores are cut to the full depth of the course being placed. There is no statement indicating the protocol that should be followed if a core separates unevenly or if the core has underlying material from a previously placed layer attached to it.

Massachusetts Department of Transportation (MassDOT)

MassDOT supplemental specifications [4] indicate that the acceptable range of in-place density of asphalt pavements is 95% ± 2.5% of the maximum theoretical density as determined via AASHTO T209 [5]. The engineer is to obtain all of the core samples with the assistance of the contractor, be present to direct the sample extraction and to take immediate possession of the samples. The specification further states that the contractor shall have acceptable coring and core retrieval equipment for the coring operation and that the cores shall be protected from damage. According to the supplement, the cored specimens shall have their G_{mb} determined via AASHTO T 166 [2], AASHTO T 275 [6] and AASHTO T 269 [7]. There are also requirements for determining the random locations of the acceptance cores. There is no language regarding the handling of the cores with respect to uneven separation or the presence of underlying material or specifically how to handle those situations.

New Hampshire Department of Transportation (NHDOT)

NHDOT [8] requires in-place air voids to be determined based on cores in accordance with AASHTO T269 [7]. The specification requires full depth cores containing all new pavement layers to be collected by the contractor in the presence of the Engineer. The specification further states the complete sample (unseparated) shall be transferred to the NHDOT testing lab location. There is no language regarding the method of separation of the pavement layers, removal of underlying material or a procedure for uneven surface.

Vermont Agency of Transportation (VAOT)

VAOT [9] requires acceptance testing of asphalt pavements via core density as determined by AASHTO T 166 [2]. The specification states that acceptance testing is conducted by agency personnel but that the cores are to be obtained and provided by the contractor. The cores are to be obtained in the presence of the Engineer or the Engineers designee. The specification further states that cores must be submitted to the engineer in a suitable container. If the cores are not delivered in a container that is suitable then they are to be rejected. Agency personnel are to process the cores in accordance with the stated method within 10 days and report those results to both the Engineer and the contractor. It is stated that all *cores will be saw cut*. *The contractor shall mark the cores for saw cutting in the presence or the Engineer or the designee for verification of cut locations.*

VAOT also specifies that cores will be used to evaluate the degree of compaction at the longitudinal joint. There is no language regarding saw cutting the joint compaction specimens and there is a statement indicating that joint cores need not be subject to the provisions of the previous specification subsections, which require saw cutting of acceptance cores. There are, however, requirements as to the transverse location of the core with respect to the visible joint line. The location of the core on a longitudinal butt joint is centered over the visible joint line on the surface. The transverse location of the core on a tapered joint is offset from the visible joint line about 50% of the taper width.

Maine Department of Transportation (MaineDOT)

MaineDOT [10] requires that compaction acceptance be conducted via core samples in accordance with AASHTO T-166 [2]. The contractor is to obtain the cores at the specified locations no later than the end of the day following the day that the pavement was placed. The contractor is to turn the core samples over to the department immediately. The cut cores are placed in a container that is provided by MaineDOT. At the time of sampling, the contractor and representative from MaineDOT will mutually decide if the core specimen is damaged and if necessary, obtain a new specimen. Also at the time of core extraction, the contractor and MaineDOT will *mutually decide if saw cutting is necessary and will mark the core at the location where sawing is necessary. It is further stated that the saw cutting may be performed by the contractor in the presence of a MaineDOT representative or by the department in a MaineDOT facility. The specification states that saw cutting is not to disturb the layer being tested and that saw cutting is intended to remove underlying layers of pavement, gravel or RAP.*

New York State Department of Transportation (NYSDOT)

NYSDOT [11] requires that the engineer will select coring locations for each project sub lot. The locations are to be determined after the rolling/compaction process has been completed. The cores are to be obtained no more than 1 day following placement of the material. The specification recommends cooling the pavement if necessary so that the cores are not damaged during the coring process. It is then stated that *If the core sample does not de-bond during coring, do not intentionally separate the pavement core from the underlying material. The Regional Materials Laboratory will separate the pavement core layer required for testing from the underlying material by sawing, if necessary.*

New Jersey Department of Transportation (NJDOT)

NJDOT [12] requires that core samples be cut at random locations determined by the Resident Engineer at least 12 hours after the mat was paved. The specification states that during coring, the full depth of the course shall be recovered for air void determination. It further states that if thickness testing is also required, the core should be drilled through the full depth of the pavement. The department will then test the full depth cores for whatever thickness measurements are required as well as surface course air voids. There is no mention of the method to remove underlying layers.

Collection and Processing of Acceptance Cores from CTDOT

CAP Lab personnel traveled to the CTDOT central testing facility on several occasions during the 2012 and 2013 construction seasons to collect cores that may have been used for acceptance purposes. In an effort to collect cores in an unbiased manner, the days when CAP Lab personnel collected cores were chosen at random. The purpose was to obtain a snapshot of several random days involving multiple construction or paving projects and multiple paving contractors.

A total of 717 cores were collected from CTDOT during the 2012 construction season. This included a combination of both joint and mat cores. An inventory database of the cores was developed in order to designate cores that separated cleanly and those that did not. The database was developed with FileMaker® Pro. The data entry fields included the following:

- Project #
- Lot #
- Producer/facility
- Mix Type
- Gmm (from CTDOT acceptance data)
- Gmb (from CTDOT acceptance data)
- Placement Date
- Core ID
- Mat or Joint Core
- Clean or Unclean Separation
- Initial Core Thickness as determined by ASTM D 3549 [13]
- Final Core Thickness (if core was saw cut)
- Underlying Material Present (yes/no)
- Initial Image of the Bottom of the Core

It was observed that there were several cores retaining underlying material (base course or binder course), which was not removed. The amount of material ranged from an entire layer to a partial layer attached to the bottom side of the cores. An example of such a core is shown in Figure 1.

Figure 1. Core with Partial Underlying Layer Attached

At this point CAP Lab personnel along with CTDOT acceptance testing personnel spent time experimenting with underlying layer identification methods. The group also spent time experimenting with different methods of separating those identified layers including chisel method and the saw cutting method. During this process inventoried cores were damaged through experimentation and could not be used for any sort of surface texture analysis. It was then decided that this investigation would be extended to involve the collection of cores from the 2013 construction season as well.

CAP Lab personnel with assistance from CTDOT acceptance testing personnel collected an additional 426 cores on random days over the course of the 2013 construction season. All of the necessary testing data and information was provided by CTDOT with the 2013 cores, as well. Random checks were made to verify the accuracy of the initial reported bulk densities from which there were no discrepancies. A negligible number of the cores collected during the 2013 season contained any observable underlying material. In addition, there were 190 (of the 426) cores collected from the 2013 season that did not separate cleanly. It should be noted that the research team was calling a separation unclean if there was any sign of irregular surface relief, noticed through simple observation. This means that there are (were) varying degrees of unclean separation of the pavement layers as it was unknown at that point in time what an acceptable amount of surface relief was. Figure 2 provides examples of two different levels of unclean separation, as they were termed for purposes of this research.

Figure 2. Different Levels of Unclean Separation on Cores

These 190 cores in addition to the cores that were remaining from the 2012 collection became the pool of samples, which were selected from at random for measurement of surface relief and density.

Determination of Surface Relief Measurement

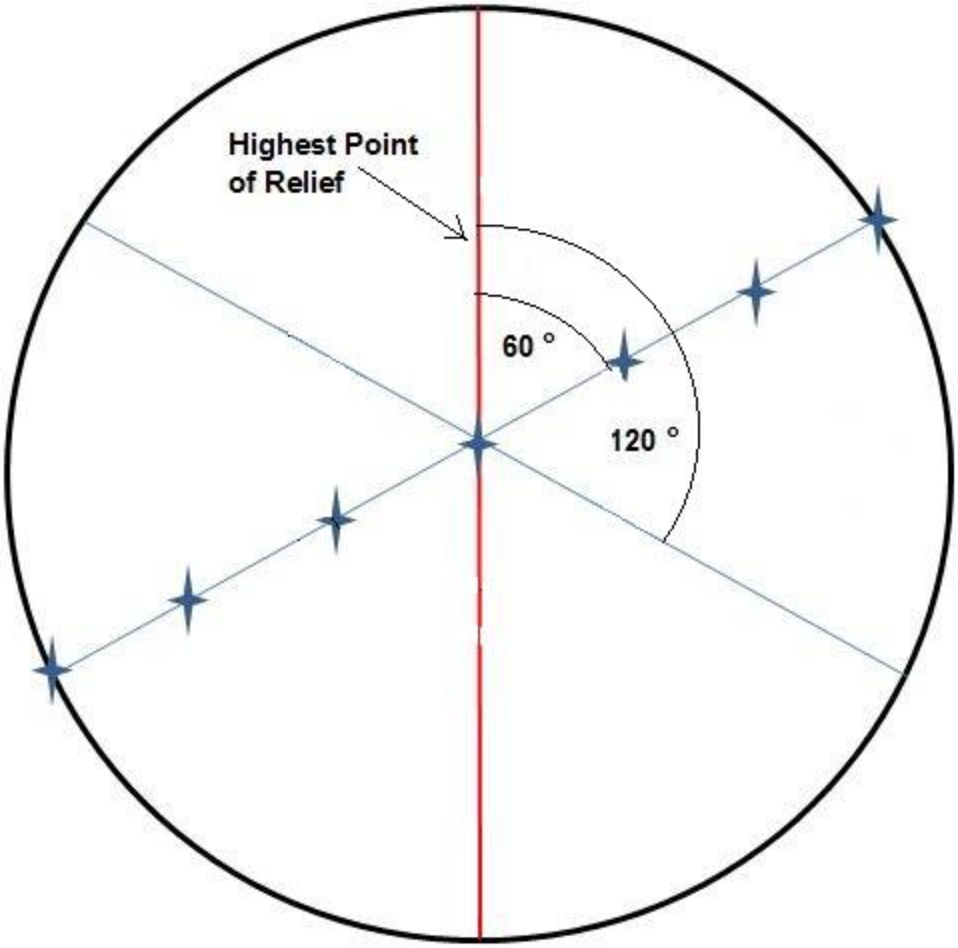
Several attempts at measuring surface relief were made. The first was the highest and lowest point on the irregular surface from the face/top of the core, measured with digital micrometers. Given the varying amount of relief between the highest and lowest point of a given core, (especially on cores with higher levels of surface texture) this method was quickly abandoned.

The next attempt involved using a contour duplication gauge as shown in Figure 3.

Figure 3. Contour Duplication Gauge

This method involved pressing the gauge down evenly to match the contour of the irregular surface plane for three locations on the core bottom surface. The locations of lines for measurement were selected by first using a diameter that crossed the highest peak on the surface. The other two lines of measurement were then selected to be at 60° and then 120° from the first measurement line as shown in Figure 4.

Figure 4. Core Contour Relief Plan



Measurements were then taken with digital micrometers from the base of the contour gauge to the point at which the gauge came into contact with the core at seven points along the core as shown by the star graphics along one of the measurement lines in Figure 4. This was repeated on all three lines on the cores' bottom surface. This provided 21 measurements of relief at 19 locations. The 21 relief measurements were then summed to give a value that was intended to be used as a singular relief value, which could then be compared to density as saw cuts were made.

There were problems associated with this method, as well. First, the operator had to be sure that contour gauge was being lowered onto the core in a manner that was parallel to the top of the core, which proved difficult. The contour gauges also did not fair very well with all of the measurements that were made resulting in damage to the gauge itself. These measurements took an unreasonable amount of time to obtain. Finally it was found that this method was not repeatable or consistent as the amount of relief on the core was quite variable, and measurement on three lines may not have been enough to enumerate the relief.

The research team then took the approach of measuring the core density after a saw cut was made and comparing that density to the initial density. After this, a second saw cut was made, which, for the majority of the cores, left no more relief on the core. Each time a saw cut was made the width of the cut was as close as possible to the width of the blade on the saw. That width is 4.5 mm. The intention behind this approach was to gain insight as to what effect sawing off irregular surfaces would have on density. If sawing off one blade width on the core surface had little or no impact on density then perhaps saw cutting of certain cores would not be necessary for obtaining accurate density readings.

Eighty cores with irregular surfaces, but containing no underlying material, were selected for this analysis. This included both mat and joint cores of varying initial density from 24 projects. The data from 72 of these cores was used for the analysis as there were eight values that were determined to be statistical outliers as tested via the Modified Thomson Tau method. In addition to those 72 cores, a group of 23 cores, which were deemed to have no measurable surface relief, were selected for comparative analysis. The data from 21 of these cores was used for the analysis as there were two values that were determined to be statistical outliers as tested via the Modified Thompson Tau method.

In an attempt to avoid confusion among the groups of cores which underwent comparison, the following categories of conditions were established:

- Condition A – No noticeable surface relief. Core surface was considered to be smooth.
- Condition B – Core surface was considered smooth after one saw cut, which was the width of the saw blade. Core initially had 4.5 mm or less of surface relief depth.
- Condition C – Core surface was considered smooth after two cuts, each cut being the width of the saw blade. Core initially had more than 4.5 mm of surface relief depth.

Table 1. Categorized Core Conditions

Core Condition	Description	Surface Relief Depth	# Saw Cuts Needed
A	**Core surface is smooth**	0 mm	0
B	**Core surface slightly irregular**	≤ 4.5 mm	1
C	**Core surface excessively irregular**	> 4.5 mm	>1

*** Saw blade cuts are 4.5 mm in thickness**

Results of Saw Cutting and Resultant Density

All of the cores with irregular surfaces were cut for the initial analysis involving one saw cut (removal of 4.5 mm). 25 of those core surfaces were completely planar after one cut and did not require an additional cut. 43 of those cores were in need of one additional cut (removal of > 4.5 mm) to become completely planar. Table 2 shows the change in density from the initial condition to the density after the first cut, and the density after the second cut of those cores requiring an additional cut. These numbers reflect conditions after the removal of statistical outliers from the data pool.

Table 2. Change in Density After Saw Cuts

# of Cores	Saw Cuts to Become Planar	Relief Removed	Increase in Density (% MTD)
25	0 to 1(first cut)	4.5 mm	0.27
43	0 to 2(both cuts)	9.0 mm	0.88

***Original density was the density measured and reported by CTDOT**

It is readily seen from Table 2 that those cores needing only one cut to become totally planar with respect to surface texture resulted in an average increase in density of 0.27% of maximum theoretical density. The cores that required two cuts to become planar had an average density increase of 0.88% of maximum theoretical density. To statistically verify that this disparity between Condition B cores and Condition C cores is significant, a Student's t-test was performed using a two-sample test and assuming unequal variances. The results are displayed in Table 3.

Table 3. Student's t-test after 1^{st} and 2^{nd} Saw Cut

	Δ Density* (B cores)	***Δ Density*(C Cores)***
Mean	0.268822177	0.883556754
Variance	0.067492619	0.164438626
Observations	25	43
Hypothesized Mean Difference	0	
df	65	
t Stat	-7.610888572	
P(T<=t) one-tail	7.16925E-11	
t Critical one-tail	1.668635976	
P(T<=t) two-tail	**1.43385E-10**	
t Critical two-tail	1.997137908	

The p-value is essentially zero so it is without question that saw cutting the cores needing only one saw cut has a statistically lower effect on density than those in need of two cuts.

A remaining question is what part of the average 0.88% measured change in density is a result of the inability of the plastic bag to conform to the specimen during the CORELOK AASHTO T331 method, and what part may be due to a lower density at the bottom 9 mm of a pavement layer as a result of construction compaction, compared to the upper portion of the core.

If there is no error with the AASHTO T331 test, and all of the average 0.88% change is due to lower density at the bottom of the pavement layer, then the question arises: Why would the average density change (0.61%) from 4.5 mm to 9 mm from the bottom of the core, which is more than twice as much as the change in density of 0.27% from 0 to 4.5 mm (the lowest section) of the "A" cores?

It appears then that the results found are a combination of the two conditions. Based upon the evaluation of the designated "A" cores, the average change in density due to distance from bottom of core might be assumed at 0.27% per 4.5 mm, or alternatively a 0.06% increase per mm from the bottom. With that assumption made, the change in density for the bottom 9mm should be approximately 0.54%, (0.06% X 9). The actual measured average change of 0.88% minus the theorized 0.54% due to assumed change in density equals 0.34%, which is the additional average density change found for the "C" cores. This additional 0.34% average density change could be attributed to error during the AASHTO T331 Test, (when a rough core surface is in excess of 4.5 mm).

It was then necessary to determine if the average value of 0.27% increase of maximum theoretical density percentage on the cores needing only one saw cut warranted the extra work of saw cutting or if those cores were close enough to planar that saw cutting may not be necessary. This was done by comparing those cores to a group of cores that separated perfectly but were cut once as well. Twenty three cores from the pool of remaining cores were identified as not needing to be cut and selected at random. They were then cut one time shaving off only one saw blade width. Table 4 shows the comparison of the change in the mean density value as well as the statistical comparison of the group. Note that only 21 observation values from the group needing zero cuts were used as two of them were deemed statistical outliers.

Table 4. Student's t-test Condition A Cores vs. Condition B Cores

	Δ Density* (A cores)	***Δ Density* (B cores)***
Mean	0.281673684	0.268822177
Variance	0.062966529	0.067492619
Observations	21	25
Hypothesized Mean Difference	0	
df	43	
t Stat	0.170250585	
P(T<=t) one-tail	0.432805799	
t Critical one-tail	1.681070703	
P(T<=t) two-tail	0.865611597	
t Critical two-tail	2.016692199	

With a t-statistic well under the critical value and a p-value of 0.87, it is clear that this analysis points towards a statistical similarity between these two groups of cores. This lends credence towards the notion that the cores needing only one saw cut to become completely planar may not need to be cut at all as they behave statistically the same as cores that don't need to be cut. That is, Condition B cores are statistically the same as Condition A cores and there is no benefit gained from saw cutting. It can also be seen that cutting the bottom layer off of a core that is planar starts to increase density (although not statistically significant). This is likely due to the removal of a blade width of material over the complete cross section of the core. This should be expected with the removal of that amount of material from the bottom of the core.

An argument could be made that the dissimilar distribution of air voids among the two different sets of cores from Table 4 could bring the statistical values in this analysis into question. Because of this possibility, the research team made the decision to compare the average difference in bulk specific gravity after both the first cut and the second cut of the cores to the single-operator precision acceptable range of two results as defined in AASHTO T-331 [1]. These are values that AASHTO states to be the acceptable limit of difference between two sets of results. The results are shown in Table 5.

Table 5. AASHTO T-331 Precision Comparison of Bulk Values After Saw Cuts

1st Cut ΔG_{mb} (Cores B)	2nd Cut ΔG_{mb} (Cores C)	AASHTO 1 Operator Precision Limit
0.004	0.014	0.035

Although both groups fall within the acceptable precision limits of the test, it is clear that the group of cores needing two cuts (the C cores) comes much closer to approaching the acceptable limit than the group which was only cut once. Finally, a statistical comparison of the change in G_{mb} among those two groups was conducted. The results of that comparison are shown in Table 6.

Table 6. Student's t-test 1-Cut Cores and 2-Cut Cores

	Δ Gmb (B cores)*	*Δ Gmb*(C Cores)*
Mean	0.004308048	0.014159563
Variance	1.73335E-05	4.22313E-05
Observations	25	43
Hypothesized Mean Difference	0	
df	65	
t Stat	-7.610888572	
P(T<=t) one-tail	7.16925E-11	
t Critical one-tail	1.668635976	
P(T<=t) two-tail	**1.43385E-10**	
t Critical two-tail	1.997137908	

Given the low p-value in Table 5 it cannot be concluded that the difference in the averages of these two groups of data is due simply to chance. They are statistically different even though they are within the AASHTO precision limits shown in Table 5. There was also the increase of more than 0.88% density on the Condition C cores shown in Tables 2 and 3. There is a discrepancy among the analyses shown in Tables 3, 5 and 6. The statistical comparisons shown in Tables 3 and 6 indicate these groups of cores are different while the AASHTO precision statement shown in Table 5 indicates that the changes in density among the two groups are the same. It is the opinion of the research team that because they are statistically different that they be treated that way.

Given the analyses shown in Tables 2 through 6, it is the opinion of the research team that cores needing to be cut a second time to become completely planar (Condition C cores) are subject to a significantly increased possibility of accuracy error when being tested via AASHTO T-331 relative to those cores that separate cleanly (Condition A) and those only needing one cut (Condition B) to become planar.

In an effort to examine whether or not mat cores should be treated differently than joint cores, similar analyses were conducted separating each group (A, B and C) into those respective categories. The results of those analyses are summarized in Table 7.

Table 7. Mat and Joint Core Analyses Results

Group	# Cores	% Group	Δ Density	StDev	% of Change	(A) Cores
Mat	13	62%	0.35	0.2	0.217	
Joint	8	38%	0.17	0.28	0.0646	
					0.28	**Total Δ Density**

Group	# Cores	% Group	Δ Density	StDev	% of Change	(B) Cores
Mat	14	**56%**	**0.32**	0.23	0.1792	
Joint	11	**44%**	**0.2**	0.18	0.088	
					0.27	**Total Δ Density**

Group	# Cores	% Group	Δ Density	StDev	% of Change	(C) Cores	
Mat	29	**62%**	**0.27**	0.57	0.3534		**After one cut**
Joint	18	**38%**	**0.44**	0.63	0.2394		
					0.59	**Total Δ Density**	

Group	# Cores	% Group	Δ Density	StDev	% of Change	(C) Cores	
Mat	26	**60%**	**0.8**	0.36	0.48		**After two cuts**
Joint	17	**40%**	**1.01**	0.44	0.4		
					0.88	**Total Δ Density**	

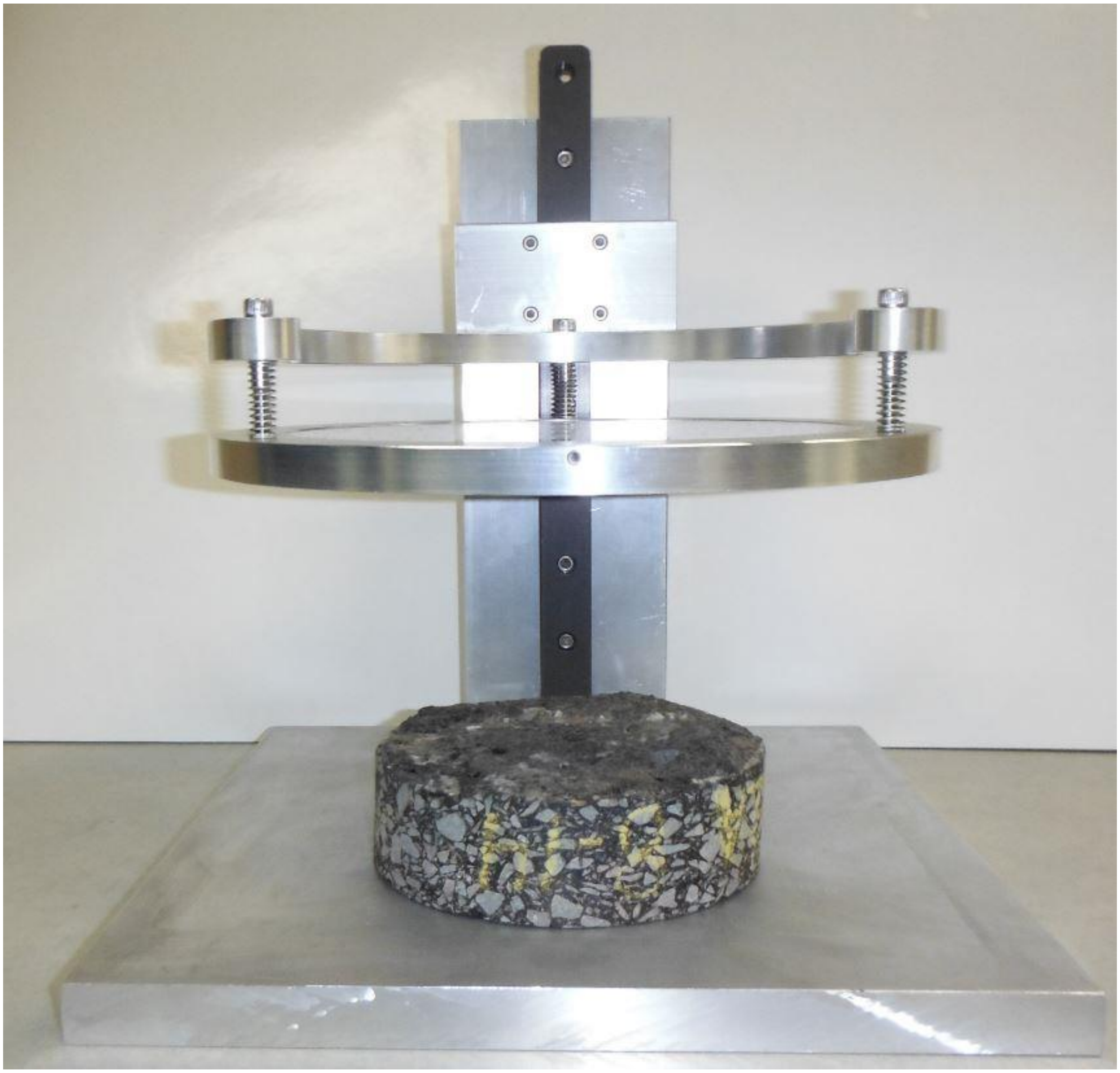
Because the percent of change contribution for both mat and joint cores for each of the groups was a significant portion of the total percent change as shown on Table 7, the research team is not of the opinion that they need to be treated differently.

Determination of Cores to be Saw Cut

It was discussed in the previous section that cores in which one saw cut was adequate to make the surface planar, (Condition B cores), do not need to be saw cut at all to achieve accurate density results. Cores identified as needing to be cut more than 4.5 mm (Condition C) in order to be made planar need to be saw cut to negate any potential for error in determination of density. The problem with this paradigm is accurately determining which cores need to be saw cut and which ones do not, and making this determination in an expedient manner (which are the Condition B vs. C cores). The diamond saw blade that was used for this study was 4.5 mm in thickness. 4.5 mm of surface irregularity then is the threshold for determining which cores need to be saw cut. It should be readily evident to the practitioner that cleanly separated cores will not have 4.5 mm of surface irregularity and as such, do not need to be cut. Other cores may be clearly broken to the point where it is obvious that more than one saw blade width would be necessary to bring the core to a planar texture. For some cores, however, it is not readily apparent what amount of surface irregularity exists. It may not be possible to make that determination through visual examination alone.

The CAP Lab in cooperation with UCONN Technical Services Department developed a simple surface texture depth gauge to determine whether a core will need to be cut based on the 4.5 mm blade width, which was used for this research. The core surface texture depth gauge is shown in Figure 5.

Figure 5. Core Surface Texture Depth Gauge



The gauge is constructed from a combination of stainless steel, glass and a nylon slide. To operate the gauge a core must be located face down on the center of the base plate as is seen in Figure 5. A 4.5 mm ball bearing is then placed in the deepest crevice of the surface as shown in Figure 6.

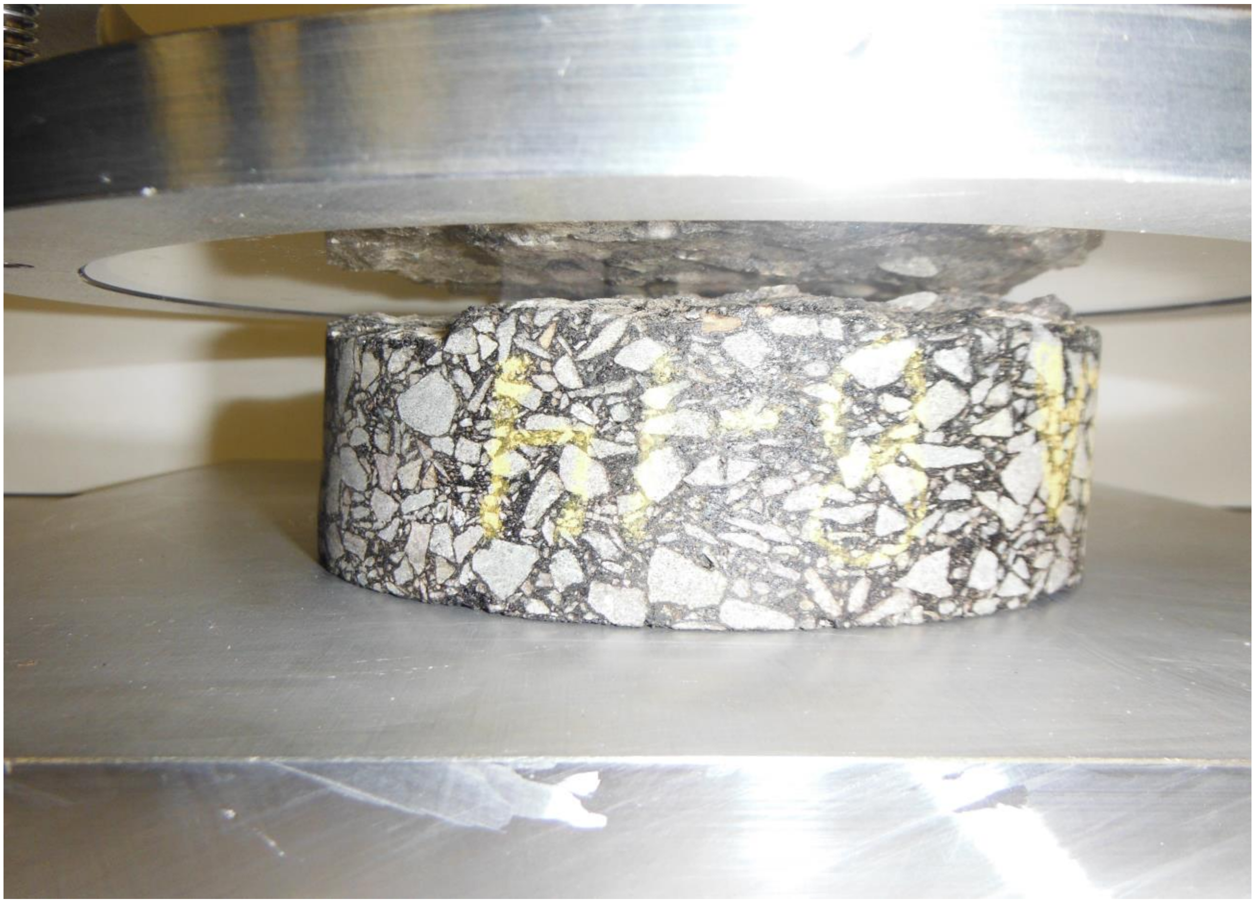
Figure 6. Ball Bearing Placed in Deepest Crevice of Core

The glass plate is then lowered down the slide until it comes into contact with either the core or the ball bearing as shown in Figure 7 and Figure 8.

Figure 7. Texture Gauge Glass Plate Lowered onto Core via Slide

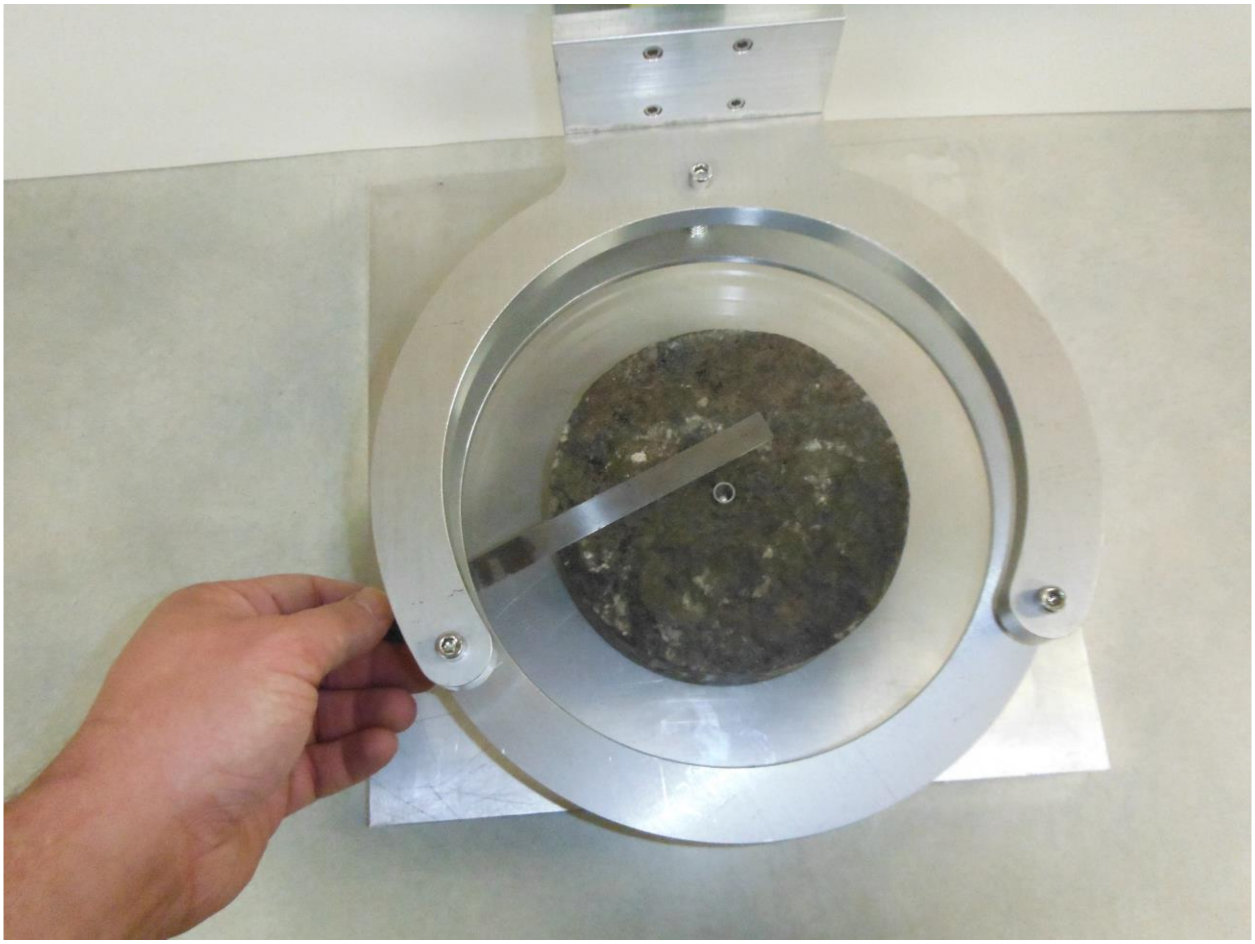
UCONN has available drawings and sketches of the gauge. There are springs that expand underneath the frame to the glass plate that allow for a small amount of vertical movement. It may be desired that the neck of the gauge be fitted with a pivoting head to accommodate cores that are not parallel from top to bottom.

Figure 8. Texture Gauge Glass Plate in Contact With Core



If the glass plate comes into contact with the ball bearing and not the core, then the amount of surface relief on the core is less than 4.5 mm. In that case the core would not need to be saw cut. If the glass plate contacts the core without contacting the ball bearing then the relief is in excess of 4.5 mm and the core should be saw cut. If it cannot be visually determined what the glass plate is contacting, a piece of very thin gauged metal or feeler stock or even a piece of paper can be slid between the glass and core until it stops. The point of contact can then be observed through the glass plate. This is shown in Figure 9.

Figure 9. Thin Gauge Metal Used to Determine Glass Plate Contact Point



Conclusions

Surface irregularity of cores can cause errors in density determination when tested in accordance with AASHTO T-331 [1]. The surface irregularity has the potential to prevent the plastic bag from coming into complete contact with the core, which may result in measurement errors. These errors have the potential to impact results as cores are cut and density is measured. It was determined that cores with surface irregularity in excess of one diamond saw blade width of 4.5 mm (Condition C) can have statistically significant errors in density accuracy per the analysis shown in Table 6. These errors in density measurement accuracy may be in combination with a higher void level on the bottom of the core. Surfaces that would only need to be cut one saw blade width or less to become completely planar (Condition B) were shown to exhibit a statistically insignificant change in density after a saw cut. It is difficult to quantify the surface irregularity of a core. Practitioners will quickly recognize cores that separated cleanly during the extraction process as not needing to be saw cut (Condition A) prior to determining density. They will also quickly recognize when cores contain underlying material or separated uncleanly to the point where it would take multiple sawblade width cuts to make the core surface completely planar (Condition C). Not all cores falling within the limits of this spectrum will be determinable visually. The CAP Lab in conjunction with the UCONN Technical Services Department developed a core surface texture depth gauge, which may serve as an accurate and reproducible method of making this determination where visual analysis will not suffice. The design of the core surface texture depth gauge is well documented and information needed for reproduction of the gauge is available through the CAP Lab.

Recommendations

Based upon the information gathered over the course of this study the research team makes the following recommendations:

- Proper and careful core cutting through the desired layer and extraction should be emphasized to contractors
- There is no reason to consider handling joint cores differently from mat cores because the density changes after various saw cuts produced statistically similar results
- Cores that contain underlying material attached to the bottom from underlying pavement layers should be saw cut at the interface to remove underlying material
- If less than 4.5 mm needs to be removed (Condition A and B as defined by this report) to make the core completely planar then the core does not need to be saw cut
- Cores that did not separate cleanly and clearly would need to have more than 4.5 mm removed (Condition C) to become planar should be saw cut
- Cores that cannot be easily determined to be in need of saw cutting should be analyzed with the core surface texture depth gauge developed at UCONN
- 4.5 mm ball bearings should be used to make the determination with the core surface texture depth gauge because that is the width of the saw blade used to make the cuts associated with this research
- CTDOT may wish to consider a process change that would require all acceptance cores that did not separate cleanly to be saw cut. This would alleviate the steps needed to determine whether a cut is necessary (i.e., steps defined above)

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