The Application of CT Technology to the Experimental Study of Highway Icing

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1. ABSTRACT

The applicability of CT technology to the study of highway icing and its use in studying an ice adhesion enhancing mechanism referred to as “keying” were investigated. An understanding of the relationships between the texture of a roadway's surface and the adhesion ice and its control may be greatly furthered if experimental investigations can be made at the scale of the surface and surface connected voids. The ability to examine one sample, in various states (dry, wet, ice covered etc.) along a particular cross-section is particularly desirable for observations at the surface level. Cross-section images obtained via x-ray CT were found to provide acceptable resolution and be of sufficient quality for use in observing and measuring several surface connected void parameters. Observation of the infiltration patterns and the extent of infiltration of several materials, water, ice and anti-icer, may be of interest in icing studies. Because the density of bitumen is the same as water and very close to that of ice and anti-icers a clear distinction between the materials in a CT image can be difficult or impossible. Clear observation was found to be possible if a dry state reference cross-section was subtracted from the identical cross-section image of the same specimen when water, ice, or anti-icer were present.

An mechanical mechanism that may enhance the adhesion of ice to pavement, “keying”, was studied for three pavement types, super pave, grade b, and chip sealed. Grade b was found to have the smallest key width (0.39mm) of the three pavements (1.78 mm for chip sealed and 1.34 mm for super pave). Grade b also had the smallest ratio of total keyway width to pavement length of the three, 0.109, 0.146, and 0.503 respectively. In terms of the force required to lift ice from the surface of each, in the absence of all other adhesion mechanisms and friction grade b would require the least force. The widths of the surface opening (shear line) into the keying voids was also measured. Grade b had the smallest average length of 1.03 mm vs. 4.43 mm for super pave and 5.27 mm of chip sealed. The ratio of the total shear line length to pavement length was largest in the chip sealed, 0.57, followed by grade b at 0.13 and super pave at 0.09. The shear lines are related to the force required to shear the ice “keys” at the pavement surface.

2. Introduction

During the winter, maintenance activities by Transportation Departments are often concerned with the persistence of ice and snow on roadways. Actions taken to control snow and ice are typically plowing, sanding, and application of anti-icing and deicing chemicals. Anti-icing and deic-

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ing chemicals are freezing point depressants. The terminology refers to the time of application, that is, prior to an anticipated icing event or after the fact [1].

Basically there are two ways in which roadway icing occurs. One results when liquid water present on a road surface subsequently freezes. The other arises due to vehicular compaction of road snow cover. The mechanisms responsible for the ice to pavement bond determine the strength of that bond. Ultimately chemical application aims to reduce the strength of the ice-pavement bond [2] for effective ice and snow removal.

Bonding of ice to pavement is partly due to surface adhesion. It may be enhanced through a mechanism called “keying”. Water, in the liquid or solid state, can key by flowing into cavities at the pavement surface. The cavities function like keyways into which a key fits. Keying of snow is likely to occur primarily through compaction and perhaps temperature related viscous flow.

Experimental verification of keying is problematic. To make the observations it is necessary to examine the interface of a layer of bonded ice or snow to pavement. One of the ways in which such an observation might be made requires that a sample be sliced into two parts to expose a cross-section of the ice-pavement interface. Cutting pavement generates considerable heat [3] which will alter the insitu ice morphology.

An experimental investigation was conducted which aimed to verify the existence of “keying” using a non-destructive imaging technique, namely x-ray CT (x-ray Computed Tomography). The investigation was carried out in two parts. The first dealt primarily with issues concerning an ability to observe a pavement’s surface structure. In addition the technique was applied to water, ice, and anti-icers at the pavement’s surface and within its surface connected voids by using cross-section images produced via x-ray CT. The second part, which was dependent upon results of the first, was aimed at verifying the presence of a “keying” mechanism and provide some preliminary measurements of size and frequency of occurrence in three different pavements types, grade b, super pave, and chip sealed.

For CT imaging of pavement to be useful as an investigative tool which can be used in place of traditional section and polish techniques it must, at the least, provide access to the same information. Section and polish techniques provide access to the internal geometric state, i.e. arrangement of aggregate, air voids, and bitumen. Observations of water within voids or ice cover attachment at a pavements surface are not feasible with traditional methods since the process of sectioning usually requires application of water to cool the cutting blade. A tool that allows imaging of a wet, dry, with ice cover, etc. pavement samples, in such a way that the state is not altered during the imaging procedure, is of considerable interest. One of the major goals of this project was to determine if x-ray Computed Tomography would be such a tool.

Experimental investigations requiring observations of a material's internal structure have traditionally relied upon physical sectioning techniques. A major disadvantage of physical sectioning is that it destroys the sample and may even modify the structure along the sectioning plane. A non-destructive approach to observing a material's internal structure is X-Ray CT, which will be referred to in the report as CT. Its capabilities and limitations as a tool for investigating highway icing are currently undocumented. In this study interest is centered on observing pavement surface and surface connected voids as well as the penetration of liquid water, ice/snow, and anti-icers into these voids.

3. A Brief Description of X-Ray CT

CT is a tool that can be used to non-destructively inspect the internal structure of a material. In CT, radiographs, i.e. x-ray pictures, are digitally recorded. To produce a digital cross-section of material requires two steps. During the first step, a specimen is rotated through 360 degrees in a set of discrete increments. At each increment a digital radiograph, or projection, is obtained. A projection is an x-ray picture of only a thin slice of the body (Figure 1). All of the projections are of the same slice. In step two the projections become the input to a mathematical routine [4] which produces as output a picture of the original slice.

X-rays, with energies less than 1.022 MeV, interact with a material body by absorption and scattering. As a result, the original x-ray beam is attenuated so that the intensity of the beam exiting the material is reduced from its original value. For a mono-energetic beam, the amount of attenuation over a distance depends upon the energy of the incident x-rays and upon the material itself [4] (density and chemical composition). The reconstructed image is a map of the x-ray attenuation of every point of the cross-section. Each image point, or pixel, has a value which is a measure of the average attenuation of a small volume of material containing that point. The numeric values, gray levels, are integers between 0 and 65565 for the camera used in this scanner.

The MSU CT scanner can resolve features, depending upon scanner configuration, ranging from 25 to 200 µm. 15 cm is the maximum diameter allowed of specimens when scanning at 200 µm resolution. At 100 µm resolution a specimen may have a maximum diameter of ≈ 11 cm. A specimen can have no more than approximately a 2 cm diameter with the system at a 25 µm resolution. It was determined in this study that, for pavements, a good compromise between sample size and resolution is the 11 cm maximum diameter and 100 µm resolution.

Three important scan parameters are the X-ray voltage, the number of projections per scan, and the exposure time for each projection. As already stated, the amount of attenuation is dependent upon the x-ray energy. That energy is adjusted through the voltage. The best pavement images were obtained for x-ray voltages of greater than 110 kv. Generally the lower the kv the

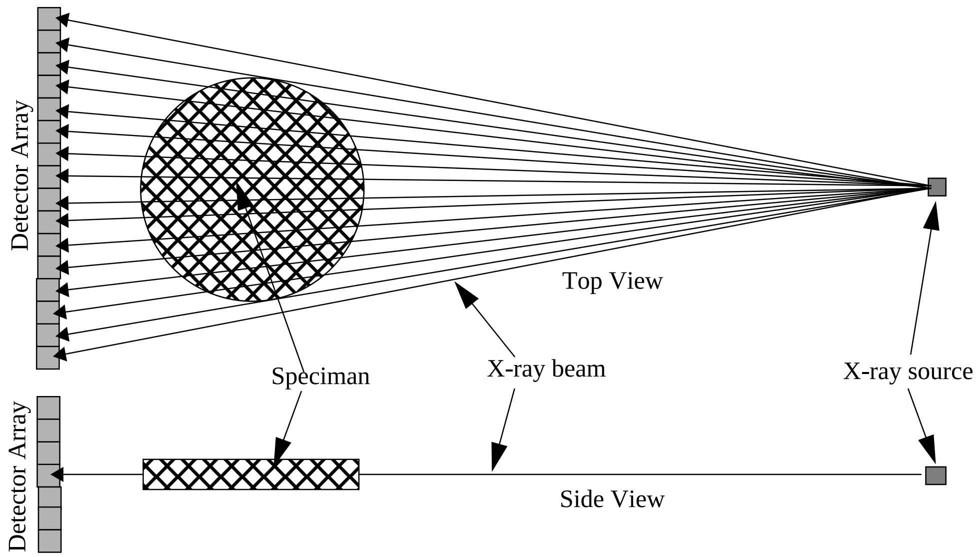

Figure 1. Top and side view of the relationship between an x-ray beam plane and specimen. The x-rays used to image a specimen all lay within a thin plane which passes through the specimen.

better the resulting image contrast. The disadvantage is that longer exposure times are required. It was found that for voltages of 120 kv, exposures times of 3 seconds per projection were adequate. Most of the images in this report were reconstructed from 360 projections. It was found that 360 projections were the best compromise between total scan time (≈35 minutes, 3 second exposure per projection) and image quality.

4. Pavement Imaging By X-Ray Computed Tomography

The first project question to be answered was whether additives such as water, ice, and anti-icer could be distinguished from pavement's constituents, bitumen and aggregate. For visual identification of additives to be effective there must be sufficient separation between their respective gray value and the gray value of each pavement constituent. Resolving the bitumen cement from the listed additives proved problematic since its density is very close to the densities of the listed additives, and it is density that has the most influence on the measured attenuation. Water and bitumen have virtually identical specific gravities, ice at -20C has specific gravity of 0.9197 and anti-icer (Double Ought FreezGard; Great Salt Lake Mineral Corporation) has a specific gravity of around 1.3.

CT scans were made of each additive and bitumen. Samples of each material were placed in a 3.8 cm diameter tube which was then scanned at settings of 120 kv, 3 second projection exposure, and 360 projections per scan. An area was then selected from each sample's CT scan and the gray level was measured. In each case the representative gray level was the mean value for the area. As can be seen in the distribution plots which accompany each of the CT scans in Figure 2, the pixels associated with a material don't have a single value as might be expected, rather they fall along a distribution of values.

The importance of density as a factor in attenuation can be easily seen in the case of water and bitumen which, as mentioned above, have nearly identical specific gravities. They have the same mean gray levels and their distributions are almost identical. As a result visually distinguishing between the two is not possible. A difference of about 20 gray levels was found to exist between bitumen and ice. In the absence of noise that difference might be enough for the two to be distinguishable. Because their gray level distributions overlap to such a large extent even the use of false color did not resolve the problem. Anti-icer is the one additive that one would reasonably expect to be distinguishable from bitumen. A difference of nearly 100 gray levels exists between the two materials. Also there is no overlap of their gray level distributions. Those are not guarantees, though, since noise, proximity to other materials, and possible overlap of the gray level distribution with those of other constituents may also be important.

Even where it works, visual identification suffers from subjectivity. For reasons of accuracy, particularly near boundaries, a better approach to identifying constituents and additives is needed. Thresholding techniques, though not based upon visual identification, but rather numeric values, are not adequate due to overlap of gray level distributions. An alternative that isn't affected by the overlapping of gray level distributions takes the difference of two CT scans. Two images, a reference and one modified by an additive are needed. Both images must be of an identical sample cross-section, which means both must be from the same specimen. In order to scan identical cross-sections precise specimen alignment between its reference and modified state is needed. That requires a specialized mounting stage which was not available. Design and construction of one was beyond the scope of this project.

It was still possible to test the feasibility of differencing, for water and anti-icer additives since the mounted reference sample could be partially modified without disturbing it. The procedure was to first mount the specimen inside of a plastic cup which was mounted to the scanning stage. Once the reference scan was completed, one of the liquid additives was poured into the cup, to a level above the scan plane. It was necessary to mount a pavement specimen so that its surface was vertical (Figure 3b). In that position the liquids were unable to penetrate into the subsurface voids in a normal manner, i.e as they would under the influence of gravity when the surface was horizontal. Note, even in the horizontal position the infiltration of liquid water or anti-icer into the subsurface voids may still not be representative of what would occur under natural conditions since effects of traffic are also likely to be important.

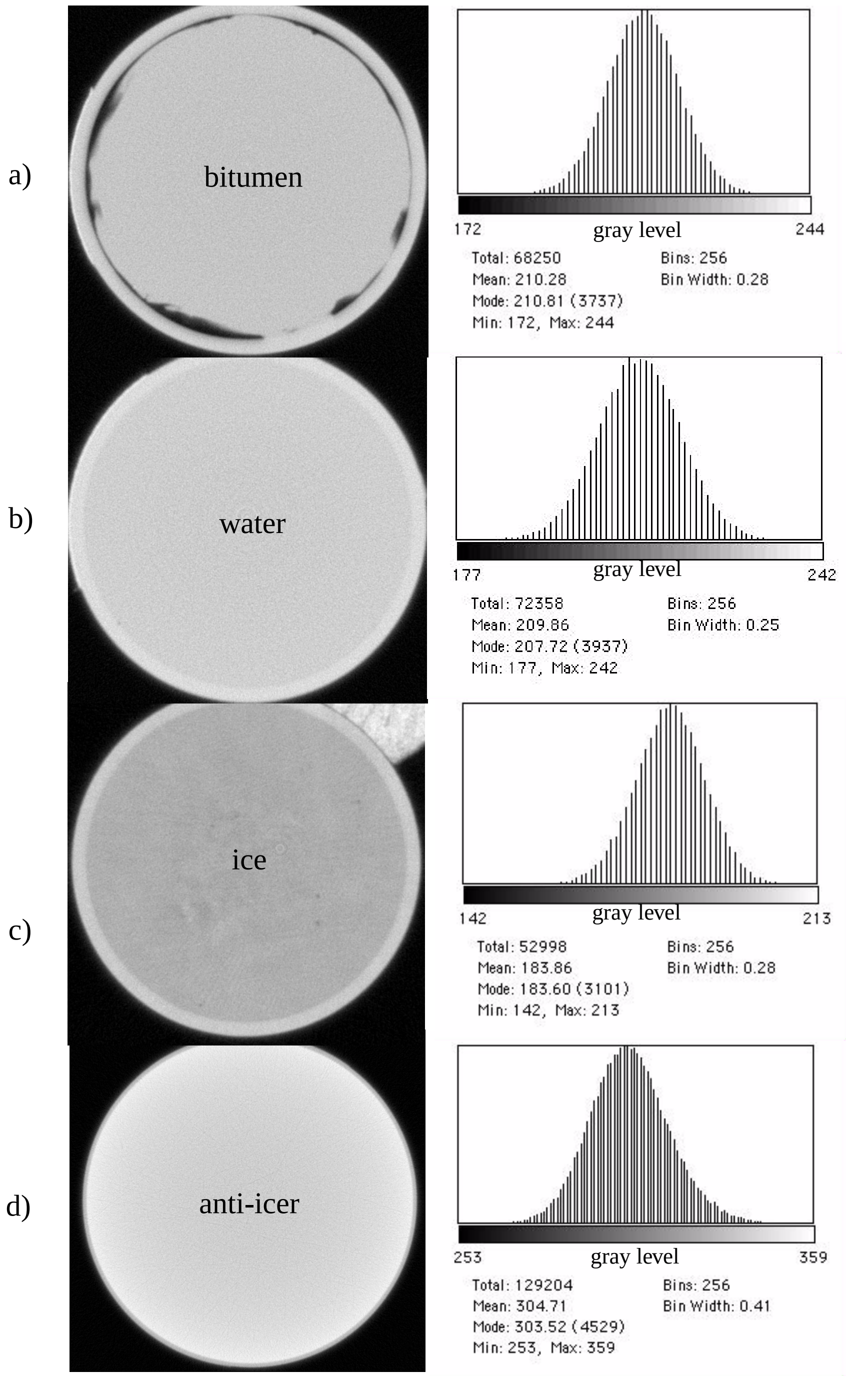

Figure 2. CT scans and histograms, a) bitumen, b) water, c) ice, d) anti-icer. There is considerable overlap of the distributions for bitumen, water, and ice. As a result visually distinguishing between them in same CT image is not practical.

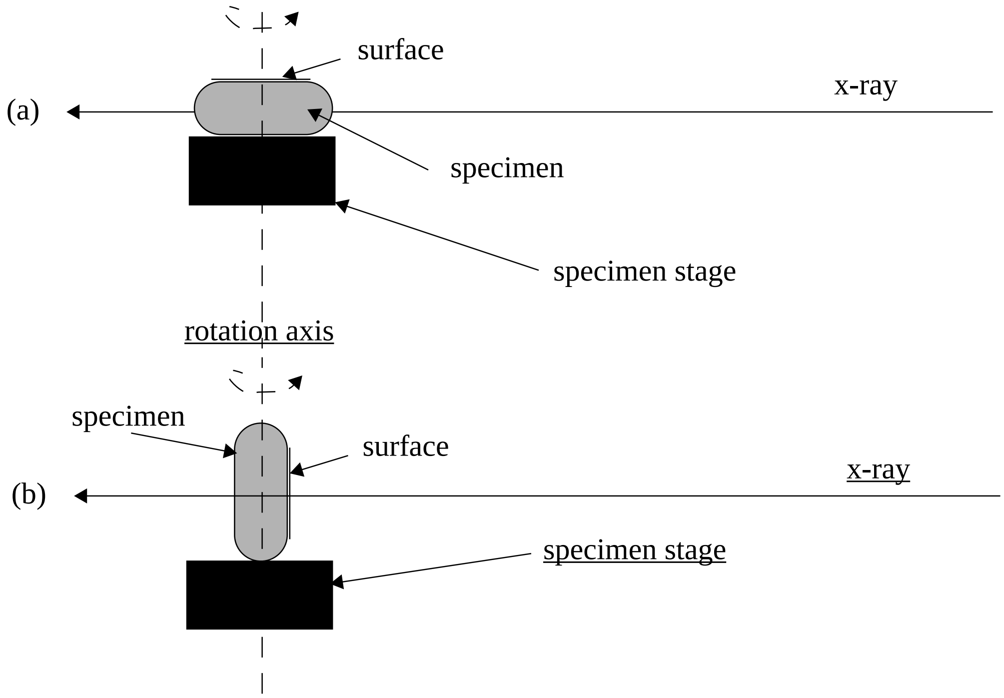

Figure 3. Two possible orientations of pavement surface relative to plane of x-rays.

Because CT imaging is non destructive, it technically allows the study of pavement samples with insitu infiltration of liquid water and anti-icers into the subsurface voids. For the infiltration patterns to be realistic, scans must be obtained from a specimen having its surface roughly perpendicular to the direction of gravity (Figure 3a). There is a draw back to using a natural orientation though. A single CT image cross-section of a sample having a vertical surface orientation provides information from the surface into subsurface voids. To obtain the same information when the sample is in a natural orientation first requires that enough cross-sections are imaged so that a 3D reconstruction can be generated. Only then, using software, can the desired cross-section be obtained.

Reference, additive, and difference images obtained from scans of the super-pave specimen are in Figure 4. The reference image used in differencing both water and anti-icer is in Figure 4a. In Figure 4b the reference has been modified by the addition of water. Figure 4c is the difference between Figures 4a and 4b, where the water is black. With Magnesium Chloride-Based anti-icer (Double Ought FreezGard; Great Salt Lake Mineral Corporation) as the additive, the CT image of Figure 4d was obtained. The difference between it and the reference image is Figure 4e where the anti-icer is black. As can be seen from the images, the differencing procedure produces an image with clearly defined boundaries between the pavement and both the water and anti-icer.

The procedure used for liquid water and anti-icer could not be used for ice. Icing requires that the specimen be removed in order to freeze the water. An attempt was made to obtain a difference image when ice was the additive. The lack of an appropriate mounting stage rendered the attempt unsuccessful.

A 3D digital reconstruction can be generated by stacking a sequence of parallel CT cross-section images. At a 100µm pixel resolution, a 3D reconstruction extending from the surface to a depth of 1 cm would require 100 cross-sections. Twenty CT scans would be required if a single CT scan yields 5 cross-sections. A scan takes approximately 35 minutes using a 3 second exposure for each projection and 360 projections per scan. Reconstruction of one section plane takes about 6 minutes. At a bare minimum it would then take 22 hours to generate the 100 section planes, not counting the processing of the data from each CT scan that precedes reconstruction of the individual planes, nor image processing.

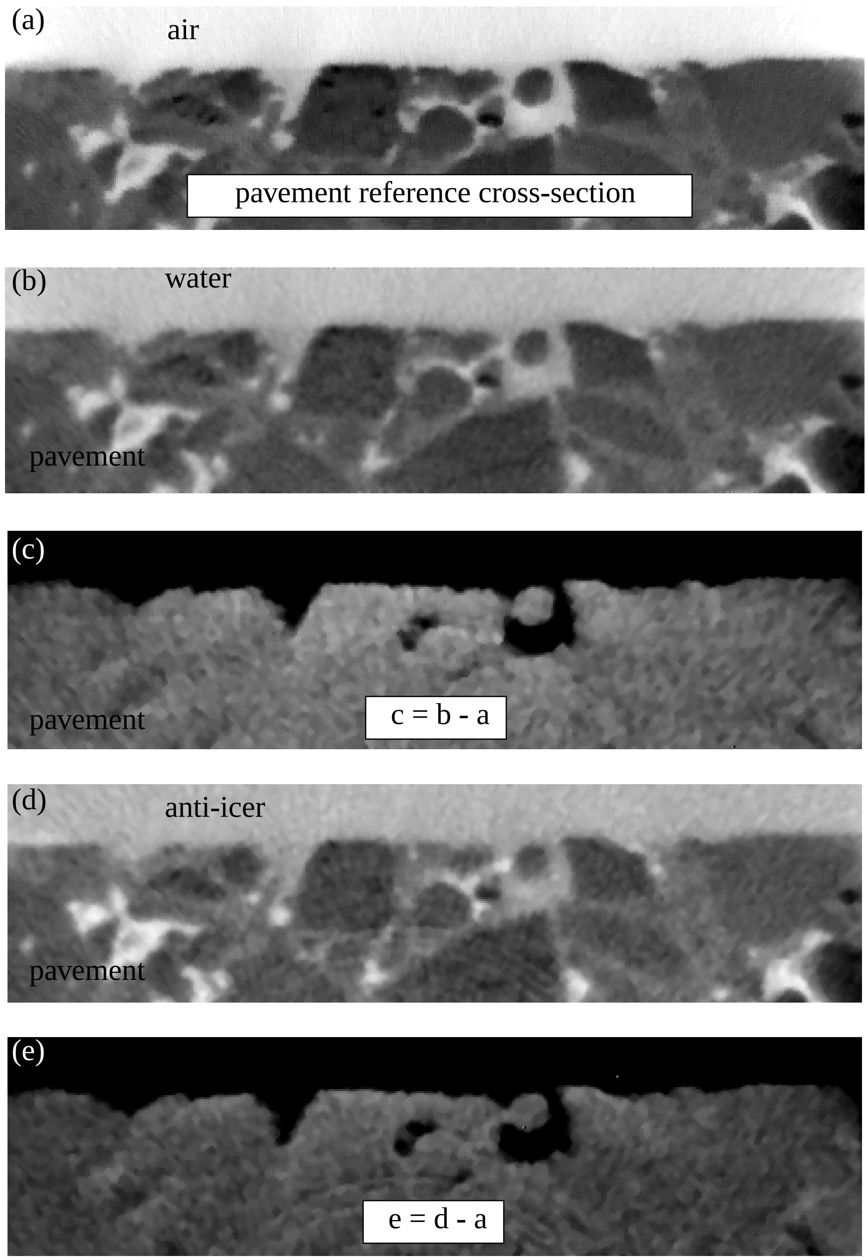

Figure 4. Infiltration patterns of water or anti-icer into surface cavities and surface connected voids can be observed by image subtraction. Image (c) is the difference between (b) a cross-section where the specimen was immersed in water and (a) the same cross -section when the specimen was immersed only in air. Image (e) was obtained by replacing water with anti-icer and subtracting the cross-section image (d) from the reference image (a). In (c) and (d) the black region marks the location of the water and anti-icer respectively.

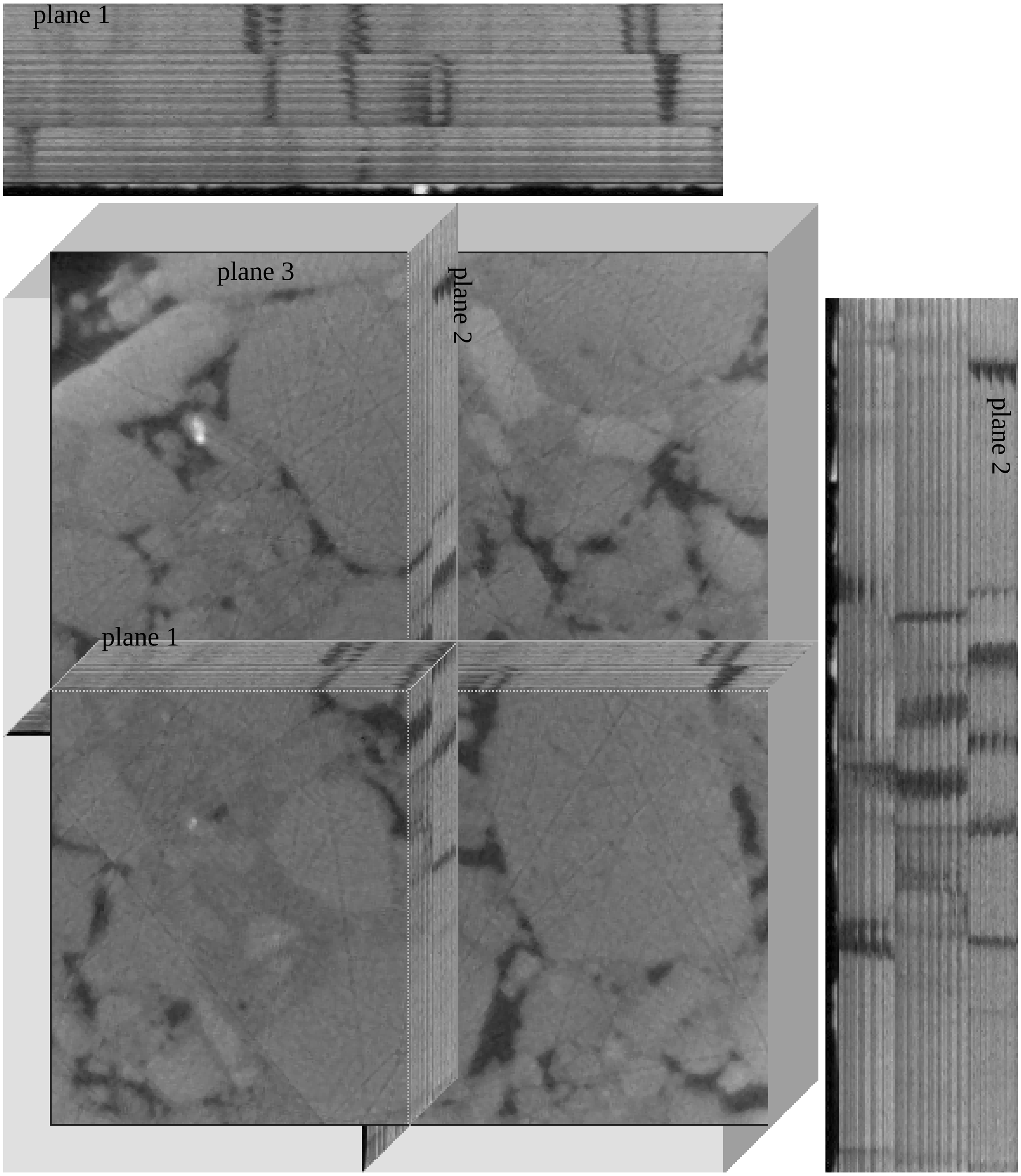

Figure 5. Three cross-sectional views of a 3D pavement reconstruction. The air and air filled pore spaces are the black and dark grey regions. The remaining areas are aggregate and bitumen.

Numerous attempts were made to obtain scans for a 3D reconstruction but all failed. All total over 150 hours of scan time was spent. Equipment malfunctions, only partially resolved prior to the end of the project, were responsible. In the end one scan sequence was completed. Unfortunately the results were quite disappointing. Figure 5 is a 3D view of the final reconstruction. Very poor image quality can be seen in the two vertical cross-section view (top and right) where for example void definition is quite ambiguous. The quality expected was that of the face-on view (one of the section planes). Because of time constraints no further attempts were made to produce usable 3D reconstructions. Resolution of the reasons leading to the poor quality of the completed reconstruction will need to be worked out upon completion of this project.

5. Pavement "Keying"

Ice "keying" in pavement refers to a mechanical means by which ice attaches to a pavement's surface. It acts in addition to chemical/electrostatic adhesion. One of the major tasks to be performed in this study was to verify the existence of pavement "keying" sites. Several related, simple measurements were devised and obtained from pavement CT scans. Those results are reported on in this section.

Conceptually the attachment mechanism of ice "keying" works like the hook mechanism that prevents a key in a keyway from being removed once turned. In pavement water infiltrates into surface connected voids. Some of those voids have widths greater than that of their openings. Subsequently, when the water freezes the ice cannot be pulled from the void without fracturing the ice. The essential geometric concepts of a keyway are illustrated in Figure 6. For purposes of this study and because the measurements were to be obtained from plane cross-section images of the pavement, the relevant "keying" concepts are defined relative to a plane. The opening width,

w_o, is measured relative to the lower of the two adjacent surface peaks. The keyway width, w_k, refers to the narrowest width of the void, where $w_k \leq w_o$. The void width, w_v, is taken as the maximum width of the void. The requirements for a surface connected void to be classified as a keyway are, $w_k \leq w_o < w_v$ and their order along the z axis is such that, in the same plane, the maximum void width w_v is at a greater depth than the narrowest width, i.e. depth $w_o \leq$ depth $w_k <$ depth w_v.

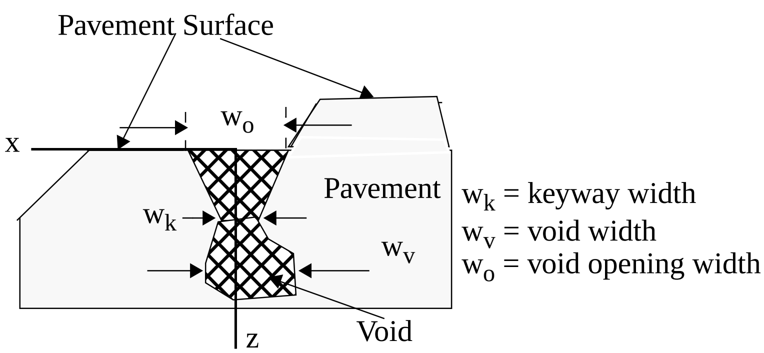

Figure 6. Keyway schematic.

“Keying” was investigated for three different pavement types, grade b, super pave, and chip sealed. Samples of each were provided by the Montana Department of Transportation. Specimens suitable for CT scanning were prepared by cutting approximately 6 cm x 6 cm x 4 cm sections from the original cores. One specimen of each type was then CT scanned along three parallel planes, spaced 1 cm apart (Figures 7-9). Each of the resulting images was reconstructed from a set of 360 projections, each of which was obtained with 3.0 second exposures at 120Kv.

In all cases the specimens were dry. Originally, the intent was to scan each specimen when dry and iced and then apply differencing to observe the actual ice penetration. Though the approach is technically feasible under the scope of this project it could not be carried out for a dry and iced combination. Doing so would have required removing the specimen in order to apply the ice cover. Once iced it would then need to be maintained at a temperature below freezing, and at the same time be repositioned so that it coincided precisely with its original, dry state, position

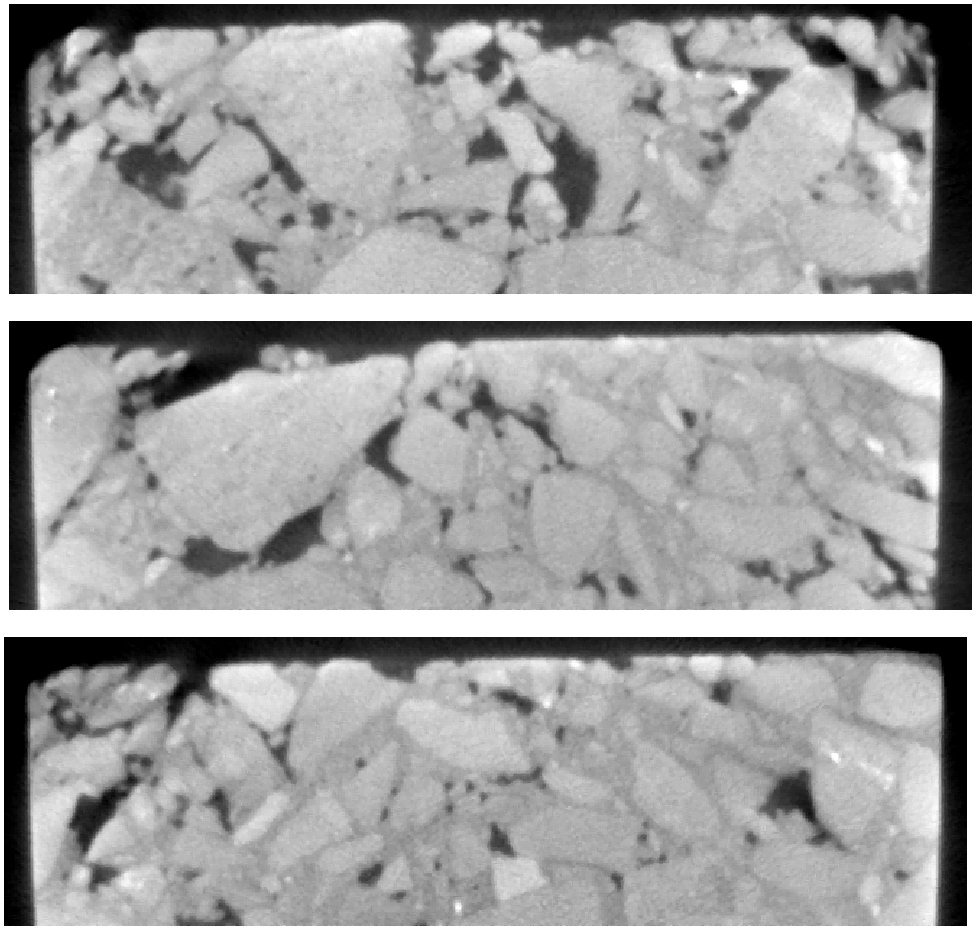

Figure 7. Super pave pavement CT cross-sections. Regions of dark grey through black are air and air filled pores. Lighter grey regions are aggregate and bitumen.

and orientation. Currently, it is not possible to meet those requirements. Scanner modifications are currently being undertaken that will allow those requirements to be met at a later date. Because of the problems just mentioned the task became identification and measurement of “potential” keying sites. The difference between “potential” and observed keying sites being that while the potential sites have the requisite geometric characteristics, water might or might not actually penetrate into the site, where it could then freeze to form an ice key. Analysis of the CT images (Figures 7-9) revealed the existence of numerous “potential” keying sites.

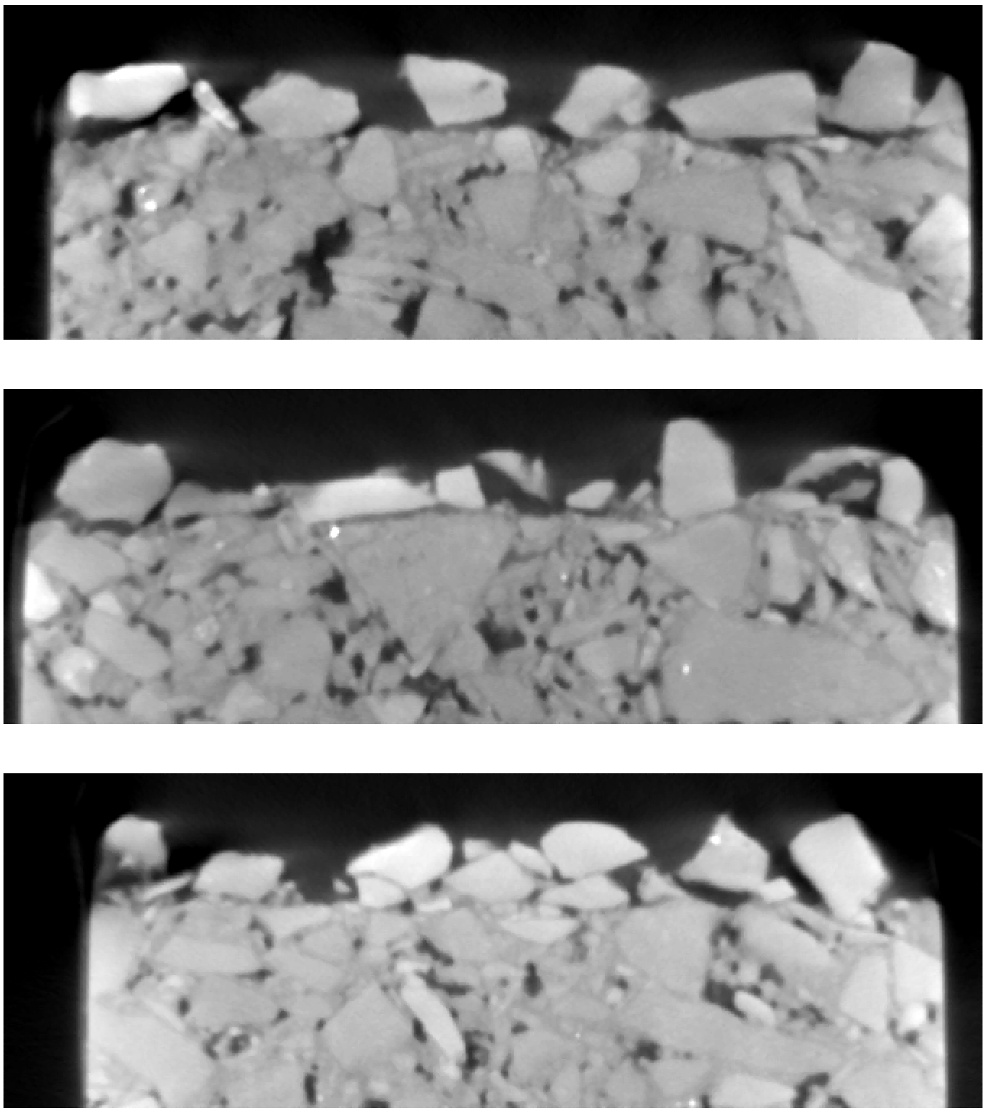

Figure 8. Chip seal pavement CT cross-sections. Regions of dark grey through black are air and air filled pores. Lighter grey regions are aggregate and bitumen.

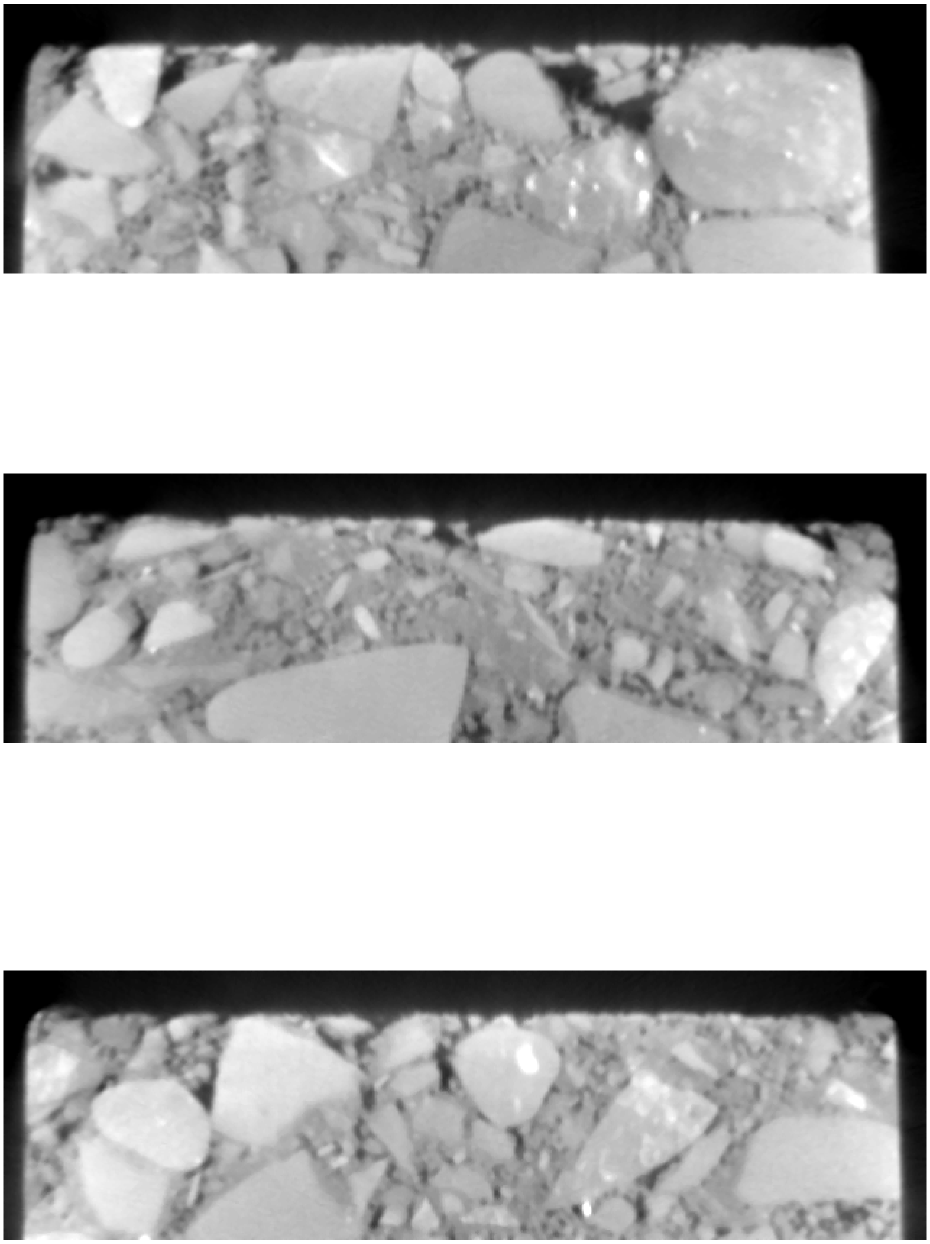

Figure 9. Grade b pavement CT cross-sections. Regions of dark grey through black are air and air filled pores. Lighter grey regions are aggregate and bitumen.

Keyway width is really the defining parameter of keying. To understand its importance suppose that an isolated region of pavement surrounding a keyway is frictionless and that there is no chemical adhesion between the ice and pavement. If a lifting force were applied normal to the ice surface and the keying criteria were not satisfied the ice could be lifted from the pavement with only the force required to lift the ice's weight. If a lifting force was applied but the keying criteria were satisfied then it would take not only the force required to lift the ice's weight but also an additional force increment needed to break the ice keys. The maximum average tensile stress in the ice key would occur along the line defining the keyway width, i.e. the narrowest width where the stress concentration would be the largest. As such that would be the weakest point of the ice key under a tensile lifting load. Average keyway widths for the three pavements types are plotted in Figure 10. The super pave sample had the largest mean keyway width, 1.78 mm, while the

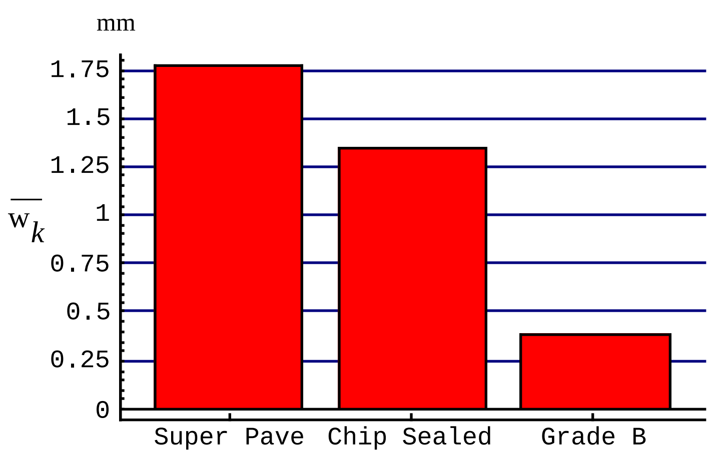

Figure 10. The average keyway width versus pavement type.

grade-b's mean keyway width, 0.39 mm, was over four times smaller than that of the chip sealed which was 1.34 mm. That suggests the lifting force required to rupture an ice key in the super pave would on average be larger than in that required for either the chip sealed or the grade b pavements.

The density of keyways, when combined with the average keyway width, is related to the average lifting force that would be required to rupture all the ice keys along their width lines. The grade b pavement contained nearly twice as many sites as the chip sealed and nearly three times as many sites as the super pave (Figure 11). At the same time the ratio of the total keyway width to the length of the test section of the super pave (0.109) was over twice that of the grade b (0.503) while the chip sealed (0.146) was nearly three time larger (Figure 12). For a given length of pavement then, the average lifting force required to rupture all the ice keys would be greatest for the chip sealed, followed by the super pave and the grade b.

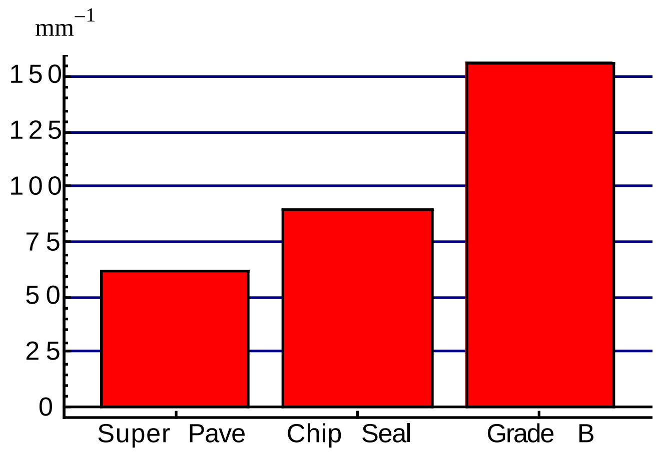

Figure 11. The average number of keyways per unit length of pavement.

Another concept that was considered in relation to keyways was that of shear lines. Again assuming a frictionless contact of ice to pavement and that the only mechanism by which the ice is attached to pavement is keying, the shear line is taken as the length of ice over which shearing might occur at the opening of the keyway. Only shear lines at keyway sites were considered in this analysis. The shear lines are related to the force required to shear an ice cover from the ice keys. At each keyway site the length w_o, the opening width, was measured and taken as the associated shear line. On average the chip sealed pavement had the largest shear line (5.27 mm) followed by the super pave (4.43 mm) and the grade b (1.03 mm) (Figure 13). The shear force required to shear the ice keys of the super pave and chip sealed would be over four times that of the grade b.

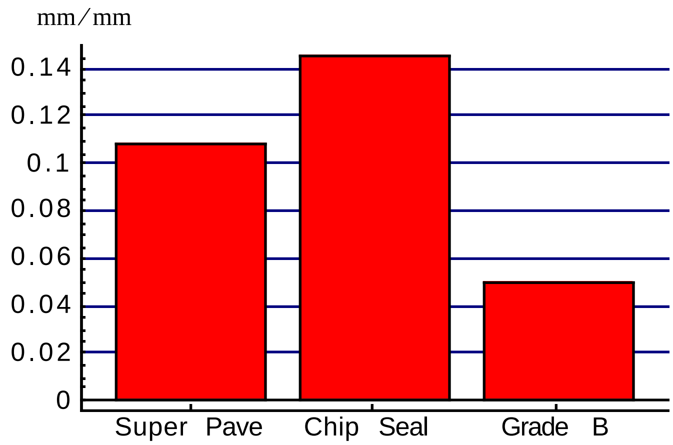

Figure 12. The ratio of total keyway width to total sample width.

Interestingly the ratio of total shear line width to pavement length was larger for the grade b (0.13) than the super pave (0.09), while the chip sealed had the largest value (0.57), being almost 5 times larger than that of the grade b (Figure 14). As a result the average force required per unit length of pavement to shear all the ice keys would then be greatest for the chip sealed.

The main idea is that in the absence of all other adhesion mechanisms, a vein of ice extending from the surface into the pavement increases in width at some location below the surface opening, forming an ice key and as a result it could not be pulled out with out breaking the key. Under this scenario the highest stress and therefore the most likely location of where the key breaks is along the line w_k.

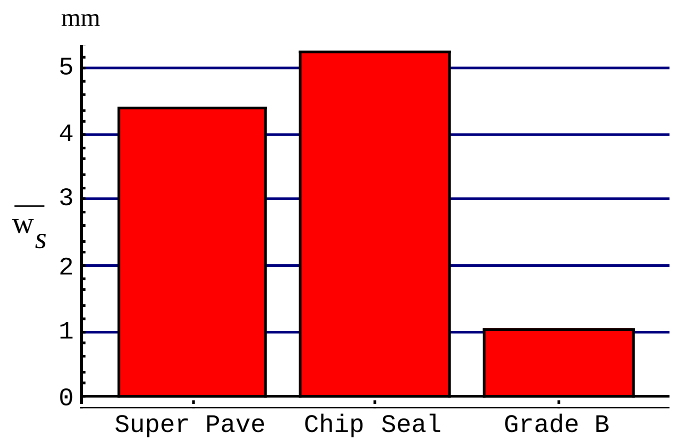

Figure 13. The average keyway shear-line length versus pavement type.

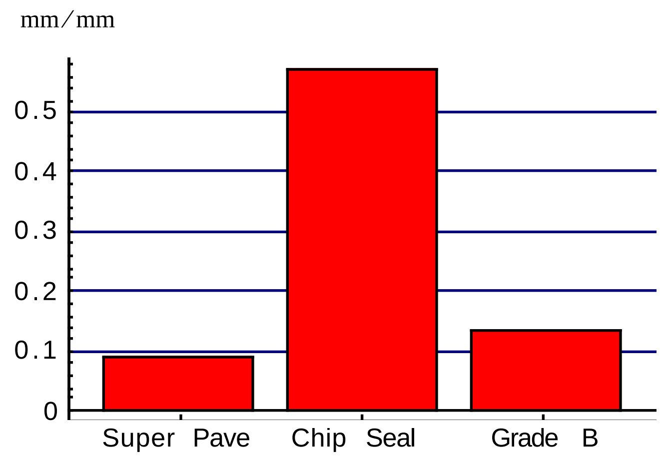

Figure 14. The ratio of total keyway shear-line length to total sample width.

6. Conclusion

To experimentally study highway icing at the scale of the pavement surface and surface connected voids, requires a means of obtaining pavement cross-sections that reveal pertinent details.

Traditional methods of obtaining cross-sections destroy a specimen. To observe the same cross-section under a variety of situations a non-destructive method is needed. The technique considered in this study was x-ray computed tomography (CT).

One of the capabilities that was deemed important in a study of icing is the depth and pattern to which water infiltrates into surface connected voids. Because the density of water and the pavement binder (bitumen) are essentially the same, direct observation of water in a pavement CT cross-sections was not feasible. It was demonstrated that by scanning the same sample when dry and wet, that images of identical cross-section planes (including identical alignment) could be subtracted to produce an image of only the water. The results obtained were useful as proof-of-concept, but, because of the orientation of the pavement surfaces during scanning, were not consistent with what would be found when the surface is oriented perpendicular to gravity. Observation of ice via the subtraction method was not attempted because the required cooling device and alignment jigs were not available.

Typically observation of liquid infiltration would be made via a 3D reconstruction of the pavement in which the surface was oriented perpendicular to gravity. Difficulties encountered, both with equipment and with the resulting scans, rendered the resulting 3D reconstructions unusable. Those problems could not be corrected within the time frame of this study. Subsequent to the completion of the experimental portion of the project progress was made toward obtaining a usable 3D pavement reconstruction. A view showing 3 perpendicular planes of that reconstruction can be found in the appendix.

In this report, “Keying”, a simple mechanism for attaching an ice cover to a roadway's surface was discussed. A 2D definition of “Keyways”, the associated mechanical attachment sites was given. As defined, measurements of several of “keyway” parameters could be made directly from pavement CT cross-sections. Two parameters, keyway width and shear-line length, were measured for each of three pavement types: super pave, grade b, and chip sealed. Based upon the measurements obtained, with an assumption of keyways being the only means by which ice attaches to a pavements surface, a relative comparison of the shear and tensile attachment strengths of ice to each of the pavement types was made. The grade b pavement type was found to have the smallest average keyway width and super pave the largest. The grade b pavement also had the smallest ratio of total keyway width to pavement width, while the chip seal pavement was found to have the largest ratio. The keyway width results suggest that on average the lifting force required to break the ice bond at a keying site would be smallest for the grade b and largest for the super pave, and the lifting force required to break all of the keyway bonds would also be smallest for the grade b but largest for the chip seal pavement. The pavement type having the smallest average shear-line length was the grade b and the chip seal the largest. Super pave was found to have the smallest ratio of total shear line length to pavement length and the chip seal the largest. In terms of shearing an ice cover from one of the measured pavement types, on average, the chip seal would require the most force both per site and in total. Per site, grade b would on average require the least force and super pave would require the smallest net force. It must be kept in mind when considering these results that all of the specimens examined were laboratory samples. As result none of them had experienced the structural changes that might occur due to traffic.

The results of this report confirm that X-ray Computed Tomography is an imaging tool that can be used to investigate highway icing. Development of several precision specimen mounting and alignment devices as well as a cooling chamber capable of maintaining sub freezing temperatures would remove most of the obstacles to fully exploiting CT. The existence of “keyways” was confirmed using cross-section images obtained using CT. The full role of “keyways” and ice “keys” in the adhesion of ice to a roadway are not known. In order to understand these roles several areas of investigation need to be pursued. In this report keying was examined at a relatively large scale, 100 μm resolution. The existence, distribution, sizes, etc., of keying sites at smaller resolutions should be examined since the net contribution of those sites to keyway bonding may be considerably greater than that of the plus 100μm keying sites investigated here. Using the image differencing techniques described in the report the infiltration patterns of ice should also be investigated. Such information would be useful for determining the smallest resolution at which keying sites act as attachment sites. In a related topic, wetting by various anti-icers should also be investigated since such information can lead to a better understanding of how the anti-icer is distributed and hence effects overall delay of ice formation. In conjunction with keying measurements, experiments should also be conducted to measure the lifting forces and shear forces required for removing an ice cover. CT imaging of before and after states would be useful in such experiments in order to understand the role of keyways.

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Appendix

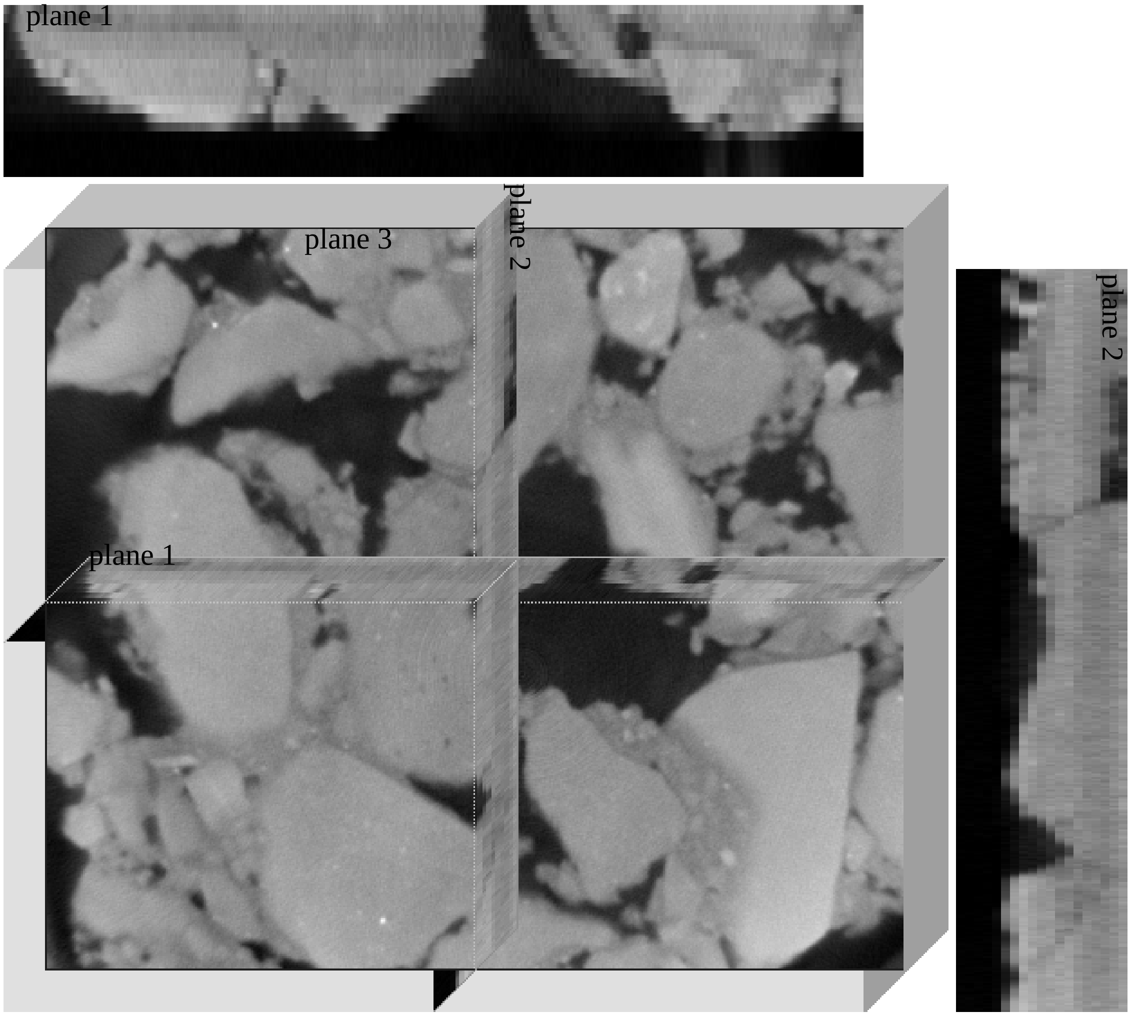

Figure 15. A successful post project 3D pavement reconstruction. Shown are three cross-sectional views of a 3D pavement reconstruction. The air and air filled pore spaces are the black regions. The remaining areas are aggregate and bitumen.