Application of Image Processing Techniques to Generate the Realistic Geometric Model for Discrete Element Method

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Abstract
To gain further insight into the interaction among the mix constituents, researchers utilized numerical simulation techniques, such as the Finite Element Method (FEM) and the Discrete Element Method (DEM). The Discrete Element Method was primarily introduced for the analysis of rock-mechanics and granular materials. In recent years, DEM has also been applied to simulate the properties of asphalt concrete. For the purpose of discrete element modeling of the materials two different mechanisms have been extensively employed, namely random geometry generation and importing pre-generated models. In order to gain more realistic simulation it is preferred to enhance more precise initial geometric models which are capable to represent the shape and arrangement of the constituents. For this purpose, two and three dimensional imaging techniques have been investigated by some researchers. In this paper, a user-defined 2D image processing technique was developed to generate the initial geometry of asphalt concrete mixtures. Asphalt concrete specimens were prepared in the laboratory and cut smoothly prior to optical scanning. The digital images were then processed and denoised by defining the appropriate thresholds. The processed images were employed to generate the initial model for DEM. The presented methodology in this paper enables researchers to have a better comparison between the simulations and the experimental laboratory tests. It also facilitates defining clusters of circular particles to provide better representation of aggregate shape and angularity which yields significant benefits for numerical modeling techniques.

Keywords: Discrete Element, Image processing, Numerical modeling, Asphalt Concrete.

1. INTRODUCTION

In order to describe the particulate mechanics problems, a model which simulates the material as a collection of individual particles that interact only at inter-particle contact points are referred as distinct (or discrete) element method (DEM) [1]. This method was first introduced by Cundall [2] and Cundall and Strack [3] for the analysis of granular materials and rock mechanics. Recently, discrete element method has been also employed to investigate the micro-macro relationships of asphalt concrete mixtures. It is believed that this method can yield significant benefits by gaining further insight into the interaction among the mix constituent, and also avoiding time consuming laboratory tests by conducting virtual testing if calibrated [4].

For the purpose of discrete element modeling of materials one of the basic inputs is the initial geometry file that mainly includes the particles’ positions. For the case of granular materials it is common to produce an initial geometry by means of a random generation algorithm that produces the initial coordination of all the particles based on a pre-introduced gradation file which states the percents of any particle size. It is believed that mechanical responses and damage behavior of geo materials like asphalt concrete is strongly dependent on their in-homogeneities and internal microstructure. More realistic characterizations of the mechanical responses of these materials under loading necessitate the consideration of the in-homogeneities and microstructures of the materials [5, 6]. For this purpose, digital image processing would seem as a powerful technique. This term would be defined as the conversion of the video pictures into a digital form, and applying various mathematical algorithms to extract significant information from the picture [5]. Nowadays, several image processing techniques are being used in different fields of science and engineering, e.g. biology, genetics, engineering, and so forth. During the recent years the application of these techniques gain momentum in the field of engineering problems, however most of them have been employed in the
continuum approaches. The representation of particle shapes in the material science could be mainly discussed in two main categories, namely two Dimensional and three dimensional cases. The application of three dimensional techniques is strongly dependent on expensive instrumental facilities and precise scanning methods like Computer Aided Tomography and X-ray tomography. All the methods mentioned above are known as non-destructive methods which are still under further investigations by researchers to be fully calibrated for the engineering purposes. In contrast to its significant benefits, obtaining a 3D representation of the internal structure of the materials is also accompanied by some difficulties which the most important ones could be mentioned as: processing limitation, noise removal problems, overlap detection, and also the expense of analysis [6]. On the other hand, there are destructive techniques that have the advantage of lower price while would best be used for the simulation of non-destructive or semi-nondestructive tests. These methods use the images obtained from optical scanning after cutting the specimens with a circular masonry saw or any similar instruments that can provide a smooth surface and cut the specimens into multiple vertical or horizontal plane cross sections.

Based on the facts mentioned above, this paper describes the developed digital image processing technique which is capable to represent the realistic internal structure of the asphalt concrete mixtures, to be employed in a discrete element model. It should be noted that regarding to the limitations of the paper it was avoided to provide all the processed results and the body of the code developed in MATLAB. Hence, it was tried to provide the complete methodologies and the outputs by providing some examples through the following sections.

2. IMAGE ANALYSIS ELEMENTS & BASICS

Referring to image processing resources, one can find a vast amount of data and definitions about digital images and their basics. However, knowing whole of this information seems not necessary to achieve the objectives of this research. Hence, this section provides a summary of the required definition that is necessary to find a better understand of image processing techniques and therefore those employed to develop the present technique.

During optical scanning of a picture in grayscale, which is the reference mode in this research, the scanner generates a rectangular array of square shaped elements with unit dimensions. These elements, which are known as pixels, are formed as a result of the intersection between vertical and horizontal scanning lines. The basic unit size of any pixel is scaled regarding to the ratio between the actual image size and that recorded by the digital scanner. For instance, one of the sectional areas obtained in this study that was used for optical scanning had an actual size of 93mm×64mm, while the associated image was recorded with 2188×1500 size digitally. One can calculate the unit value by dividing the related dimensions of actual size by the image size and finding the minimum value. It could be recognized that the unit width of any pixel for this case was 0.0425mm. In the next layer of information, any of these unit squares are assigned an integer code value from 0 to 255, known as a 256 gray level system, regarding to their sensed brightness intensity during the scanning. Figure 1 presents 1/400 of an image obtained through this research activities to show the rectangular variant gray level constitution of any digital image by focusing on the top of an aggregate element.

![Figure 1. Gray level variation of pixels](image_url)

The other term that is widely used in pre-processing and pre treatment purposes is histogram. A histogram of an image is used to display the distribution of gray values in the image. It is a function to show,
for each gray level, the number of pixels in the image that have that gray level. It is common to modify the histogram by equalizing it in the pre-processing phase to obtain a better quality prior to final image processing phase. There are many routine algorithms for equalizing the histogram in most of the image editing applications. One can use any of the available equalizing algorithms which will be more discussed through the related section.

3. EXPERIMENTAL STUDIES

The research activities presented in this paper were carried out following to a comprehensive pavement materials research entitled evaluation of the permanent deformation characteristics of Stone Mastic Asphalt (SMA) using Discrete Element Method. Hence, the laboratory prepared specimens were in accordance to fulfill the minimum requirements for SMA mixtures and the conventional hot mix asphalt mixes in that research. It should be noted that any other asphalt concrete mixture would be used for the purpose of the image processing activities discussed here regarding to the required precision of the outputs. Six different Asphalt concrete mixtures were prepared in the laboratory including two types of conventional Hot Mix Asphalt (HMA) appropriate for binder and Topeka courses, and four SMA mixtures with different Nominal Maximum Aggregate Sizes (NMAS), namely 19mm, 12.5mm, 9.5mm, and 4.75mm. All the mixtures were prepared with the appropriate bitumen content and volumetric properties according to the mix design. The SMA mixtures were following to the guidelines presented in NCHRP-425 report [8]. The design method is out of scope of this paper and could be found in the associated reference mentioned above. The specimens were left for a minimum of 24 hours to reach the normal environment temperature. As a result of the destructive nature of the dynamic creep and indirect tensile strength tests in this study, a set of samples were prepared and their bulk densities were measured precisely. The samples were then divided to provide a uniform bulk density distribution to be able to provide a better estimation of simulation results. It should be noted that for other researches, the specimens could undergo non-destructive testing methods like indirect tensile stiffness modulus testing (ITSM), elastic modulus test or the like prior to cutting. Regarding to the appropriate sections required for simulating the mechanical tests, the selected specimens were cut through the pre-determined lines drawn on the specimens’ surface. It should be noted that cutting would be different depending to the conventional purpose to be used. For instance, one who is going to use the image processing results to simulate the indirect tension test, ITSM or other diametrical load application would cut the specimens parallel to the diametrical plane, while others who intend to simulate elastic modulus test or any axial loading mode should cut the specimen along the height. In this study, specimens were cut with a circular masonry saw into multiple rectangular plane cross sections and also circular sections. Figure 2 shows the schematic of the specimen through optical scanning.

![Figure 2. A view of the scanning process and sample slices.](image)

3. PRE-PROCESSING & TREATMENTS

After preparing the slices of the specimens in desired dimensions the next step was to obtain the digital images of any section and then improving the quality of them to be used in final processing. The essential
item to achieve to a realistic representation of the internal structure, both in 2-D or 3-D modes, is to obtain images with the resolution and qualities high enough for the purpose of image processing. Regarding to the definition of some digital imaging terms like dots per inch, which is generally known as dpi, the minimum required resolution were directly determined based on the smallest aggregate size that was going to be captured. In the case of micromechanical modeling of asphalt concrete it is common to model all particles with dimensions greater than or equal to 0.6mm, remaining on the sieve no.30, as independent aggregate, and the remaining fraction with the bitumen as the mastic phase. So in this case, to obtain a satisfactory input file, scanner should be able to assign any pixels a minimum dimension of 0.6mm. As a rule of thumb it could be expressed that a maximum resolution of 300 dpi for most of cases would be enough [6]. Besides scanning the sectional areas, all the slices’ dimensions were measured precisely and recorded as actual image size. These values were recorded to be used as inputs for the developed image processing algorithm at the future. Figure 3 represents some cross sectional images obtained from the specimens with different NMAS’s.

Figure 3. Preliminary scanned images: a) NMAS 19mm, b) NMAS 9.5mm, c) NMAS 4.75mm

The net images obtained from optical scanning could not be used for several reasons, e.g. the variable ranges of colors in aggregates, noised that are common in optical scanning, and the virtual boundary conditions that must be imposed to the models. In this step, the basic editing tasks were carried out on the net images. The first basic edit related to balancing the contrast of the pictures. For this purpose, a simple user-defined algorithm was developed in MATLAB to set the appropriate contrast and brightness levels by introducing the darkest and brightest pixels by the user. It is also possible to do this step by means of other ready packages. In other words most of the treatments and pre-processing activities could also be carried out by means of a set of other applications and software that are developed for imaging and photography. The main part of this research is related to the code that extracts the particle co-ordinations and material properties. This code writes these data into desired location in the form of Excel and Text files. However, the images could be directly obtained in grayscale scanning mod; in this study they were preliminary obtained in colorful mode to be used for further studies on the aggregate sources and quality. In order to obtain the discrete particle geometry the images were turned in grayscale mode and any other color channels were discarded. It is notable that the gray scale image might not still be used and should be converted to the binary ones that can represent the microstructure of the asphalt concrete mixture in two separate phases. A binary image or so-called black and white image would be obtained from a grayscale image by setting the threshold, H, to an appropriate level. As discussed previously, grayscale picture determines any pixel by the light intensities by means of integer values from 0 to 255. The threshold is then defined as the value that leads to transform greater intensity than H to 1, and the lower values to zero, as defined by the function in the Equation 1.

\[
T(i, j)= \begin{cases} 
1 & g(i, j) \geq H \\
0 & g(i, j)<H 
\end{cases}
\]  

(1)

where \(T(i, j)\) is the transform function of the pixel with coordination \((i, j)\), H is the threshold value that should be obtained by the user for each image, and \(g(i, j)\) is the gray level of pixel \((i, j)\) that could vary between 0 and 255. Based on the results of this study the appropriate threshold value was determined in the range of 79 to 114. It is clear that based on the environmental conditions, type of material being scanned; scanning instruments and quality these values may differ. Converted all the 36 grayscale images into equivalent binary ones, noise removal techniques were applied to improve the quality of images for the second time. For this purpose Image-pro plus package can significantly facilitate the de-noising process using the predefined filters available in the package. Among several noise removal filter, median filter was used. An advantage of this filter is the ability to remove noise while preserving the edges of the particles which is an important part of the image data. Figure 4 shows the grayscale and binary version of the NMAS 9.5 specimen which the colorful version was previously shown in Figure 3.
4. **Final Processing & Outputs**

All the steps discussed above were conducted on 36 images obtained from the slices of Asphalt specimens. In summary the slices were optically scanned in color mode with imaging resolution of 300dpi for the four coarse grained mixtures and 600dpi for the two fine grained mixes to achieve a higher accuracy. The images were then converted to grayscale and underwent basic editing activities, namely contrast and brightness level balance, histogram equalization. The pre treated images were finally transformed into the binary ones by setting the threshold. Noise removal process was carried out on these black and white images by means of the median filter that preserves the edges of the elements.

All the activities mentioned above, led to input files that were capable to generate the geometry model from the internal structure of asphalt concrete specimens and to be used for Discrete Element Models. For this purpose, a user defined code was developed and linked to MATLAB program which imports the pre-processed binary images as inputs. To use the program one should enter the actual size of the sections, the digital image size, the desired process mode for output files, desired disk shaped particle sizes. Two different process modes were considered while developing the code: 1) generating circular particles with same radii equal to the minimum particle size, and 2) generating each particle by combining different circles with various radii. The latter would considerably reduce the total number of particles and therefore has significant effects on cost of computation in simulations. The first mode is also preferred in some micro-fabric analysis; however considerably increases the time of computation. Indeed, the second algorithm uses the first one in the first step by filling all the detected particles with the smallest allowed circles. In the next step a linear search algorithm starts to determine the maximum possible combinations of the adjacent circles by a larger circle. As noted here, in order to obtain to the desired objectives it is necessary to distinct the particles boundaries. For this purpose, an edge detection algorithm was implemented in the developed code to extract the particle boundaries from the binary images. In this case, a technique similar to that employed successfully by Yue et.al [5] in the case of continuum mesh generation was used. In this method the first order derivative of the gray level variation in i and j directions were calculated. The algorithm uses the concept that the first order derivative of pixel’s gray level in the aggregate and matrix interfaces should be either a positive maximum or a negative minimum value. The first order derivative in i and j directions were calculated according to the Equations 2 and 3. These equations were used to calculate the absolute gradients of gray levels of two adjacent pixels by Equation 4.

\[
\nabla_i g = \frac{\partial g}{\partial i} = \frac{1}{2}(g(i+1,j) - g(i-1,j))
\]  

\[
\nabla_j g = \frac{\partial g}{\partial j} = \frac{1}{2}(g(i,j+1) - g(i,j-1))
\]  

\[|\nabla g| = \sqrt{\left(\frac{\partial g}{\partial i}\right)^2 + \left(\frac{\partial g}{\partial j}\right)^2}
\]  

where the parameters were defined previously. Figure 4 shows a sample output of the edge detection phase after running the code for binary image obtained from an HMA sample slice. The boundaries were then used to make the aggregate phase distinct from the mastic phase.
Detecting the boundaries by the algorithm, the code begins to fill the inner area of enclosed curves which represent the aggregate phase with uniform radius circles. As the second mode of data extraction was determined by the authors, the code automatically started to search for the replaceable adjacent circles. The output data was then printed as excel file with “.xls” extension, however it was possible to save the output as text file. The latter was postponed up to obtaining the other fraction of data related to mastic phase. In the next step the code automatically generated the remaining mastic phase particle position and wrote it as another excel file for further use. Each of the excel files included seven column of data. The number of rows was equal to N+1, where N was assumed to be the number of independent circular particles. At the final step using a Macro code the two excel files were combined and sorted in a single data sheet. A view of the final output data sheet is presented in Figure5.

<table>
<thead>
<tr>
<th>code</th>
<th>X-C</th>
<th>Y-C</th>
<th>R</th>
<th>Mtrl</th>
<th>cluster</th>
<th>area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0</td>
<td>0</td>
<td>1.76715</td>
</tr>
<tr>
<td>2</td>
<td>1.35</td>
<td>0.6</td>
<td>0.6</td>
<td>1</td>
<td>1</td>
<td>1.13097</td>
</tr>
<tr>
<td>3</td>
<td>1.65</td>
<td>0.3</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
<td>0.99034</td>
</tr>
</tbody>
</table>

The first column indicates the code assigned to the independent circular particle. The second and third columns, entitled “X-C” and “Y-C”, represent the coordination of the center of the associated particle. The fourth column, labeled “R”, determines the radius of the particle. The fifth column that was named “Mtrl” as an abbreviation for Material type stands for the type of material that the particle in that row is related to. For instance, as a pre-assumption the zero value was assigned to a particle of mastic while the similar value is 1 for a particle included as aggregate. The data presented in this column enabled the authors to assign different material properties to each of the two categories of the particles following to the constitutive and contact laws implemented in the DEM code. The column labeled as cluster determines all the aggregate particles that are located in a detected boundary. For all the mastic particles this value was set to be zero. On the other hand the maximum value of this code represents the number of real particles detected. This column was used to generate the representation of the shape of aggregates by defining high bonding strength and fixing moments in the discrete element code. And finally, the last column shows the area occupied by each particle. Based on the methodology mentioned here the internal structure of asphalt concrete specimens were extracted in the form of excel files that includes all the data required to conduct the micro-structural analysis mentioned before. The result of micro-structural analysis not mentioned here was separately explained in another paper and was out of scope of the present paper.
9. CONCLUSIONS

The present investigation provided step by step methodology accompanied by scientific backgrounds that was employed to develop a user-defined digital image processing code to extract the micro-structure of asphalt concrete specimens. The following conclusions could be drawn:
- A quality of 300dpi for most of the micro-structural DEM analysis for asphalt concrete mixtures seem to be satisfactory, however higher resolution should be employed for self studying of the mastic phase.
- The threshold to separate the aggregate and mastic phase in the current study was observed to vary in a range of 79 to 114. The other ranges might be appropriate for other research purposes.
- Two adjacent pixels were successfully used for the edge detection algorithm in this study.
- A median based noise removal filtering, as employed in this investigation, is suggested to preserve the edge pixel data which are crucial in micro-structural studies.
- The results and outputs of the image processing technique developed in this study, has the ability to provide all the data required to import as an initial model geometry file both in user-defined codes and available DEM packages; However some changes in data arrangement maybe necessary for employing in different DEM packages.

10. ACKNOWLEDGMENT

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11. REFERENCES