Image processing techniques applied in concrete research

Article briefs fundamental techniques of image processing in concrete research and includes discussion on examples.

INTRODUCTION

Cementitious materials are used extensively in civil engineering applications due to their high strength and durability. However, it is difficult to ensure that the structures designed with cementitious materials perform following their design specifications when exposed to natural conditions. In order to address this issue, image analysis techniques have been increasingly employed in the civil engineering field. It is generally agreed upon that image analysis techniques are valuable in many engineering fields, but their potential is particularly useful in civil engineering. This is because of the development of advanced tools that can gather significant data to help with various construction projects' planning, design, construction and maintenance phases. The ability to automatically identify the material shape, size distribution and texture has been beneficial in this process.

Digital image hardware and software have revolutionized the way engineers can investigate the inhomogeneity and microstructures of materials. This technology has primarily been used for quantitative analysis, but there are a few exceptions where it has been used for more qualitative analysis. This technology has made it possible to study materials in ways that were previously impossible, and has opened up new possibilities for research and development in many fields.

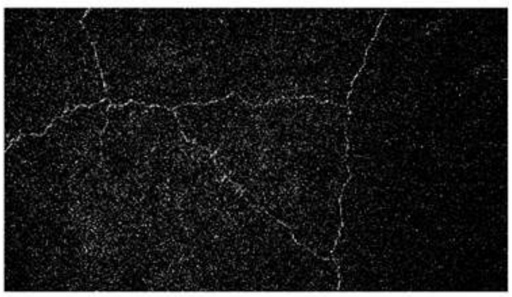
Image analysis is the process of extracting quantitative information from images of concrete structures or materials. Digital image analysis systems are typically comprised of a camera, a light source, and software that processes the images captured by the camera. It involves using sophisticated software to identify features of interest, such as material shape, size distribution and texture. This information can be used to assess the performance of cementitious materials under different conditions and to make necessary adjustments to the design of construction projects. The main advantage of this method is that it can be applied directly to an image acquired by a conventional digital camera, thus eliminating the need for high-end equipment such as electron microscopes or diffraction devices.

The image processing technique is a process that involves several steps, including creating an initial mask using the thresholding method and using morphological operators to separate particles from the background and form the regions. Therefore, this article describes some of the image analysis techniques used to investigate the concrete surface and aggregate properties.

IMAGE ENHANCEMENT

Contrast enhancement, also known as brightness enhancement, is a technique in which the brightness of pixels is adjusted. A goal of contrast enhancement in image analysis is to improve the visibility of details, such as the edges of objects like aggregate particle edges and cracks within an image, as shown in Figure 1. This is accomplished by adjusting pixels' lightness and/or darkness to create more contrast between them. Image contrast enhancement techniques are usually applied based on two types: spatial domain methods and frequency domain methods.

Figure 01: Image contrast enhancement and edge detection for the cracks in the concrete surface [6



Spatial domain methods: This method remaps the levels of grey in a digital image by using a probability distribution for the input level of grey [1]. This is typically applied as a pre-processing step to improve the quality of the image. Contrast enhancements in this category usually consist of histogram equalization, adaptive histogram equalization, edge detection and dilation, median filtering and others [2,3]. Moreover, different types of enhancement techniques, such as modification, morphological, evolutionary and stochastic resonance, are utilized in this method [4]. Modification is most effective in detecting and modifying the discontinuous particle surface within an image. Morphological can be used to detect, remove, and create small portions of the image. An evolutionary algorithm has been employed to detect noise in a digital image, smooth edges of images that are markedly pixelated and make them perfect for the appropriate investigation of the concretes and material's properties.

Frequency domain methods: This method manipulates image coefficients, which are obtained by transform methods such as Wavelet Transform (WT) and Curvelet Transform (CT) [5]. While wavelet transform (WT) helps to enhance the contrast of images by extracting material's features at different scales and sub-bands, curvelet transform (CT) extracts better surface edges than WT for multi-scale edge enhancement. The Curvelet transform method, therefore, can be applied to noisy images for contrast enhancement. Moreover, the edge detection method is the most useful for evaluating concrete material properties. This method can detect lines, curves and corners in concrete surface images and easily identify the cracks in the concrete surface.

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SEGMENTATION

Segmentation is a way of partitioning an image into meaningful regions based only on the intensity of the pixels. When segmentation is applied to a grey-scale image, any pixel whose value satisfies some condition - such as being less than 10% above or below its neighbours on that same line will have its intensity set to one, while all others will be set to zero [7,8].

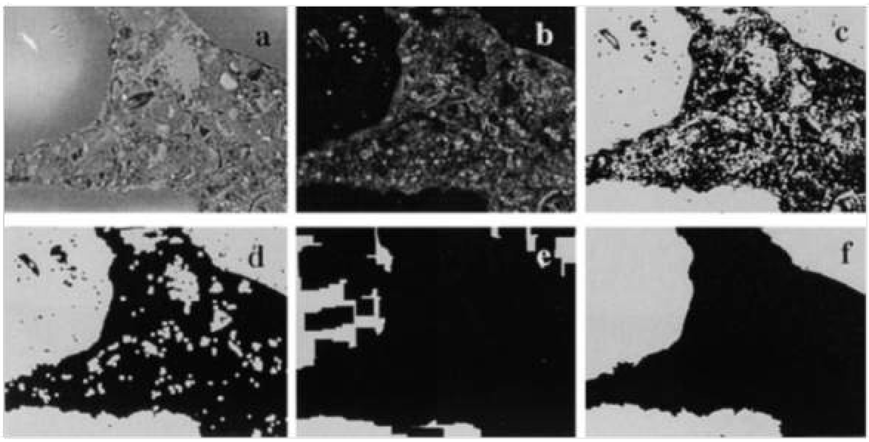
Aggregate particle segmentation by image analysis depends not only on the grey level of each individual particle, but also on other characteristics such as texture and paste matrix. Moreover, the distribution of grey levels is more uniform in the aggregate than in the paste matrix. Therefore, the image analysis algorithm can be used to automatically segment an image into diverse groups, using a combination of several existing techniques in most modern image analysis software packages.

The first step in aggregate particle segmentation is edge detection by the gradient technique, which involves generating an image whose grey levels are defined as differentials of grey levels in a grey-scale image. The second step involves the application of a thresholding technique to the edge-detected image, which is used to separate the background from the foreground. The third step involves the application of a morphological opening operation to the edge-detected image, which is used to eliminate small holes in the aggregate particles. The fourth step involves the application of a morphological closing operation to the edge-detected image, which is used to eliminate small cracks in the aggregate particles. The gradient image emphasizes the boundaries between phases, making them appear highlighted and high in contrast. Meanwhile, the bulk of each phase is turned into a low-contrast shade that merges with other such shades from adjacent phases. The composite image is converted into a binary one by setting appropriate grey-level thresholds that separate aggregate particles as much as possible from the paste matrix. This procedure is shown in Figure 2.

THRESHOLDING

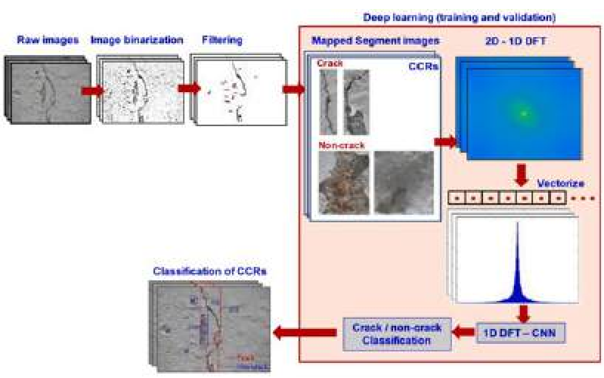
Thresholding is the process of converting a grey-scale image into a binary one. This is done by applying some mathematical operations to the input image, which results in a new image containing only two values (usually black and white). The most important thing about this conversion is that it allows us to separate an object from its background. The primary purpose of thresholding is to make it easier to analyze the content of an image, such as concrete surface characteristics and aggregate material's properties.

Figure 02: Aggregate segmentation through grey-level thresholding, filtering and binary operations. (a) edge detection (b) Grey image (c) thresholding (d) opening (e) morphological closing (f) reconstructing of binary image. [8]



The thresholding process can be divided into two categories: global thresholding and local thresholding [9]. Global thresholding is the simplest way to separate image background and foreground. Local thresholding is more accurate than global thresholding but more time-consuming. Furthermore, the threshold value can be found in two ways:

Figure 03: Adaptive thresholding approach with deep learning



1. Using a histogram method to find the peak of the distribution is suitable for images with many different intensities (colour).
2. Using a grey-scale version of the image to determine where most pixels are white or black.

There are two thresholding methods, manual and automatic, and automatic method is the simplest form of brightness discrimination [10]. Due to the large variations in grey-scale level between images, manual thresholding is not applicable from an automation standpoint; therefore, a comparative concrete investigation is typically conducted to determine the viability of using automatic thresholding and to identify the most appropriate auto-threshold type for a given situation (e.g., particular

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concrete crack investigation and micro-structure investigation).

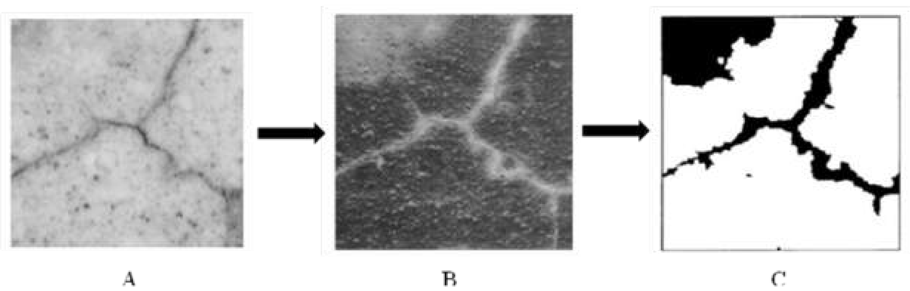
The binary image is a black and white with only two colours, white and black. In the thresholding process, the threshold value needs to be set as the grey-level value of the pixels brighter than 50% grey level. The threshold operator compares the grey values of a pixel in an image to a given value, and if the grey value of the pixel is greater than or equal to that value, the pixel is considered white; otherwise, it is considered black. The threshold operator has many applications in the investigation of the concrete surface and pastes matrix image analysis. For example, it can be used to segment aggregate and concrete objects from complex backgrounds using edge detection techniques such as the Sobel filter etc.

Adaptive Thresholding: The threshold value is used to segment the image into light and dark areas [11]. This technique will be helpful in removing noise from an image. The original image is divided into non-overlapping regions, and then the mean and standard deviation are calculated for each region. Then thresholding is done to each region using Hamming window. The final segmented image will be obtained by adding all segmented images together. After that, each area has a different threshold value. This technique will be helpful in removing noise from an image. If the threshold value is high for the dark area, then the dark area will be detected as noise and removed from the image segment. However, if the threshold value is low for light areas, light areas will be detected as noise and removed from the image segment. So, the threshold value is adjusted according to the location of pixel values. The sampling method is shown in Figure 3.

Binary Thresholding: This method is very simple to implement but can be problematic because the threshold value is assigned manually. Therefore, if the assigned threshold is too high, some important features may be missed, and if the assigned threshold is too low, then some noise might also get filtered out. In binary thresholding, it is essential to choose the correct threshold value. If we choose a small value for our threshold, then only minor changes in pixel values will be detected, and significant changes will be ignored. On the other hand, if we choose a large value for our threshold, then significant changes in pixel values will be detected, but small changes will be ignored. Figure 4 illustrates the results of binary thresholding for concrete cracks.

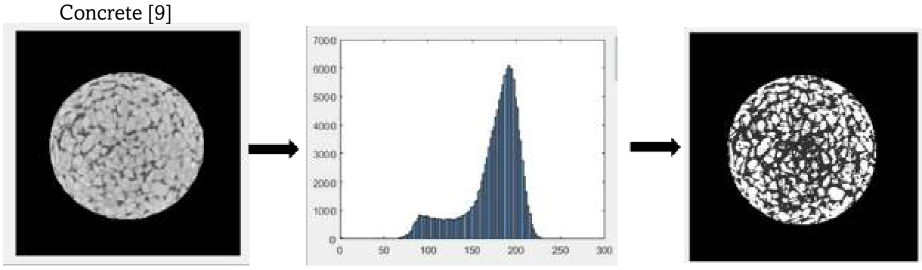
Threshold to Zero: The pixel value is compared to the threshold value in this method. An appropriate value will be assigned if the value exceeds the threshold value. Otherwise, the pixel value is set to zero [13].

Figure 04: Concrete cracks investigation using binary thresholding method (a) original concrete surface image (b) contrast/gray-scale enhanced image (c) image after binary thresholding [12]



Otsu Thresholding: Otsu's method is a popular thresholding technique for images. This method's primary premise is to divide an image's pixels into two groups. Separated aggregate or concrete material is characterized based on two factors: the ratio between the number of pixels and the mean grey level [14]. In the case of unimodal or nearly unimodal picture histograms, this approach may meet difficulty in determining a satisfactory value. In the 1-D approach, a single line is drawn through the peak of the histogram, and the thresholding value is then determined using this line. In the 2-D approach, two lines are simultaneously drawn on the diagonal of the histogram, and the threshold value is determined by using both lines. This method is effective for images with only two histogram peaks. Figure 5 displays the results of Otsu's thresholding method.

Figure 05: segmented with the Otsu thresholding method for the sliced portioned of Pervious Concrete [9]



NOISE REMOVAL

Image noise removal is a process in which unwanted noise from a captured concrete surface image is removed. The image's background can be considered the most common type of noise, but other types also exist. There are many different approaches to removing noise from images, each with advantages and disadvantages. The noise removal method is based on

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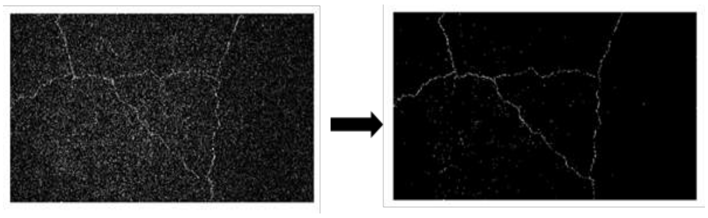
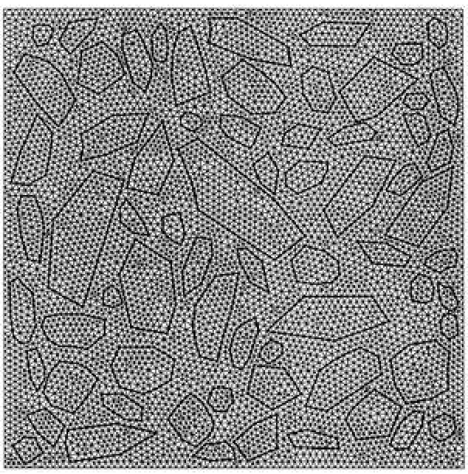
Figure 06: Image analysis using low-pass filtering (a) edge detected image with noises (b) noise removed image with low-pass filtering meth-



adaptive filtering and contrast enhancement principles. The adaptive filter removes the spatial frequency component of the noise [15], and some material structures' high-frequency component is enhanced with a contrast algorithm.

A common way to eliminate noise from aggregate or concrete material's image is by applying a process called low-pass filtering [15], which preserves the sharp details of an aggregate particle or paste matrix while eliminating other elements in the concrete surface image. This method removes noise by applying a low-pass filter and then enhancing the sharpness of the image. This method is also known as an anti-aliasing algorithm. The idea behind this technique is simple: we take a concrete structure's image and run it through a series of filters and enhance the sharpness of the image for analysis. Figure 6 shows the results of concrete crack analysis using the low pass filter method.

Figure 07: Triangular mesh generation for the aggregate characteristics investigation in the concrete surface [16]

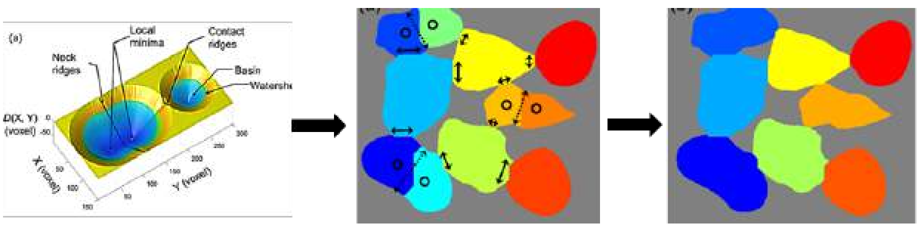


FINITE ELEMENT INVESTIGATION THROUGH FINITE ELEMENT MESH GENERATION

The finite element method (FEM) is a numerical technique that can be used to solve complex problems. In 2D image analysis, finite element methods are used to investigate the concrete material's inhomogeneity and microstructures. Furthermore, algorithms have been used to produce finite element simulations of images in order to reconstruct images using the neural network algorithm. However, the finite element method has limitations and requires access to high-performance computers.

It is important to note that the neural network algorithm does not produce exact results. The reconstructed image will be a representation of what the original image is, but it will not be identical. Reconstruction of blurred and noisy concrete surface images using the neural network algorithm has been a successful technique, as shown in Figure 7. The neural network, however, requires an intense number of parameters to be determined, which can often be solved either by trial and error or by searching through the parameter space. The FEM has been applied to image processing in order to solve some well-known problems, including segmentation and boundary detection.

Figure 08: Watershed analysis for aggregate particles (a) watershed transform (b) over-segmentation (c) joint-over segmented particles using algorithm [17,18]



WATERSHED ANALYSIS

Physically separating particles into a group of aggregate particles is one way to measure their size. However, the throughput of such an analysis system, that is, the number of particles that can be analyzed in a certain period of time, is strongly limited by factors like physical constraints and cost. A different technique used to segment small aggregate and concrete particles based on their volumes (rather than surface areas) has been developed, and is called watershed analysis [17,18].

The watershed algorithm can separate regions of high intensity from the low intensity. It may be possible to change the appearance of an image in watershed zones by examining the intensity level of that material. However, particles with constrictions do not respond well to this conventional technique because some of the concrete or aggregate particles do not have distinct borders, as shown in Figure 8. Because the watershed analysis cannot distinguish between particle interactions and "necks" of peanut-shaped particles.

The problem of identifying the different interactions between particles is addressed by using a new algorithm called "Watershed segmentation", which can be used to detect peanut-shaped particles. Moreover, watershed analysis is a powerful tool for identifying paste matrix and aggregate particle interactions. However, it does not provide information about the size of the particles that make up the interaction zones. Therefore, the method can be improved by using a different approach by applying a derivative function

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to the intensity of each pixel, it is possible to accentuate the change in intensity from one pixel to another. This technique can help separate aggregate/concrete particles with no distinct edges from those with constrictions or necks.

CONCLUSION

The traditional methods used to analyze concrete structures include physical testing, computer modelling and finite element analysis. Physical testing is the most accurate way to determine a material's strength, stiffness and durability. However, analyzing concrete structure characteristics such as cracks, aggregate properties and paste matrix is difficult because of the high cost associated with using advanced equipment. Therefore, Image analysis techniques are being increasingly employed in the civil engineering field to address this issue. Image analysis is a process that involves the use of computer programs to examine images. This can be done on an individual basis, or it can be done in a laboratory setting with automated processes that are controlled by a computer. Image analysis aims to determine specific characteristics of the objects being examined. Various types of image analysis techniques are available: Image contrast enhancement; Segmentation; Thresholding; Noise Removal; Finite element investigation, and Watershed analysis, all used to perform concrete material property investigations. However, each image analysis technique has its own advantages and disadvantages; thus, choosing the appropriate method depending on the required analysis is essential. Therefore, it is best to choose a method based on the purpose of the analysis as well as the characteristics of the material or concrete surface being analyzed.

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Authored By:

S Hareindirasarma
Department of Civil Engineering
University of Jaffna