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THE USE OF IMAGE ANALYSIS TO QUANTIFY THE ORIENTATION OF CRACKS IN CONCRETE

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Abstract

Cracks formed in concrete due to frost action (or other expansive reactions) can lead to further damage e.g. because they increase moisture transport. The extent of the consequential damage in concrete is likely influenced by the orientation of the initial cracks. Traditional quantification of the crack orientation is a time consuming manual process. In this paper, a method using automatic image analysis is proposed. The method is based on using image gradients to detect cracks and their orientation. The method produces results that concur with visual observation and manual counting in addition to being substantially quicker.

1. Introduction

Ice formation during frost action (or other expansive reactions) may result in crack formation in concrete. As a result, the concrete will have reduced mechanical strength and the cracks will lead to increased moisture and chloride transport [1]. Therefore, it is likely that the extent of further damage occurring in the concrete is related to the orientation of the cracks.

Presently, the common way to analyse the crack orientation in concrete is by using the human eye, but it is difficult and time-consuming to precisely measure the orientation. It is therefore important to develop a method that can quickly and reliably give an assessment of the crack orientations. An ideal method would be easy to use and able to produce results independent of the operator. The results should be in agreement with what can be achieved by manual counting without requiring extensive calculations. Lastly, it should require a minimum of preparation of the test specimen and the image. In this paper, an investigation was undertaken to determine if image analysis based on a so-called gradient method can fulfil these requirements.

2. Theory

A digital image is a matrix of pixel values representing the colour intensity, or in the case of a greyscale image, the brightness. This pixel value ranges from 0 to 255. Edges between areas with different colours can be identified, because there is a relatively large difference in pixel values between neighbouring pixels in the border region. This results in the largest gradients to occur orthogonal to the border. For each pixel in the image, the direction and magnitude of the largest gradient is calculated. The magnitude of the gradient is used to decide which pixels are parts of a border and the direction determines the orientation of the border. The gradients are determined through a so-called correlation process.

2.1 Correlation of image

To determine the magnitude and direction of the largest gradient between each pair of adjacent pixels, it is first necessary to determine the x- and y-components of the gradients. Furthermore noise in the image must be reduced to get the optimal results from the gradient analysis. This is done via a so-called correlation process through the application of so-called kernels. Kernels are square matrices applied to the input image, producing two new matrices. In this case, two matrices G_x - and G_y -matrix are produced. Each entry in the new G_x - and G_y -matrix is a combination between the weights of the kernel applied, and the corresponding pixels in the input image. The entry in the G -matrices is then the sum of the weights in the kernel times the affected pixel values in the input image. This can be explained mathematically as shown in equation (1):

$$g_x(x, y) = \sum_{j=-R}^R \sum_{i=-R}^R h(i, j) \cdot f(x + i, y + j) \quad (1)$$

Where $g_x(x, y)$ is the value stored in the G_x -matrix that contains the x-component of the gradients, R is the radius of the kernel, h is the applied kernel and f is the pixel value of the input picture. x and y are pixel coordinates in the input picture. The same is the case for the G_y -matrix. This process is repeated for all the pixels in the input image.

Prewitt			Sobel		
Vertical		Horizontal	Vertical		Horizontal
-1	0	1	-1	-1	-1
-1	0	1	0	0	0
-1	0	1	1	1	1
-1	0	1	-1	0	1
-2	0	2	-1	-2	-1
-1	0	1	0	0	0
1	2	1	1	2	1

Figure 1: Coefficients in the Prewitt and Sobel kernels after [2]

The two kernels shown in figure 1 are often used kernels for edge detection [2]. Both have the radius $R = 1$. There are many different kernels, but these two are highlighted due to their simplicity and ability to produce satisfactory results. The Sobel and Prewitt operators are

quite similar. The main difference between the two is that the Sobel kernel weighs the centre pixel more than the rest, and the Prewitt kernel weighs all the pixels equally [2]. The gradient operator implemented for the method described in this article, is the Prewitt operator due to its efficiency and simplicity [3]. The Prewitt kernel is furthermore well suited to eliminate low-frequency noise [4].

The difference between the kernels is demonstrated in [5]. The Prewitt method does not register edges, where there is a small difference in pixel grey level, in contrast to the Sobel method. Since the edges of the cracks (see section 3 Method) analysed in this paper are clearly defined, it is assessed that the Prewitt method is better suited for this task. In addition, the Sobel method sharpens some transitional phases that can distort the results.

2.1 Gradient calculation

The magnitude and direction of the steepest gradient is determined for each pixel. The kernel operators result in two values, one in the x-direction and one in the y-direction. The magnitude of the gradients is the difference in the pixel grey level and the direction of the gradients is the combination of the x- and y-gradients. The orientation of the cracks will then be the orthogonal direction of the gradient. The magnitude and direction of the gradient can be expressed as in equations (2) and (3) respectively, with (x, y) being the pixel position in the gradient matrices:

$$g_{mag}(x, y) = \sqrt{g_x(x, y)^2 + g_y(x, y)^2} \quad (2)$$

$$g_{\theta}(x, y) = \arctan\left(\frac{g_x(x, y)}{g_y(x, y)}\right) \quad (3)$$

3. Method

Cracks in concrete can be identified and quantified by image analysis, if the cracks have clearly defined edges. To get optimal contrast between the cracks and their surroundings, the image analysis procedure is applied on plane sections of fluorescent epoxy-impregnated concrete. The surface is photographed under UV-light, causing the epoxy-filled cracks to light up with a green hue. The rest of the concrete remains black or dark blue. The image is photographed with a high-resolution camera and stored in a lossless file format (e.g PNG) for an optimal result. The image file is then cropped to remove the image background and loaded into the image analysis program. The program was developed in Matlab, because it is easy to use and well suited for matrix calculus. The program is described in the following steps.

Because the gradient method only registers difference in brightness, it is not possible to apply it to an RGB image, which constitutes of a red (R), green (G) and blue (B) layer, and it is therefore necessary to convert the image to a greyscale image, which contains one layer.

Step 1: Convert image to greyscale. Rather than using the default method for conversion of RGB to greyscale, it turned out to be more effective to simply use the green layer of the RGB image, because the cracks in the image primarily are green. This has the added benefit of removing the risk of detecting a false edge from transition between aggregate and cement paste.

Step 2: Apply horizontal and vertical kernels to the greyscale image. This yields two matrices, G_x and G_y , containing the x and y components of the steepest gradient for each pixel in the image.

Step 3: Determine gradient magnitude and direction. This is done for each pixel in the image using G_x and G_y as described earlier. It is noteworthy that the gradients will point towards the cracks, since this is where the increase in pixel values is.

Step 4: Select threshold for the analysis. This is done by analysing selected regions with distinct geometric features, e.g. an approximately vertical or horizontal crack. This makes it easy to establish a ground truth. The threshold is then set by comparing the control image for different threshold values with the original image.

Step 5: Determine crack edges. This is done based on the magnitude of the gradient. If the magnitude is lower than the specified threshold, the pixel is not considered as being part of a crack edge, and therefore ignored. Note that the gradient between pixels located in the same crack is small, so only the edges of the cracks are above the threshold.

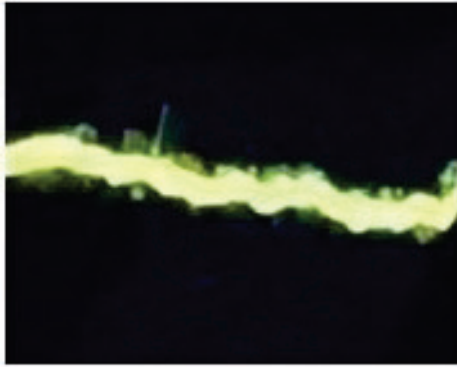
Step 6: Quality control. To ensure that the threshold has a value that produces a satisfactory result, a control image is produced. This shows the pixels where the gradient is above the threshold and should show the same cracks as can be identified in the original photo.

Step 7: Display the results regarding the direction of the gradients. Orientations (angles) are rounded to the nearest integer. Finally, the direction of the cracks are calculated as the direction orthogonal to the gradient and converted to a range between 1 and 180 degrees

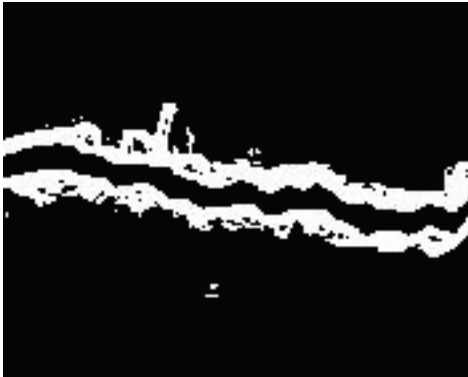
4. Validation of method

Validation has been carried out on images of concrete damaged by alkali-silica reactions (ASR), as they show very distinct crack orientations. The analysis presented in figure 2-3 is conducted on sections of figure 4a. These sections contain simple geometrical figures and it is therefore easy to evaluate the accuracy of the applied method. First, the influences of threshold values are analysed, see figure 2. The best threshold for this image is found to be $g_{mag} = 150$. Next, the method's ability to detect different orientations in the same image is tested. Figure 3 shows the results from the image analysis when run on two images with distinct geometrical features. Lastly, the analysis is conducted on two full images, ASR1 and ASR2, and compared to results obtained from manual counting. The manual counting is done by dividing the specimen into 10x10 mm sections and then identifying each crack in the section using an optical microscope. The direction of the identified crack is then calculated using a computer. [6]

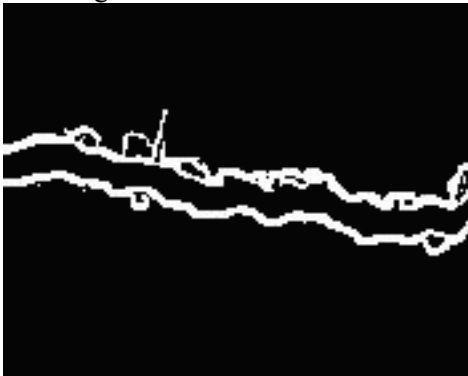
In figure 2-4, the horizontal line $y = \frac{100}{180} = 0.556$ in the histograms represents an image with evenly distributed orientations.



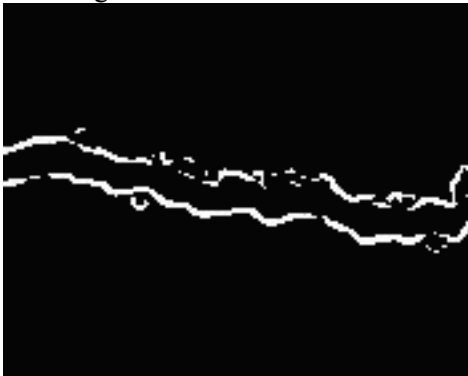
(a) Original image displaying horizontal crack



(b) Control image for threshold = 50

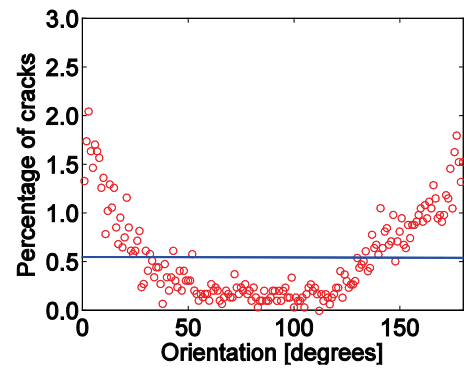


(d) Control image for threshold = 150

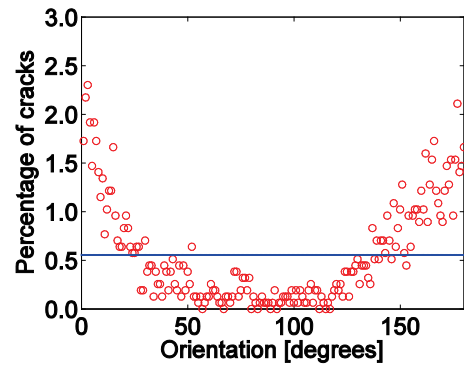


(f) Control image for threshold = 250

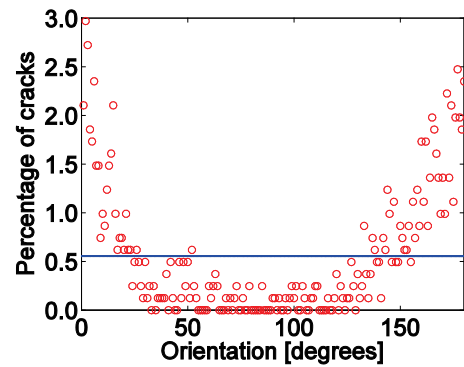
Figure 2: Test of different threshold values



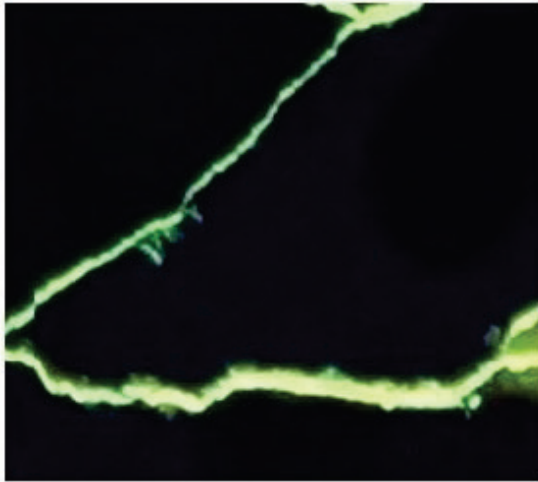
(c) Crack orientation histogram for threshold = 50



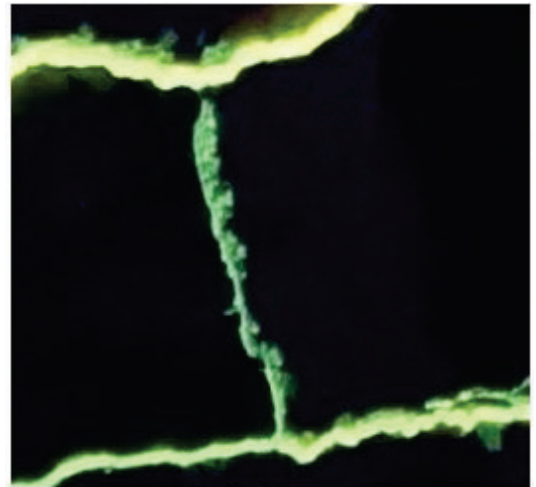
(e) Crack orientation for threshold = 150



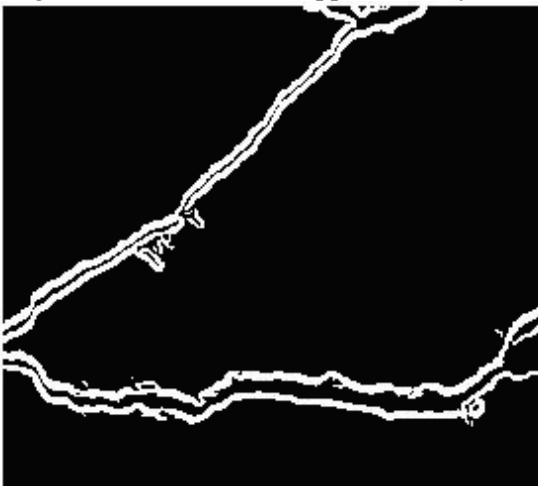
(g) Crack orientation for threshold = 250



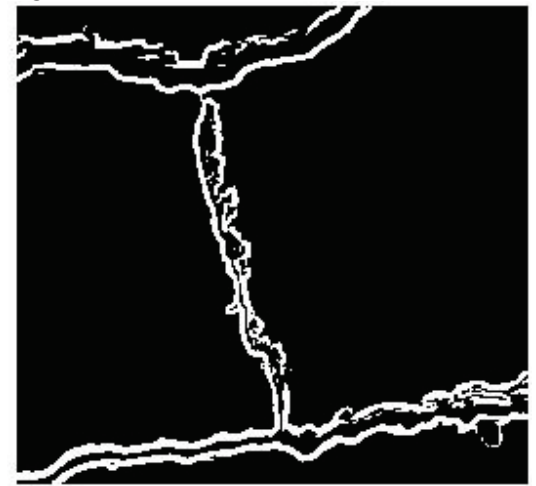
(a) Image with horizontal and approximately 45° crack



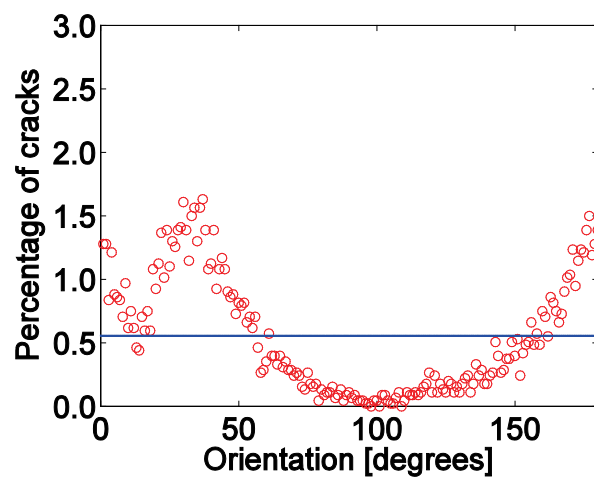
(b) Image with a vertical and two horizontal cracks.



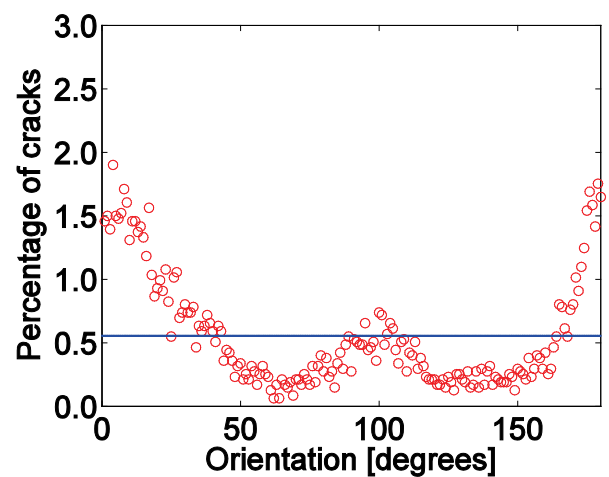
(c) Control image



(d) Control image

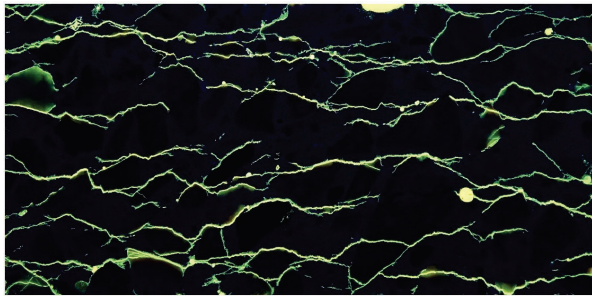


(e) Crack orientation histogram

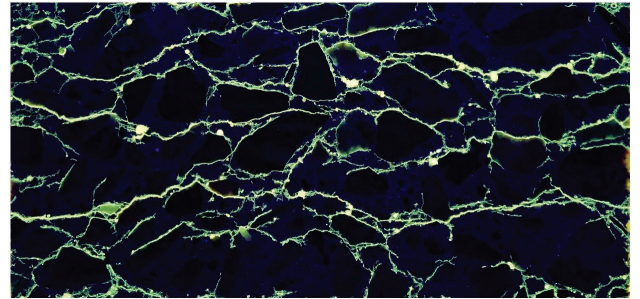


(f) Crack orientation histogram

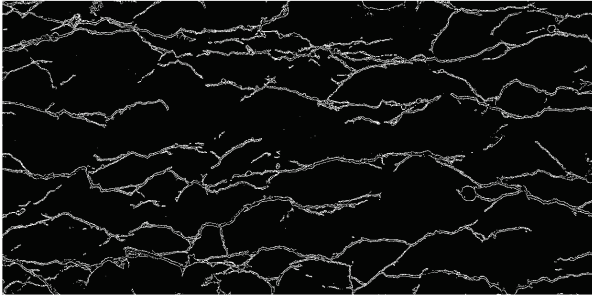
Figure 3: Test of ability to recognize distinct geometrical features



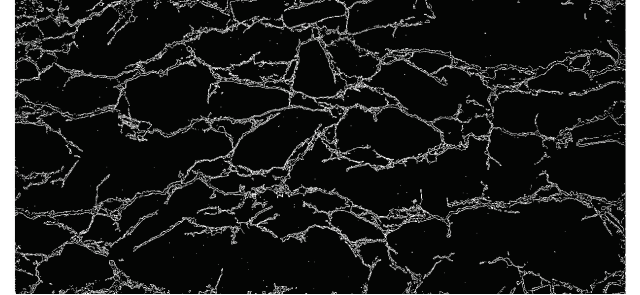
(a) ASR1 original image. The image is 100 x 200 mm and 1835 x 3725 pixels



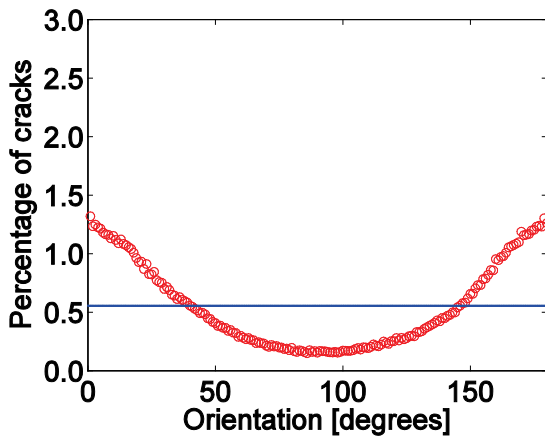
(b) ASR2 original image. The image is 100 x 200 mm and 1777 x 3713 pixels



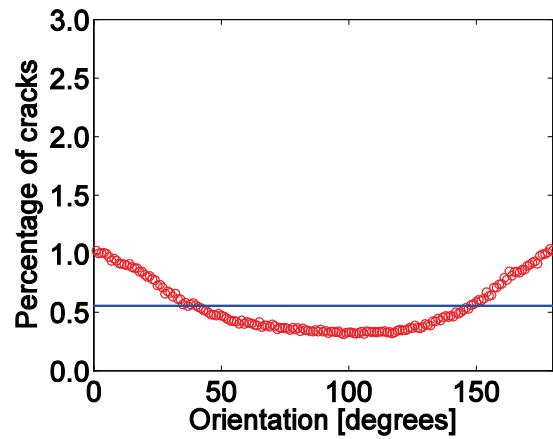
(c) ASR1 control image



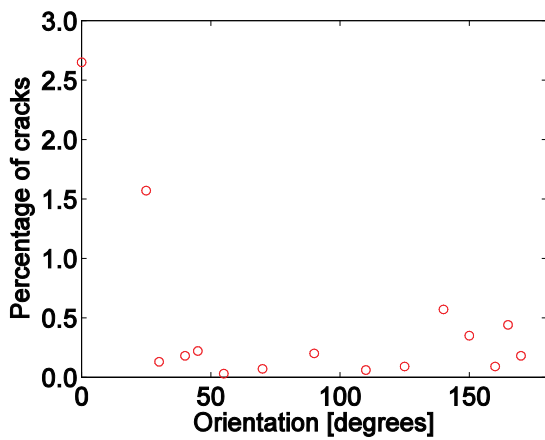
(d) ASR2 control image



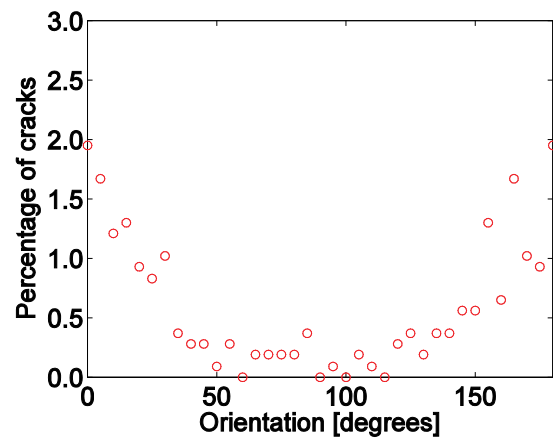
(e) Crack orientation histogram for ASR1



(f) Crack orientation histogram for ASR2



(g) Manual count of ASR1 orientations



(g) Manual count of ASR2 orientations

Figure 4: Samples analysed using gradient method and manual counting

5. Discussion

The method presented in this paper is evaluated on the criteria presented in the introduction. The method requires a thorough specimen preparation as it is necessary to embed it in fluorescent epoxy and polish the surface that is going to be analysed. The described method is very dependent on that cracks have a significantly different colour than the rest of the concrete, and therefore it cannot be used on samples without preparation. It is clear that the usage of the green value to determine the gradient would not work for specimens where the cracks are not green. The photographing of the specimens is uncomplicated; it only requires a dark room, a UV-lamp and a camera. The resolution of the camera must be high enough to ensure that the smallest crack has a width of at least two pixels and preferably higher. If the crack only has a width of 1 pixel, a gradient cannot be properly identified. It is important, however, that the specimen surface is parallel in regards to the camera lens to prevent distortion in the image. With the right setup, a large number of specimens can be photographed quickly. The only preparation needed for the images is the manual removal of background. While a lossless file format should be used, a lossy format (such as JPEG) can still produce adequate results.

The need to choose a threshold is the weakest part of the method and the only instance where the operator can influence the results, because the threshold is selected manually based on the control image. This is problematic as the method is somewhat sensitive to different thresholds, as can be seen in figure 2. A lower threshold will lead to smoothing of the results, as more noise is included in the results, whereas a higher threshold will omit parts of the crack. This becomes even more problematic as different light conditions and even the composition of the specimen can influence the magnitudes of the gradients, making it difficult to determine a universal threshold.

The method is able to identify cracks with a clear orientation as seen in figure 3. As can be seen in the figure, the Prewitt kernel identifies the edge of the crack but not the transition between the aggregate and the cement paste. When compared to manual counting (see figure 4), the method produces similar results. The difference in the results is because the gradient method registers the orientation of every pixel that is part of a crack (and unavoidably some noise), while the manual count does not register small changes in crack orientation, such as a deflection by aggregate particle or very small cracks. This will cause the results from the manual counting to be grouped more closely around dominant crack orientations. While both methods produce similar results, the gradient method is considerably faster. An image with a size of 1835x3725 pixels or 200x100 mm takes less than 1 minute to analyse on a standard laptop whereas it can take an experienced operator 2-3 hours to do a manual count. The fast analysis for the gradient method derives from the fact that it does not require any detailed calculations. For each pixel in the image, only a few simple calculations are performed.

In addition to being substantially faster, the gradient method can also be used to analyse specimens with a dense crack pattern consisting of thin, short cracks, something that is very difficult to do manually. Examples of such crack patterns can for instance be found when analysing specimens heavily damaged by frost action, as shown in figure 5.

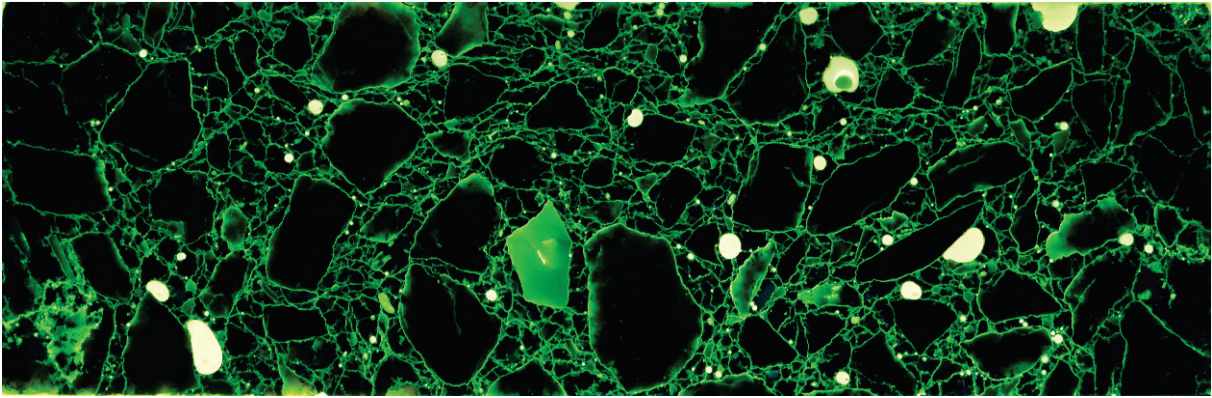


Figure 5: Specimen subjected to freeze/thaw cycles [7]

6. Conclusions

The developed method is able to produce results that are in accordance with visual evaluation and manual counting. The method has a substantial speed advantage in comparison to the manual count, as it takes less than one minute to perform the analysis on a regular laptop, in comparison to the 2-3 hours it takes an experienced operator to do a manual count. As discussed earlier, the method has its weakness in relation to the manner how the threshold is determined. The manual configuration is strongly dependent on the operator, whose experience and insight in the method will decide, how fast the process is.

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