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Measurement of pavement macrotexture through digital image processing

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ABSTRACT. The texture data of roads and airport pavement are extremely important for reducing accidents, mainly in cases of wet surface. The texture measurement is essential to evaluate the driving quality, however the conventional processes (field tests) are expensive and cause traffic interruption. The aim of the present study was to develop a practical procedure to measure the asphalt pavement macrotexture using image processing and to compare it with sand patch tests. The parameter selected to quantify the surface pavement condition was the image information content calculated by a FFT (Fast Fourier Transform) through modification in the light intensity among neighboring pixels, this modification is called spatial frequency. Seeking to contribute with traditional methods, the proposed procedure causes low interruption in traffic, being also fast, accurate, with good reproducibility, and low cost. In comparison with sand patch test, the image processing technique proved to be efficient, and suitable to be used to identify areas with texture problem, reducing the possibility of accidents.

Keywords: flexible pavement, image processing, Fourier transform.

Mensuração da macrotextura de pavimentos pelo processamento digital de imagens

RESUMO. O conhecimento da textura do pavimento rodoviário ou aeroportuário é extremamente importante para redução de acidentes, principalmente em casos de pista molhada. A mensuração da textura é fundamental para aferição da qualidade de rolamento, todavia os processos convencionais (ensaios de campo) são caros e necessitam interrupção do tráfego de veículos. O objetivo desta pesquisa foi desenvolver um procedimento prático de mensurar a macrotextura de pavimentos asfálticos usando processamento de imagens e compará-lo com medidas de mancha de areia. O parâmetro selecionado para quantificar a condição superficial do pavimento foi o conteúdo de informação contido em cada imagem e calculado por uma FFT (*Fast Fourier Transform*) por meio da modificação na intensidade de luz entre *pixels* contíguos, tal modificação é denominada frequência espacial. Visando contribuir com os métodos tradicionais, o procedimento proposto causa mínima interrupção no tráfego, é rápido, preciso, tem boa reprodutibilidade e é de baixo custo. A comparação do processamento de imagem com a técnica da mancha que comprova sua eficiência e o qualifica para ser utilizado a fim de identificar trechos com textura fora dos padrões técnicos vigentes que reduz a possibilidade de acidentes.

Palavras-chave: pavimentos flexíveis, processamento de imagem, transformada de Fourier.

Introduction

In the last few decades, Brazil has experienced a very fast growth in vehicle fleet (ANTP, 2003; IPEA, 2006), both in quantity and in car technologies, enabling the vehicles to transit with higher speed and to transport higher load volumes. Also the national highway network does not provide ideal conditions of traffic and safety (CNT, 2010).

Unofficial data estimate that in Brazil, approximately eighty thousand people die per year as a result of traffic accidents (PAVARINO, 2004). One cause of accidents is the bad preservation of roads, combined with human and environmental factors. In the case of deteriorated pavements, there may be the loss of contact tire/pavement and, consequently, the difficulty of maintaining the vehicle in the desired route (APS et al., 2003; DNIT, 2006).

Researches published in 2006 by IPEA (Applied Economic Research Institute), DENATRAN (National Traffic Department) and ANTP (National Association for Public Transport) with data referring to the biennium 2004/2005 indicate that the cost of an accident in which the person escape unharmed is R$ 1,040.00, when a victim is classified as injured the cost is R$ 36,305.00 and in the case of fatality the cost is R$ 270,165.00.

The pavement surface irregularities greatly influence the functional performance, by significantly altering the road comfort, the safety in wet road, the fuel economy, the noise level, among others (SPECHT et al., 2006, 2009). Among the layers that compose the pavement, the road surface layer is the responsible for the appropriate texture (mega-, macro- and microtexture) and to provide good conditions of friction tire/pavement.

The friction developed between tire and pavement is responsible for maintaining the vehicle route in the road, being greatly influenced by environmental conditions, mainly rainfall and presence of thin water layer on the road surface. The water accumulation on the road surface, in front of the tire, generates hydrodynamic pressures in the contact zone tire/pavement and, depending on the accumulated water volume and the vehicle speed; it may occur the loss of contact between tire/surface making impossible any driver's maneuver (aquaplaning).

The texture of a pavement can be divided into three main classes: micro-, macro- and megatexture. The microtexture is related to the surface of the mineral aggregate, which can be rough or polished, whose wavelengths vary between 0 and 0.5 mm and amplitude between 0 and 0.2 mm. The macrotexture can be characterized as the pavement surface roughness caused by the aggregate protuberances, with wavelength between 0.5 and 50 mm and amplitude between 0.2 and 10 mm, while the megatexture presents wavelength varying between 5 and 50 cm and amplitude between 1 and 50 cm.

The macrotexture is related to friction at high speeds, the pavement ability to drain surface water and to prevent the aquaplaning, spray formation, formation of night mirror effect, increased fuel consumption, tire wearing and the excessive noise (BERNUCCI et al., 2006). The most widespread way to measure the macrotexture is through the sand patch (or height) test standardized by ASTM D965-96 (ASTM, 2000; SPECHT et al., 2006). Other ways to measure are also used, mainly in foreign countries, such as continuous meters with laser and the Grip Test.

The processes that involve computational modeling and mathematics bring new forms of approach for a large number of problems, opening new perspectives of research and technological development (SPECHT et al., 2007). The image processing is a research area which has been growing in the last few years and has a large number of applications in several areas (medicine, geography, engineering etc.). It is divided into three levels: low, intermediate and high processing level.

The low level processing involves primitive operations such as pre-processing of image to reduce noise, to improve contrast and image sharpness. A low level process is characterized by the fact that both the input and output are images. The intermediate level process involves segmentation (partitioning of the image into regions or objects), describing these objects to reduce them for an adequate form aiming the computerized processing and classification (recognition) of the individual objects. An intermediate level process is characterized by the fact that the input is an image, but the output is attributes extracted from this image (borders, outlines, and the identification of individual objects). Finally, the high level processing gives meaning to the objects recognized and play cognitive functions normally associated with the human vision (GONZALEZ; WOODS, 2003).

An important element on the creation of an image is the color, and computers use the RGB system (Red-Green-Blue) in the process, in which is controlled the intensity of these three basic colors. By defining a given color in a computer, it is specified the intensity (value associated) to the transmitters R, G and B.

In the RGB system, the value (0, 0, 0) corresponds to black color, total absorption, and intensity zero in the three components. The value (255, 255, 255) corresponds to white color and total reflection (GONZALEZ; WOODS, 2003; GONZALEZ et al., 2004). The different combinations among RGB are able to generate any type of color, in which, if the three components have exactly equal values, it will be defined a tone scale of gray, called grayscale, or also known as monochrome image.

According to Gonzalez et al. (2004) the term monochrome image refers to the two-dimensional function of light intensity $f(x, y)$; the f value at any point (x, y) is proportional to the image brightness (levels of gray) at that point. A digital image is composed of a finite number of elements, where each element has specific location and value; it can be considered as a matrix whose rows and columns indices identify a point on the image, and the corresponding value of the matrix element identifies the level of gray at that point. These matrix elements are called image elements, *pixels* or *pels*, these last two, abbreviations of *picture elements*. A pixel is the basic element, of finite dimensions, on an image whose most common form is rectangular or square.

Although the size of a digital image varies according to the application, there are advantages of selecting square matrices with sizes and numbers of gray level which are integer powers of two. An image can be represented by a matrix $N \times M$, as shown in Equation 1.

$$f(x,y) \approx \begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0,M-1) \\ f(1,0) & f(1,1) & \cdots & f(1,M-1) \\ \vdots & \vdots & & \vdots \\ f(N-1,0) & f(N-1,1) & \cdots & f(N-1,M-1) \end{bmatrix} \quad (1)$$

The right side of the Equation 1 represents what is usually called a digital image. Each matrix element is named a picture element, *pixel* (GONZALEZ et al., 2004). The MATLAB Software, used in the study, does not accept null indices, and for that reason Equation 1 was represented as follows:

$$f(x,y) \approx \begin{bmatrix} f(1,1) & f(1,2) & \cdots & f(1,M) \\ f(2,1) & f(2,2) & \cdots & f(2,M) \\ \vdots & \vdots & & \vdots \\ f(N,1) & f(N,2) & \cdots & f(N,M) \end{bmatrix} \quad (2)$$

In the processing, the texture is a characteristic directly related to the physical properties of an object's surface, and contains important information on the surface structural arrangement (GONZALEZ et al., 2004; HARALICK et al., 1973; PIDWERBESKY et al., 2006). A texture is characterized by a repetition of a model in a given region, being the model exactly repeated or with few variations. Through its analysis, in the digital processing, it is possible to distinguish regions with the same reflectance, spatial pattern and frequency on the variation of gray tones and, therefore, the same colors in a given combination of bands. This makes texture an excellent regional descriptor, contributing to better accuracy of the recognition processes, description and classification of images.

Each image has a finite sum of information contained within its frontier. This information can be measured by determining the relative changes for the luminous intensity between adjacent pixels. The luminous difference is seen as the spatial frequency. On the other hand, if two neighbor *pixels* have luminous intensity approximately equal, they have low contrast and spatial frequency.

The selected parameter for quantifying the surface condition, through the reflection contrast, was the information content of each image calculated by a FFT. This approximation can be used for quantifying the information content of a digital image that uses the information theory (CHRISTIE, 1954). In this context, this study aimed to develop a practical method for measuring the macrotexture of flexible pavements using the processing of digital images, incorporating theoretical information and analyses developed through mathematical processes in order to replace and/or to complement the sand patch test information.

Material and methods

In the pavement macrotexture measurement, the captured image was transferred and processed by a computer. The format chosen was JPEG by occupying small space and reduced computational time. It was made summarizations without significant loss of quality, using the Adobe Photoshop software, and later the images were saved in the Matlab folder *work* with square dimensions of 512 x 512 *pixels* and resolution of 300 pixels inch^{-1}.

In the processing, we used resources found in the Matlab software toolbox, such as the resource of mask which reduces interferences and allows extracting interesting attributes for texture. The image was processed, and separated by rectangular regions, from outside to inside, and calculated the FFT (Fast Fourier Transform) in every region.

The FFT algorithm used for obtaining spatial information of a digital image works as follows:

- the image captured by a camera is transferred to a computer, where it is cut and saved in the Matlab folder;
- it is converted into gray tones containing the standard variety of 256 levels of gray;
- the image is processed and separated into regions as illustrated in Figure 1, it is calculated the FFT whose frequency components are segregated. The frequency components begin with the component zero at the central pixel (PIDWERBESKY et al., 2006). In the present study, the image was divided into 126 regions;
- it is calculated the FFTs sum of the local pixels in every band (or ring);
- the sums are traced as a function of the frequency band;
- it is calculated the area upon the curve until the desired ring and then the data are ready to the analysis.

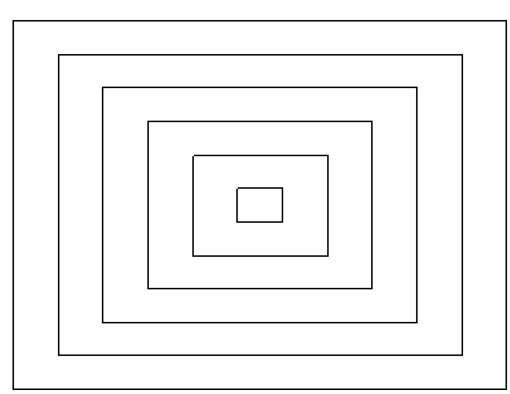


Figure 1. Rectangular frequency bands.

The Figure 2 illustrates the steps used in the present study for the images processing.

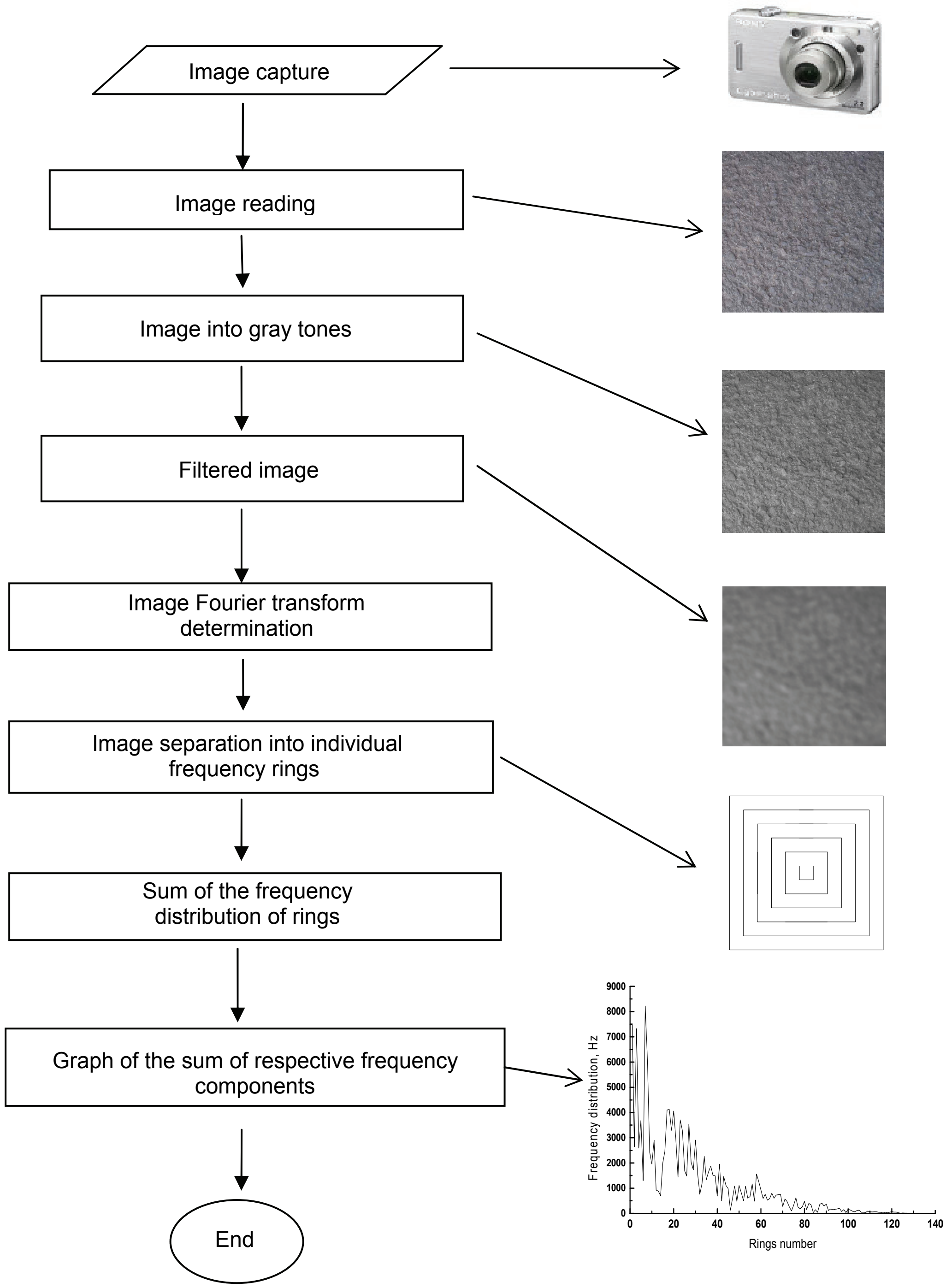


Figure 2. Protocol for image processing.

In the case of two variables, a discrete Fourier transform (DFT - Discrete Fourier Transform) can be presented:

$$F(u,v) = \frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1} f(x,y)\exp\left[-j2\pi(ux/M + vy/N)\right] \quad (3)$$

u = 0, 1, 2, ...,M - 1, v = 0, 1, 2, ...,N - 1, and its inverse:

$$f(x,y) = \sum_{u=0}^{M-1}\sum_{v=0}^{N-1} F(u,v)\exp\left[j2\pi(ux/M + vy/N)\right] \quad (4)$$

to x = 0, 1, 2, ...,M - 1, y = 0, 1, 2, ...,N – 1

The function f(x,y) represents the image intensities at various pointS of the spatial domain considered, or it is a function on spatial domain.

The Fourier transform F(u,v) represents a image as a sum of complex exponential functions of different magnitudes, frequencies and stages and serves for improvement, analysis, recovery and compression of images. This function is defined on the frequency domain.

The number of operations required to calculate F(u,v), using DFT by the formula (3), is proportional to N^2. For larges N the time of calculations is very high. In this case, the FFT is used to minimize the time of computational operations. The appropriate decomposition of this equation can make the number of multiplications and addition operations proportional to $N\log_2 N$. The decomposition procedure is known as fast Fourier transform (FFT). For the problem considered, the reduction in the number of operations has order of 10^2, which represents significant savings in the computational efforts.

Results and discussion

The efforts of the present research was focused on the attempt to establish a relationship between the measured texture through the sand height and the mathematical response obtained from FFT in asphalt pavements of varied textures.

A computational program was developed to read information contained in the images, specially the spatial frequency; the next step was to create a database of sand patch tests with their respective images; it was created a group of 26 images of the surface of pavements with varied textures, from very fine (0.15 to 0.22 mm) to very coarse (1.20 to 4.97 mm). It was then, calculated the FFT of every image and compared with the sand patches heights.

The images were achieved with conventional digital camera at right angle and without direct sun; taken at the highway RS 342 (Double Surface Treatment) and at urban highways from the municipality of Ijuí (asphalt mixtures type pre-mixed while cold and asphalt concrete), always in tangent sections.

Each image was divided into a group of 127 rings; however, it was observed that most changes in the FFT value occurs in the first 25 rings, in the subsequent rings only insignificant changes were verified for the research objectives. Therefore, the effort was focused on the first 25 rings.

The repetition or the variation in the model within a region was analyzed. It was observed that: given a coarse texture of pavement, there are relative differences in illumination between neighboring pixels and, therefore, the image has high spatial frequency as illustrated in Figure 3; but, if the image has fine aggregates or almost completely immersed in asphalt mastic, the surface will show low variations in the illumination between neighboring pixels. Therefore, they have low contrast and spatial frequency, as shown in Figure 4.

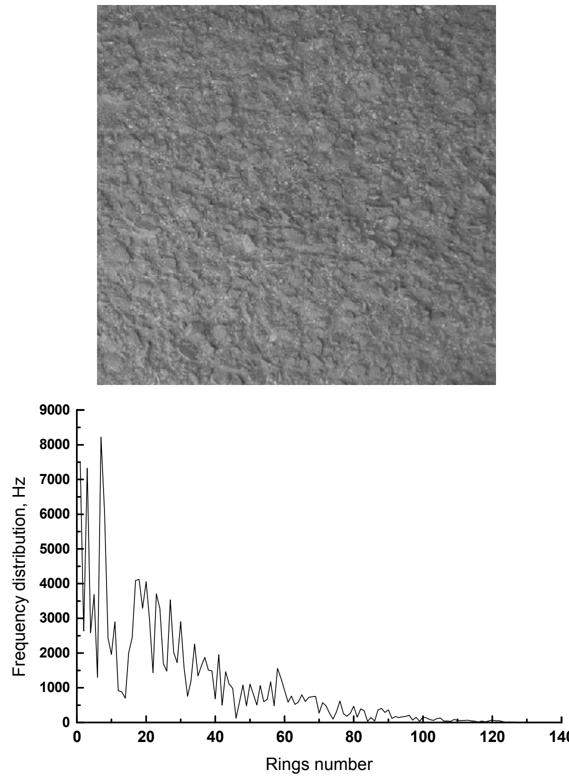
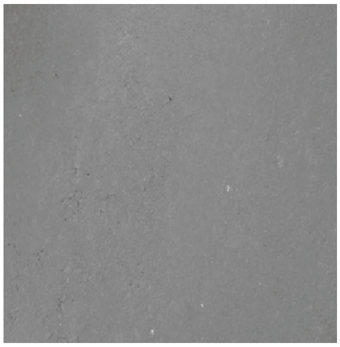


Figure 3. FFT sum *versus* number of rings considered (coarse texture).

In order to compare the 26 images database and the respective sand heights, it was developed a program that calculates the integral (area under the curve) of each image until the desired ring. The comparison between the FFT frequency distribution of the 26 images calculated in the first ring and the height obtained by the sand patch test, generated a coefficient of determination R^2 of 0.36 when compared with a second order polynomial curve, and when compared with a linear curve, R^2 was lower; by increasing the polynomial order the coefficient is improved. However, what seems to be an improvement, it is not, because only the curve complexity generated by the polynomial is improved. The second order polynomial equation generates satisfactory results.

The coefficient of determination did not show satisfactory results for the first ring. R^2 of only 36% is not acceptable in comparison with results obtained with the patch test.



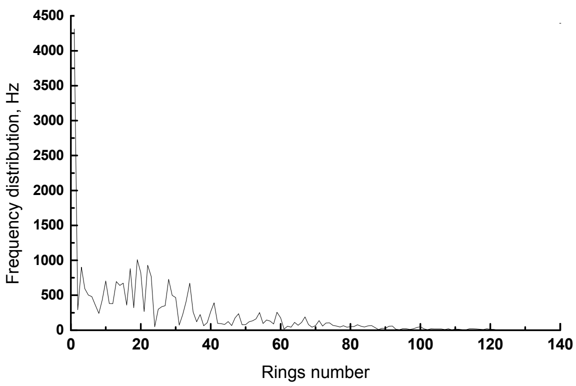


Figure 4. FFT sum *versus* number of rings considered (fine texture).

Then, we made attempts of summing the frequency distribution from the ring 1 to N (N = 127). When increased the number of added rings, it was noticed significant changes in the sum of the FFT frequency distribution, R^2 increased from 0.36 to 0.78. Such an improvement can be explained by the fact of the sum of various rings to represent significant area of the image, providing thus a lower variation in texture and more homogeneous frequency.

The best results obtained for the relationship between the R^2 versus the number of added rings was observed for the sum from the 13 to the 19 first rings (Figure 5). The highest R^2 was found for the sum of 16 or 17 first rings. It was also verified that if added rings from 20 to 30, from 30 to 40 or other sequences starting from the first 25 rings, insignificant changes would emerge.

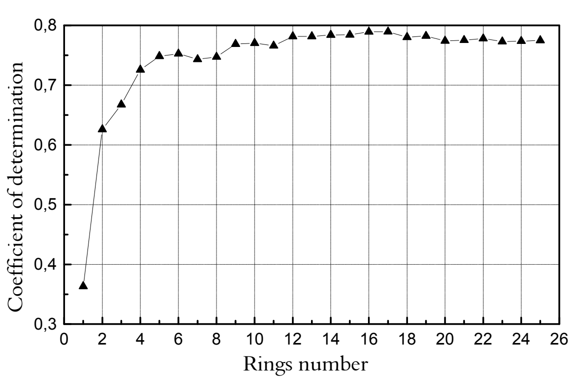


Figure 5. Coefficient of determination versus number of rings.

Figure 6 presents the distribution in the 16 first rings. Thus, the suggested polynomial equation to relate sand height (h_a) with $SFFT_{16}$ is the Equation 5:

$$h_a = -9.712 \cdot 10^{-10} \cdot (SFFT_{16})^2 + 1.049 \cdot 10^{-4} \cdot (SFFT_{16}) - 1.056 \qquad (5)$$

where:

h_a = sand height (mm);

$SFFT_{16}$ = sum of FFT until ring 16.

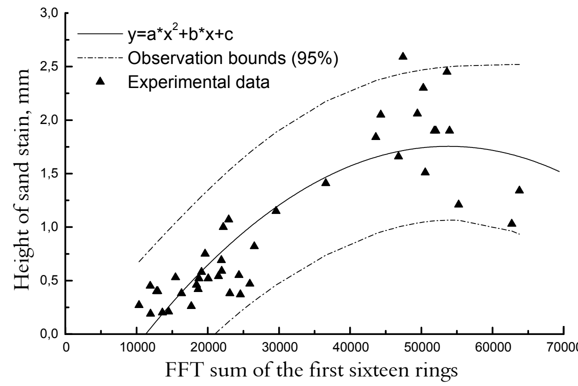


Figure 6. Relationship between the sum of FFT (until ring 16) and sand height: comparison between experimental and simulated data. R^2=0.7667; a= -9.712·10^{-10}; b= 1.049·10^{-4}; c= -1.056.

Most part of the values tested were well described by the parable (equation 5), the relationship between the sand patch heights and the FFT frequency distributions (lines in Figure 6), but there are domains where the simulated value for the patch heights can be negative, losing thus the physical sense. Obviously, the sum of FFT is related to the amount of information contained in the patch image. When surface is almost smooth, the quantity of image information and the patch heights are small and the sum of FFT is minimal. With increased roughness is increased the amount of information and h_a, reaching a maximum corresponding to a coarser texture. After this peak, despite the increase in the sum of FFT, h_a decreases due to an amplitude reduction and the dependence has a horizontal asymptote $h_a = 0$. For that reason, instead of parable (5) for generalization, can be also used the exponential function:

$$h_a = a \cdot \exp(-((SFFT_{16} - b)/c)^2) \qquad (6)$$

where:

h_a = sand height (mm);

$SFFT_{16}$ = sum of FFT until ring 16;

a, b, c = determined coefficients.

Figure 7 presents a comparison between experimental and simulated data, fitted by equation 6 for dependence between the sum of FFT (until ring

16) and sand height h_a. It can be observed that equation 6 describes better the experimental data (R^2 = 0.87) and meets the conditions at the extremities.

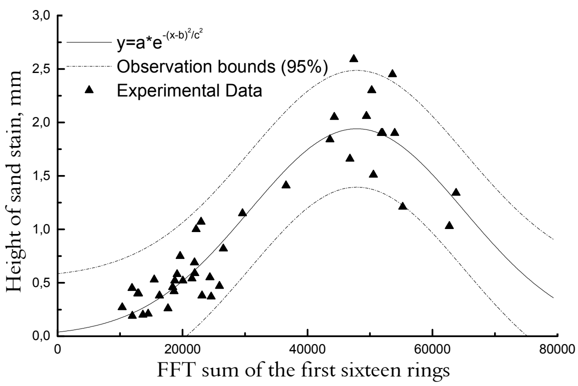


Figure 7. Relationship between sum of FFT (until ring 16) and sand height: experimental and simulated data comparison. $R^2 = 0.8693$; $a = 1.983$; $b = 4.748 \cdot 10^4$; $c = 2.359 \cdot 10^4$.

Conclusion

The experimental results proved to be possible to calculate the macrotexture through processing digital images and can, potentially, replace the sand height test by the use of a digital camera and subsequent processing. Through a set of experiments, it was possible to find the necessary tools to construct programs and mathematical equations to achieve a good correlation between the results of determination for the sand patch heights obtained by the digital processing method and by the sand height test.

The results showed that the sand height can be expressed as a function of the frequency distribution of FFT in the rings that form the digital image. The best result was obtained choosing as argument a sum of the FFT frequencies for the first 16 rings. In order to draw generalizations for the experimental data, two equations with three parameters were proposed: a second-order parable and an exponential function. The exponential function describes better the experimental data (R^2 = 0.87) and meets the conditions at the extremities.

The image processing proved to be efficient in the correlation between FFT and texture depth obtained with the sand patch test. Thus, it can complement and/or replace the sand height test, reducing the time spent to conduct the experiments and thus, the inconvenience to road users due to traffic interruptions, as well as reducing the risks to technicians that perform the test.

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