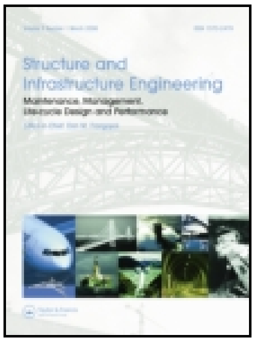

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Automatic concrete health monitoring: assessment and monitoring of concrete surfaces

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To predict the degradation of concrete structures is extremely challenging. The typical approach combines periodic visual inspections with required non-destructive tests. However, this methodology only discretely evaluates few areas of the structure, being also time consuming and subject to human error. Therefore, a new method designated 'automatic concrete health monitoring' is herein presented which aims at automatically characterising and monitoring the state of conservation of concrete surfaces by combining photogrammetry, image processing and multi-spectral analysis. The method was designed to (i) characterise crack pattern, displacement and strain fields; (ii) map damages and (iii) assess and define restoration tasks.

Keywords: concrete; durability; damage; assessment; monitoring; mapping; non-destructive tests

Introduction

Concrete is certainly the most widely used building material from the second half of the twentieth century. Consequently, there is now a significant number of structures, such as buildings, bridges or dams, requiring rehabilitation and strengthening, due to design and/or construction errors, or because the design life time is ending or simply because a different usage is being planned. Since rehabilitation costs increase exponentially with time, the ability to predict the degradation of concrete structures is extremely important and simultaneously a challenging task since different causes are often present. The typical approach consists in carrying out periodic visual inspections to detect structural damages. Whenever required, non-destructive tests are used to help establish a diagnosis and define an intervention plan. This methodology presents the following main drawbacks: (i) only few areas of the structure are discretely evaluated and (ii) the use of empirically based methods is time consuming and subject to human error.

With the recent development of low-cost optical/digital equipment, new opportunities are emerging for structural assessment. In this study, a method designated automatic concrete health monitoring (ACHM) is discussed. This method aims at automatically characterising and monitoring the state of conservation of concrete surfaces. The ACHM combines several techniques, namely, photogrammetry, digital image processing (DIP) and multi-spectral analysis, and was designed to (i) characterise crack pattern, displacement and strain fields; (ii) map damages and (iii) define or assess restoration tasks.

Automatic concrete health monitoring

The ACHM was developed within a research project based on the implementation of several specific modules. This feature enables independently upgrading different modules, as well as adding new modules, which can work cooperatively with already implemented modules. Currently, ACHM is organised into the following five modules: (1) 'MCrack – image processing of concrete surfaces', designed to identify, analyse and measure cracks in surfaces; (2) 'Visual-DSC – visualisation of displacements, strains and cracks', designed to determine displacement and strain fields and estimate crack openings; (3) 'SurfMap-DSC – mapping displacements, strains and cracks in concrete surfaces', integrating the last two modules customised for laboratory tests; (4) 'SurfCrete – multi-spectral image analysis of concrete surfaces', designed to detect, measure and analyse areas of biological

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colonisation, moisture, dirt and/or repairing materials and (5) 'Aesthetic-CCS – aesthetic characterisation of concrete surfaces', designed to characterise concrete surfaces (colour and texture).

The combination of these modules allows the automatic identification and mapping of anomalies on concrete surfaces, as well as their assessment and monitoring, during construction and/or during the structure life time. After a first identification of potentially damaged areas, the ACHM is locally applied and all relevant parameters are determined, namely (1) crack pattern, providing a map containing all relevant geometrical features; (2) displacement and strain fields in structures subject to loading; (3) identification and characterisation of areas affected with biological colonisation and with different materials and (4) identification and characterisation of areas repaired with inappropriate material from a restoration standpoint.

The equipment required by the ACHM is the following: (i) a commercial digital camera, with a minimum resolution of 10 MP, installed on a tripod and remotely triggered in order to assure maximum stability and (ii) a laptop computer, required for processing all modules developed and implemented by the authors.

MCrack

The crack pattern is one of the first signs of structural faults, being therefore vital to adequately assess it in what concerns structural health monitoring. However, most existing approaches are still predominantly empirical and do not use recent technology. For instance, the crack pattern is frequently mapped by direct sketches based on visual observation, whereas crack widths are measured with magnifiers or crack width rulers.

Recently, several methods have been developed which are based on DIP, therefore, taking advantage of surface cracks as discontinuities in a digital image (Barazzetti & Scaioni, 2009; Dare, Hanley, Fraser, Ridel, & Niemeier, 2002; Lange, Benning, & Siering, 2006; Sinha & Fieguth, 2006; Yamaguchi, Nakamura, Saegusa, & Hashimoto, 2008). However, most existing applications were only validated by means of a single crack, on a single stage of analysis, thus inhibiting the possibility of monitoring a complete surface.

MCrack was developed using DIP and Mathematical Morphology (Gonzalez & Woods, 2002; Marchand-Maillet & Sharaiha, 2000) in a combined global–local approach, which significantly enhances crack detection and characterisation for a complete surface. For each stage, a binary image is produced enhancing the discontinuities at the surface of the specimen. The main steps of MCrack are the following (Valença, Dias-da-Costa, & Júlio, 2012): (1) image acquisition using a low-cost digital camera with internal parameters obtained from the conventional bundle adjustments method (Granshaw, 1980); (2) selection and processing the global region of interest, which is a window defined by the user with the monitored surface; (3) definition of local regions of interest (LROIs); (4) detailed analysis of each LROI according to the user demand and finally (5) reconstitution of all LROIs to obtain the complete and final crack map. Crack characterisation can be carried out at each LROI (Valença, Dias-da-Costa, & Júlio, 2012) using a sequence of the following three main sub-steps allowing to evaluate length, width and area of any crack: (i) localisation of the crack (Figure 1(a),(b)), (ii) definition of the boundary edges (Figure 1(c)) and (iii) assessment of the length and corresponding opening at each point of the boundary (Figure 1(d)).

MCrack was validated in a vast campaign of push-off tests, by which an area of approximately 25 cm × 55 cm was monitored until the complete failure (Valença, Dias-da-Costa, & Júlio, 2012). A Canon 400D with 18 mm lens was installed on a tripod at approximately 2.5 m of the surface of the specimen. In Figure 2(a), one of these push-off specimens is briefly shown, where 66 stages have been acquired during the complete test, taking nearly 30 min. The resulting crack pattern at failure is highlighted in Figure 2(b), whereas a crack monitored along the seven most relevant stages is shown in Figure 2(c).

MCrack allows recording the crack path at an unlimited number of pre-defined stages. Furthermore, there is a significant increase in both speed and reliability in relation to traditional methods, simultaneously gathering comprehensive information, since automatic image processing is applied. This method is also non-contact and cost-effective, since it does not require professional cameras or technical expertise for data processing. It should also be highlighted that natural discontinuities present at the surface, e.g. due to natural heterogeneities, are often wrongly identified as cracks.

Visual-DSC

Most of the traditional methods for monitoring displacements and strains at a surface of a specimen present several constraints, namely: (i) limitations in hardware positioning, (ii) costly equipment and human resources and (iii) time-consuming data processing. Consequently, the development of new methods capable of eliminating these drawbacks is of utmost interest. More recently, new techniques have been developed:

- Optical fibre sensors (Huang, Liu, Sham, Chan, & Ng, 2010) are experiencing a growing interest. Nevertheless, for high-precision measurements, all drawbacks found on traditional devices are still present, namely the need for cable connections for full-field strain monitoring.

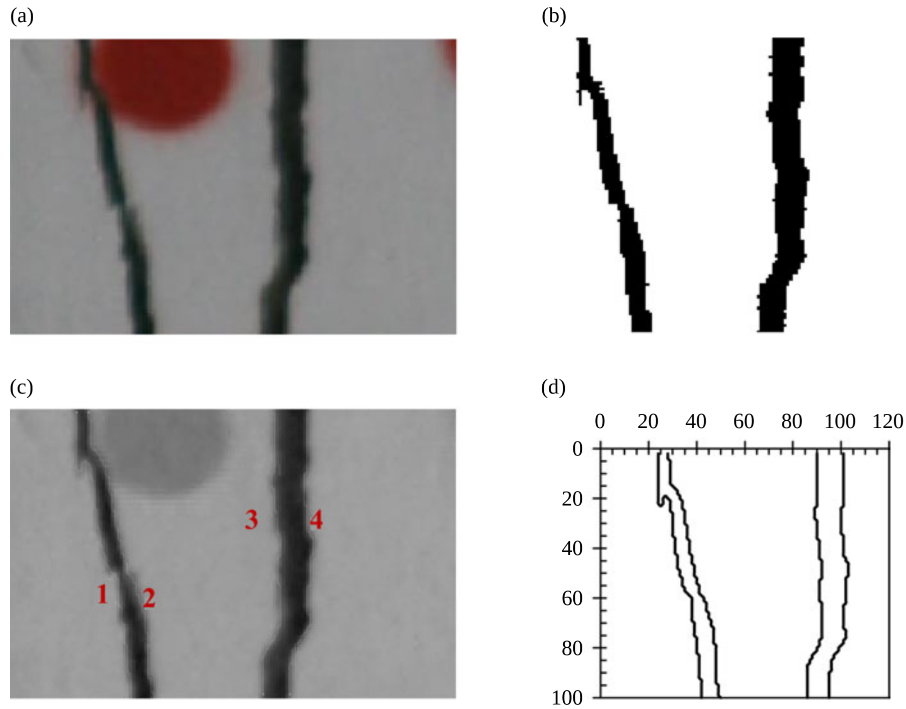

Figure 1. MCrack: (a) image, (b) detection of cracks, (c) definition of edges and (d) geometrical characterisation of the cracks.

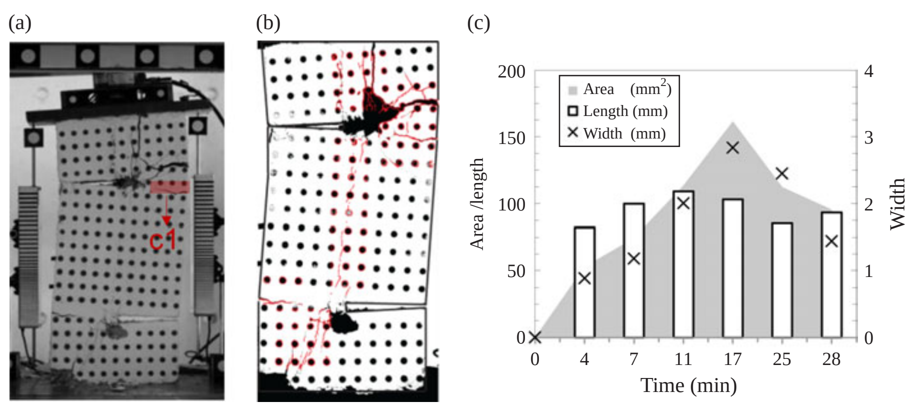

Figure 2. MCrack: (a) specimen, (b) crack pattern at failure and (c) characterisation of crack c1 (width, length and area) during the test.

- Shearography, digital image correlation, laser speckle analysis, thermal imaging and laser scanning vibrometry (Huang et al., 2010; Marazzi, Tagliabue, & Corbani, 2011) are examples of other new available techniques. With all of these, positioning is no longer a drawback, but expensive equipment and deep technical expertise are required.
- Photogrammetry aiming at monitoring displacements or strains (Ferrero, Migliazza, Roncella, & Tebaldi, 2008; Fraser, 2001; Fraser & Riedel, 2000; Jáuregui, White, Woodward, & Leitch, 2003; Jiang & Jáuregui, 2007; Jiang, Jáuregui, & White, 2008; Maas & Hampel, 2006; Whiteman, Lichti, & Chandler, 2002). Most published studies concern the computation of displacements, whereas few publications address the measurement of strain fields. For example, Sachtleber, Zhao, and Raabe (2002) evaluated the displacement field and the corresponding plastic strains, whereas Thomas and Cantré (2009) aimed at evaluating the strain field of cracked soils. However, the strain field is still constrained to narrow areas and good results were achieved mainly using metric cameras (Koelbl, 1976; Meneguette, 1985).

Aiming at exploring new techniques and at improving the drawbacks of photogrammetric tools, a new module was introduced. The Visual-DSC uses photogrammetry and post-processing tools to compute and illustrate both displacement and strain fields, and also cracks developing at the surface of the specimen (Dias-da-Costa, Valença, & Júlio, 2011). The following main steps are required: (1) image acquisition of each desired stage of loading, (2) image processing to obtain the coordinates of circular targets previously painted on the surface of the specimen (see Figure 2(a)), (3) definition of an auxiliary mesh using all circular targets through Delaunay triangulation, (4) computation of the strain fields by applying the standard finite element strain–nodal displacement matrix derived using the auxiliary mesh to the surface displacements and (5) gathering of most relevant information considering structural monitoring using a finite element post-processing software.

In order to validate Visual-DSC, namely to adequately characterise both displacement and strain fields and also to correlate the latter with cracking, the method was applied to the campaign of push-off tests mentioned above. In this case, a Nikon D200 camera with 28 mm lens was installed at approximately the same distance as before. Figure 3 shows the specimen previously analysed with MCrack (see Figure 2) with the identification of the strain field and principal directions at the failure stage. Furthermore, it can also be noticed that these directions have a good agreement with the geometry of the cracks present at the surface of the specimen.

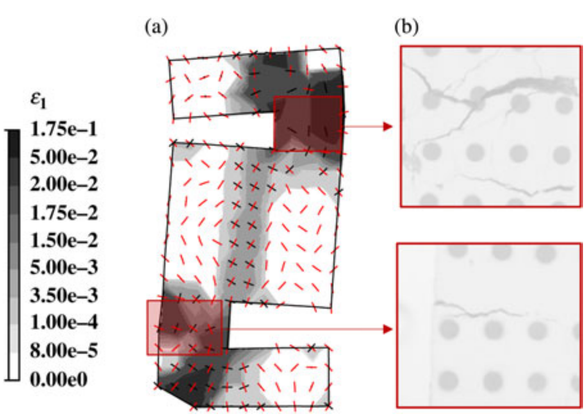

Figure 3. Visual-DSC: (a) strain field and principal directions and (b) details at failure.

It is highlighted that the structural behaviour of the specimen until complete failure is achieved using this procedure, which would be unfeasible, or at least very time consuming, with more traditional methods. The following advantages are identified: (i) a virtually unlimited set of pre-defined points can be monitored without placement restrictions or limited equipment; (ii) low-cost digital camera and laptop are used, thus avoiding the acquisition of expensive hardware; (iii) both displacement and strain fields can be automatically characterised at any stage of the test and (iv) since there is no restriction concerning large strains, the process of crack formation and the evaluation of crack orientation, as well as the corresponding opening, can also be easily obtained by direct integration of the strain profile.

SurfMap-DSC

SurfMap-DSC integrates the last two modules, benefiting from the advantages of both. In summary, the strain field obtained from photogrammetric data is used to map the cracked areas where image processing is then applied. All processing is completely automatic since only a threshold value, related to the width of the crack, needs to be provided. The module is composed by the following main steps (Valença, Dias-da-Costa, Júlio, Araújo, & Costa, 2013): (1) image acquisition, (2) data processing, (3) photogrammetry and (4) image processing. The specimen is previously marked with a regular grid made up of circular targets (Figure 4(a)). Then, the whole process is fully automatic and includes the following main sub-steps: (i) computation of the spatial resolution inside the grid and of the corresponding coordinates of each target, at any selected stage of the test, using a single image per stage; (ii) estimation of the strain field using finite element procedures to map the critical areas and (iii) application of image processing to the critical region and elimination of surface imperfections (which are not consistent with the geometry of a crack) by means of Mathematical Morphology techniques.

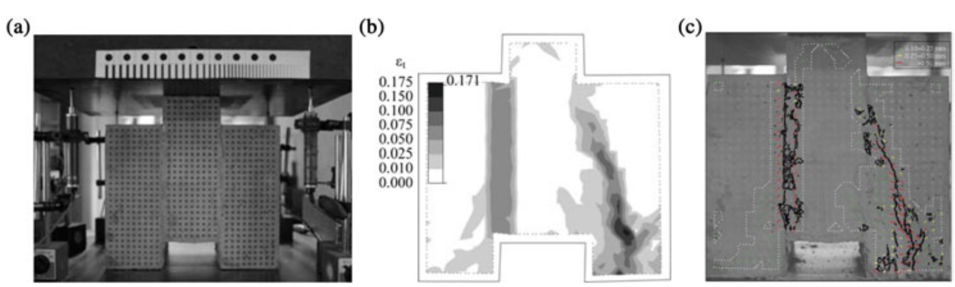

Figure 4. SurfMap-DSC: (a) specimen before loading; (b) strain field and corresponding final (c) crack pattern.

A campaign of direct shear tests was selected to validate the method with all specimens being monitored up to failure on an area of approximately 30 cm × 25 cm. In this, the Nikon D200 with a 28 mm lens was installed on a tripod at approximately 90 cm of the surface of the specimen. Figure 4 shows the results of one of these tests: (a) specimen before loading, (b) critical areas at the failure stage automatically defined using the strain field and (c) final crack pattern. In each of the elements that compose the critical area, a sequence of DIP and Mathematical Morphology techniques were applied (Valença, Dias-da-Costa, et al., 2013).

SurfMap-DSC can characterise a complete concrete surface from crack formation up to failure using photogrammetry combined with image processing. All data are quickly and automatically processed after the input of a single threshold value related to the width of the crack. The drawback of this module is similar to that identified in MCrack, i.e. imperfections eventually already present on a concrete surface can be incorrectly identified as cracks. For instance, in the specimen studied in this section, a significant number of false cracks are detected at the joints of the three concrete layers.

SurfCrete

Mapping damaged structures implies a detailed visual inspection, usually followed by many office hours. In fact, inspection requires the acquisition of a large number of images and involves the manual sketch of the damaged areas and the systematic study of all gathered information and, afterwards, compilation in a simple and intuitive format. Naturally, this can become a laborious mission, particularly in the case of larger structures. Therefore, the possibility of using multi-spectral image processing is also herein explored (Gonçalves, Fonte, Júlio, & Caetano, 2009; Hemmleb, Weritz, & Maierhofer, 2005; Hemmleb, Weritz, Schiemenz, Grote, & Maierhofer, 2006; Lerma, 2001, 2005; Lerma, Cabrelles, & Portalés, 2011) with SurfCrete module in order to detect, measure and analyse areas of biological colonisation, moisture, dirt and/or repairing materials. The method includes the following main steps (Valença, Gonçalves, & Júlio, 2013):

(1) *Image acquisition*: besides the visible spectrum (RGB), it can also be captured by near-infrared (NIR) information (Figure 5(a)).
(2) *Definition of class nomenclature*: this step requires a previous analysis of the image to define the anomalies and/or material to be detected.
(3) *Selection of training data-set*: this consists of selecting sets of pixels belonging to each class (Figure 5(b)).
(4) *Spectral analysis of the training data-set*: this is an interactive process ending when a satisfactory spectral separability is achieved (Figure 5(c)).
(5) *Classification with soft classifiers (*Gonçalves et al., 2009; Valença, Gonçalves, & Júlio, 2013): for each soft classifier, a map is produced expressing the probability of each pixel belonging to a class. Then, a sample data-set is used to evaluate the most accurate classifier in the training area [testing 1 in Figure 5(b)].
(6) *Assessment of the map*: this involves selecting a second testing data-set (testing 2), which consists in a stratified random sampling of 100 pixels per class, selected from the entire image scene (Ruiz, Lerma, & Gimeno, 2002).

As a final output, SurfCrete allows creating concrete damage maps (CDMs) aiming at identifying different materials as well as damage, including biological colonisation, repairing materials and cracks.

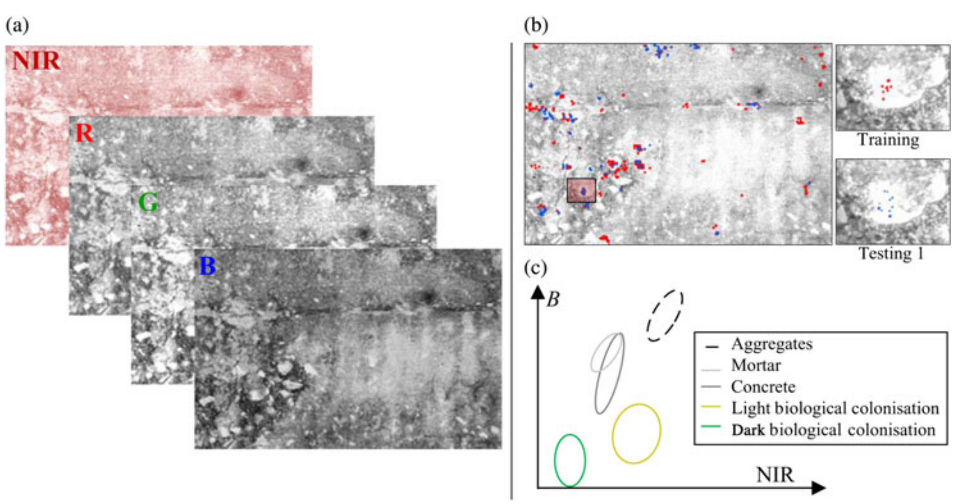

Figure 5. SurfCrete: (a) image RGB + NIR, (b) training and testing 1 data-set and (c) spectral separability.

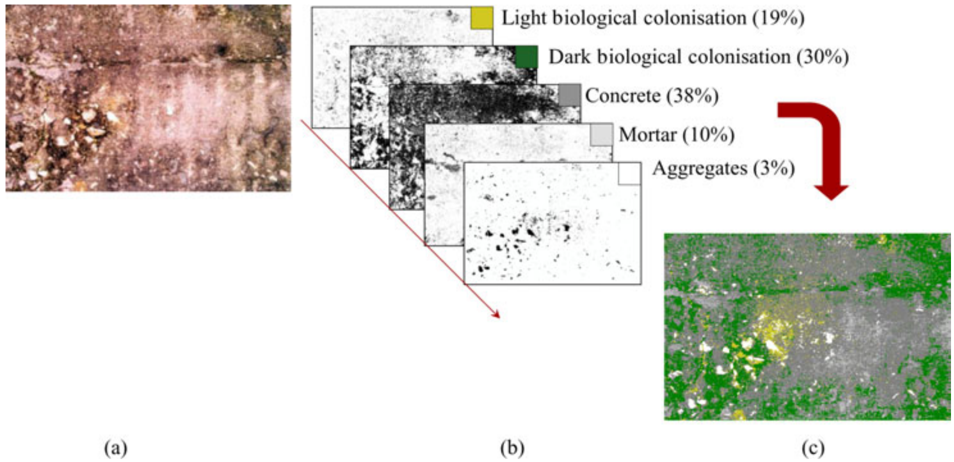

Figure 6. SurfCrete: (a) concrete surface, (b) map of each class and (c) final CDM.

The method was applied to plain concrete surfaces of a building façade (Figure 6) covering an area of 25 cm × 16 cm, being a Nikon D60 camera placed on a tripod at 1 m of the concrete surface. It is highlighted that this camera was modified in order to remove the internal IR cut-off filter. The visible spectrum images are then acquired using an external IR cut-off filter, whereas for the NIR images, an IR filter is used to capture wavelengths above 950 nm. The best results were achieved using both the NIR and the visible data, automatically producing a CDM reaching 94% accuracy (obtained by comparing with a visual classification in testing 2). It is highlighted that this technique is more efficient, robust and much faster than traditional manual mapping techniques, since surface mapping, image processing and statistical treatment of results are automatically obtained and recorded.

Aesthetic-CCS

After the assessment of the concrete structure, repairing works may be required. In those situations, the wide spread repairing known as 'patch repair method' is usually applied which consists in removing deteriorated concrete and replacing it by repairing mortars. When intervention is carried out on Concrete Heritage, besides all specifications of a standard repairing mortar, in terms of strengthening and compatibility, it is necessary to customise both colour and texture of the restoration mortar to match the substrate (Armbruster, 2011; Macdonald, 2003).

Aesthetic-CCS aims at supporting the definition of appropriate patch repairs, from an aesthetic point of view (i.e. in terms of colour and texture; Valença, Almeida, & Júlio, 2012). The methodology consists in the following main steps: (1) image acquisition, (2) identification of intervened areas, (3) characterisation of the concrete substrate by DIP and definition of requirements to apply the mortar, (4) application of the mortar made with customised chromatic and finishing requirements and (5) image acquisition and evaluation of the success of the intervention.

In Figure 7, five specimens of different mortars, produced with different percentages of pigment, are shown. Their colour characteristics were obtained directly by applying DIP. The images were captured using

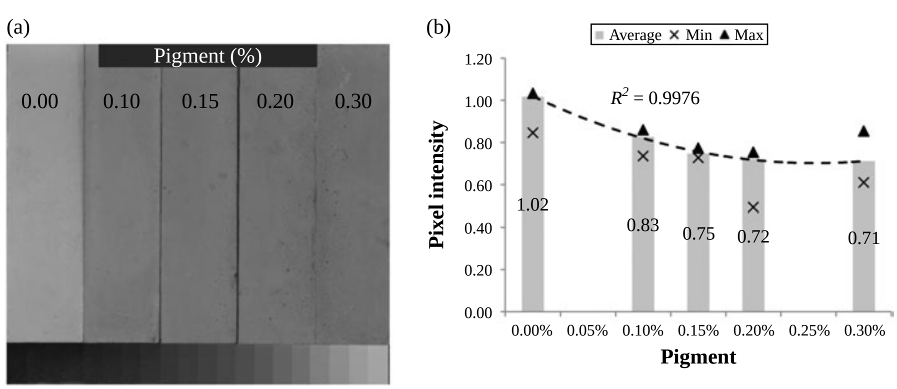

Figure 7. Aesthetic-CCS: (a) produced repairing mortars and (b) colour assessment.

controlled lighting conditions and a standard colour pallet was placed together with the specimens in order to normalise the values. Figure 7(b) depicts the average colour intensity of each mortar produced. Results demonstrate high correlation between the increase of pigment used and the colour intensity. The campaign of laboratory tests, carried out with different repairing mortars, is still ongoing. Currently, the measurement of the colour of the mortars is being calibrated using accelerated ageing tests. Note also that different textures and finishing types will be applied, in order to improve the final chromatic result captured by the human eye.

Conclusions

The method 'Automatic Monitoring State of Conservation of Concrete' (ACHM), herein presented, was developed to automatically evaluate the state of conservation of concrete structures. The implemented approach uses photogrammetry, image processing, and multi-spectral analysis, using the visible and the NIR spectrum.

The ACHM is able to automatically and continuously characterise concrete pathology. Thus, the ACHM is an important tool to: (1) support the laboratory tasks of scientific research projects in the field of structural concrete, (2) carry out inspections and diagnosis of concrete structures and (3) define restoration techniques for 'Concrete Heritage'. The ACHM is also an accurate and cost-effective method. Furthermore, ACHM is the first approach to evaluate the applicability of the methods/techniques to assess and map concrete surfaces pathology.

The ACHM was validated using several different case studies. Currently, the procedure is being generalised to the entire surface of building façades. In fact, this procedure is straightforward since the several modules can run in parallel in order to analyse all data. Then, the final result can be easily represented in a mosaic, thus, gathering the most relevant information. Further ongoing research aims at developing an 'intelligent concrete health monitoring' method using machine learning algorithms and advanced imaging equipment.

Notes

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