

Performance evaluation of patch repairs on historic concrete structures (PEPS): a methodology for in situ and laboratory analyses

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Abstract. While there have been many studies on the performance criteria of concrete patch repairs, there are few specific studies on the long-term performance of patch repairs designed to preserve the aesthetic significance of the original fabric of culturally significant concrete structures. In order to address this issue, the Getty Conservation Institute (GCI), Historic England (HE) and the Laboratoire de Recherche des Monuments Historiques (LRMH) commenced work on an international collaborative research project, 'Performance Evaluation of Patch Repairs on Historic Concrete Structures' (PEPS). Begun in 2018, the PEPS project aims to produce practical guidance that will help those repairing historic concrete through the assessment of case studies in the USA, England and France within a variety of climatic and environmental conditions, typologies and repair materials. The operational phases of the research project consist of *in situ* tests and laboratory analysis performed on both the original concrete and previous patch repairs. This paper provides an overview of the assessment methodology that has been developed by an inter-disciplinary team of professionals working in the field of concrete conservation, and includes a variety of traditional and non-traditional non-destructive, mechanical, chemical, and electro-chemical characterization and diagnostic techniques.

1 Introduction

While there is detailed guidance on the assessment and repair of concrete structures generally, there is a lack of widely accepted guidance on the conservation of culturally significant concrete structures. This is an area of growing concern as the number of culturally significant structures from the 20th century that require ongoing maintenance and repair continues to increase. Concrete conservation presents both technical and philosophical challenges beyond those inherent to contemporary concrete repair. For example, conservation work may aim to incorporate principles such as minimal intervention, preservation of the original fabric, retreatability and 'like-for-like' repairs. In addition, the use of novel techniques and materials can fall outside the scope of published repair guidance.

One specific challenge that has been identified (1) is the long-term performance of patch repairs designed to preserve the aesthetic significance of the original fabric. The lack of studies and published guidance in this field, has led to inappropriate repairs being carried out which

may have an unacceptable impact on the aesthetic significance of the structure and/or result in poor quality repairs with short life cycles and ultimately physical damage to the structure.

In order to address this issue, the Getty Conservation Institute (GCI), Historic England (HE) and the Laboratoire de Recherche des Monuments Historiques (LRMH) commenced work on an international collaborative research project, 'Performance Evaluation of Patch Repairs on Historic Concrete Structures' (PEPS). The project team is also joined by expert consultants Rowan Technologies (England) and Wiss, Janney, Elstner Associates (USA). Begun in 2018, the PEPS project aims to produce practical guidance to help those repairing historic concrete through the process of the selection of appropriate repair approaches, procedures, and materials. Case studies were assessed in the USA, England, and France, with a variety of climatic and environmental conditions, typologies, and repair materials. The project is composed of four stages of work:

- Phase I Project development
- Phase II Preliminary assessment

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- Phase III Detailed diagnostic
- Phase IV Synthesis & conclusions

This paper provides an overview of the assessment methodology for Phases II and III. Results from these phases will be presented in subsequent publications. Additional information regarding the background and development of the project can be found in previous publications [1, 2, 3].

2 Phase II: Preliminary Assessment

2.1 Establish Case Histories

The preliminary assessment aimed at evaluating up to ten case studies per country. Twenty have been completed so far (ten from England, six from USA, and four from France). Prior to conducting site visits, desk studies were undertaken on each site to establish each site's case history and provide insight into how the repair strategies were developed and executed, and support interpretation of current conditions observed on site. The desk study included not only a review of existing building specifications and repair documentation, but also interviews with owners, asset managers and other relevant individuals who could validate the history of the repairs.

2.2 First Site Visits

During the first site visits, approximately ten patches were assessed per case study using only non-destructive tests (NDT). The selection of patch repairs to include in the study was done following an initial walk through the site to identify, whenever possible, patches representing different degrees of deterioration, exposure, and vintages. These initial assessments were conducted following established guidance [4, 5, 6] and internal protocols, and included the following:

- Visual and tactile observations;
- Sounding to determine delamination, poor consolidation, or voids;
- Photographic documentation using scale, colour checker, and crack gauge;
- Water spray to test repellence and possibility of hydrophobic treatments;
- Rebound hammer and scratch test to determine differences in surface hardness between repairs and adjacent concrete;
- Covermeter survey of patch and adjacent concrete to identify reinforcement location and depth of cover.

Upon completion of this phase of work, each patch was assigned a designation (good, fair, poor, very poor) based on its aesthetic and technical performance. The first set of preliminary assessments were key in defining the research goals for the next phase of work.

3 Phase III: Detailed Diagnostic

Following a review of the results of Phase II, 5 English, 3 American, and 4 French case studies were selected for a more thorough assessment. The Phase III work required returning to these sites to undertake a more detailed in-situ procedure of both NDT and invasive testing, as well as the removal of samples which would be analysed in both internal and external laboratories. In each site, five patches were chosen for this phase of work to represent the various performance designations observed.

3.1 In-Situ NDT

3.1.1. Visual Examination and Surface Observations

Visual examinations were performed on all patches included in Phase III. During this examination, sounding and photographic documentation were repeated to determine and record any changes that had occurred since Phase II. In addition to these, surface observations were recorded using Dino-Lite field microscopes (20-220x).

3.1.2 Colorimetry

Colorimetric measurements were carried out in accordance with EN 15886 [7] '*Conservation of Cultural Property. Test Methods. Colour Measurement of Surfaces*', using Konica Minolta CR-410 colorimeters with D65 CIE standard illuminant, a 2° CIE standard colorimetric observer angle, and a measurement area of \varnothing 50 mm. The number of measurements taken per site was dependent on the size of the patch and variability of the material. However, a minimum of 6 representative areas were measured per patch, with a further minimum of 6 measurements taken on the original concrete adjacent to each patch.

The results were recorded in CIELAB colour space, where:

- L^* is the lightness coordinate, the scale for which ranges from 0 (black) to 100 (white);
- a^* is the red/green coordinate, with $+a^*$ indicating redness and $-a^*$ indicating greenness;
- b^* is the yellow/blue coordinate with $+b^*$ indicating yellowness and $-b^*$ indicating blueness.

Differences in colour, ΔE , were calculated using the following formula:

$$\Delta E = [(L_p^* - L_a^*)^2 + (a_p^* - a_a^*)^2 + (b_p^* - b_a^*)^2]^{0.5} \quad (1)$$

Where:

- L_p^* is the mean value of L^* in the patch;
- L_a^* is the mean value of L^* in the adjacent area;
- a_p^* is the mean value of a^* in the patch;
- a_a^* is the mean value of a^* in the adjacent area;
- b_p^* is the mean value of b^* in the patch;
- b_a^* is the mean value of b^* in the adjacent area.

3.1.3 Initial Water Absorption

Initial water absorption was determined in accordance with UNI 11432 [8] ‘*Cultural Heritage. Natural and artificial stone. Determination of the water absorption by contact sponge*’. Contact sponge measurements were carried out on 5 patches per site, with 3 measurements per patch, and a further 3 measurements taken on the original concrete adjacent to each of the 5 patches. While the amount of water and contact time of the sponge must be determined on a case-by-case basis depending on the material, a time of 90 seconds with 4 ml of water was typically found to be suitable in this study.

The amount of water absorbed was calculated using the expression:

$$WA (g/cm^2.sec) = (Pi - Pf - Pe)/(S \times t) \quad (2)$$

Where:

- Pi is the initial weight, in grams;
- Pf is the final weight, in grams;
- Pe is the weight of any foreign material, in grams;
- S is the contact surface of the sponge, in cm²;
- t is the contact time, expressed in seconds.

3.1.4 Surface Hardness

Surface hardness was assessed using two methods: firstly, by rebound hammer in accordance with EN 12504-2 [9] ‘*Testing Concrete in Structures - Part 2: Non-destructive testing - Determination of rebound number*’ and, secondly, by Mohs’ hardness scratch test. Rebound hammer measurements were carried out on 5 patches per site as well as the original concrete adjacent to each patch, with a minimum set of nine valid readings obtained from each area to provide a reliable estimate of the rebound number. For the Mohs’ hardness scratch test, attempts to scratch the surface of the concrete were carried out using standard hardness picks of different hardness values. If the scratch was successful, the hardness of the pick was decreased, and if scratch was unsuccessful the hardness of the pick was increased. This procedure was repeated until the hardness picks at which the concrete is scratched and not scratched, respectively, are identified. The hardness of the concrete itself is then considered to be between the two pick values.

3.1.5 Cover Depth & Position of Reinforcement

The depth of concrete cover and position of steel reinforcement was determined in accordance with BS 1881-204 [10] ‘*Testing Concrete. Recommendations on the use of electromagnetic covermeters*’. Cover depth was measured and recorded along the length of the reinforcement both within the patch repair and adjacent concrete. The location of the reinforcement was marked with chalk for photographic documentation and to aid with the subsequent electro-chemical testing.



Figure 1. Chalk markings of patch outlines (green) and rebar (blue) identified during the covermeter survey.

3.1.6 Electrical Resistivity

Electrical resistivity was measured using a Wenner four-probe (Proceq Resipod) with 50 mm probe spacing and following the recommendations given in RILEM TC 154-EMC [11] ‘*Test methods for on-site measurement of resistivity of concrete*’. Measurements were taken in a grid-based survey with measurements taken at spacings of 250-500 mm, and diagonally inside the rebar mesh where possible.

3.2 In-Situ Invasive Testing

3.2.1 Bond Strength of Repair (Pull-off)

Determination of bond strength was carried out in accordance with EN 1542 [12] ‘*Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off*’. A diamond core drill (internal Ø 51 mm) was used to penetrate through the patch repair to a depth of 15 ± 5 mm into the concrete substrate. A dolly Ø 50 ± 0.5 mm with thickness ≥ 20 mm (steel) or ≥ 30 mm (aluminium) was then applied to the surface face of the core with rapid-hardening epoxy. Once fully hardened, the pull-off test was undertaken using an EN 1542 complaint test rig. For each of the patch repairs to be tested, a minimum of 3 cores were targeted. With the tensile bond strength, the type of failure (adhesive or cohesive) was also noted for each core.

3.2.2 Opening Inspection

In order to visually assess the condition of the steel reinforcement, determine the bar size, and provide a direct contact point for electrochemical testing, an inspection opening was created in each patch repair. This was done either with the coring rig, an angle grinder or hammer and chisel, as required. The size of the opening varied between locations and according to the specific conditions of the site. In some cases, it was possible to completely remove the patch repair from the substrate at the bond line and observe the steel reinforcement.

3.2.3 Half-Cell Potential

Half-cell potential measurements were carried out in accordance with ASTM C876-15 [13] ‘Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete’ and the recommendations found in RILEM TC 154-EMC [14] ‘Half-cell potential measurements - Potential mapping on reinforced concrete structures’. Measurements were taken using copper-copper sulfate electrodes along a pre-defined grid at 10 cm centres which extended beyond the area of the patch repair in all directions to determine the differences in potential in both the original concrete and patch repairs.



Figure 2. Preparation of the concrete surface for half-cell potential survey using a pre-defined grid ‘mask’.

3.2.4 Linear Polarization Resistance (LPR)

LPR measurements were carried out following the recommendations given in RILEM TC 154-EMC [15] ‘Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarization resistance method’. Several measurements were made on both the patch repair and surrounding original concrete, with the polarization time set to 100 seconds, and with a confinement ring.

3.2.5 Sample Removal

Samples for further testing were removed from the original concrete substrate and several patch repairs on each site. Typically, Ø 50 mm cores were taken using a water-cooled diamond core rig. However, in some cases the geometry of the patch and location of reinforcement meant it was not possible to take cores and, in these instances, the samples were removed with an angle grinder.

Table 1. Samples removed from each site and reason for removal.

Area	Objective	No.
Good Patch 1	Interface characterization	1
	Bond strength	3
	Contaminants at different depth	1
	Material characterization	2
Good Patch 2	Bond strength	3
	Material characterization	2
Fair Patch	Interface characterization	1
	Bond strength	3
	Contaminants at different depth	1
	Material characterization	2
Poor Patch 1	Interface characterization	1
	Contaminants at different depth	1
	Material characterization	2
Poor Patch 2	Material Characterization	2
Original Concrete	Material Characterization	2
	Contaminants at different depth	1

3.3 Internal (LRMH/GCI/WJE) Laboratory Testing

Analyses of the samples removed from the sites was carried out by the authors in the laboratories of both LRMH and the GCI, with petrographic examination of thin sections performed by specialists at WJE, and some additional specialist analyses subcontracted to external laboratories in France.

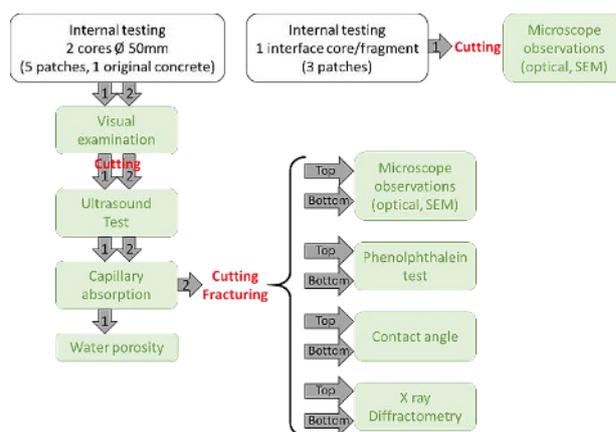


Figure 3. Summary of internal testing protocol.

Analyses of historic concretes in the laboratory are complicated due to the limited amount of material that is often available and both the chemical and physical alterations which occur over time [16]. As a result, several of the test procedures had to be slightly modified to account for this, and an optimized system had to be developed to maximize the amount of data obtained from a minimal amount of samples. In most cases, the modification of test procedure was limited to using samples that were below the size requirements or older than the age limit specified, and in all tests where the relevant standard required the samples to be dried, this was done at no higher than 45°C to prevent any further chemical or physical degradation.

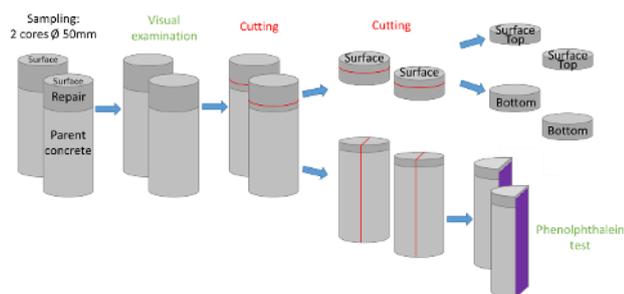


Figure 4. Overview of initial sample preparation and testing stage for deep repairs. Original concrete and shallow patch repairs were processed in a similar manner.

Additional complications arose from the fact that two fundamentally different approaches to patch repair were encountered on the sites studied – ‘form and pour concrete’ and ‘hand-applied mortars’ – which resulted in significant differences in the depth of repairs and size of the aggregates used depending on the repair strategy that had been adopted. As such, two slightly different processes for analysing samples had to be adopted to accommodate these differences.

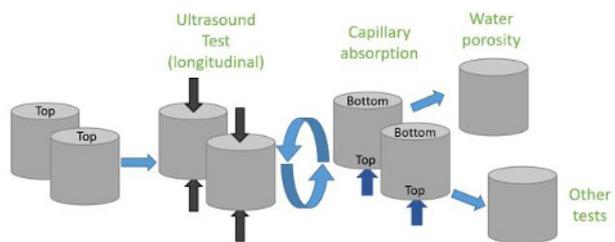


Figure 5. Overview of second stage of testing deep repairs and original concrete.

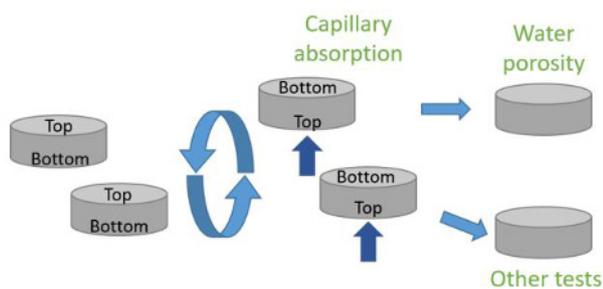


Figure 6. Overview of second stage of testing shallow repairs.

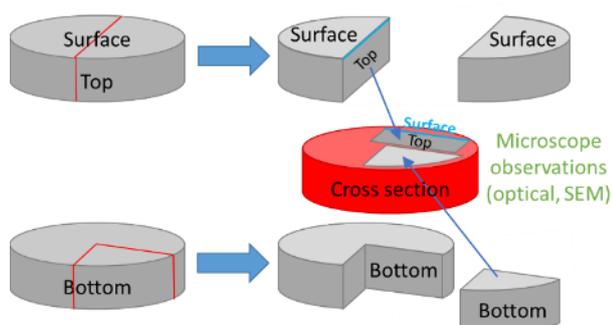


Figure 7. Overview of the third stage of testing.

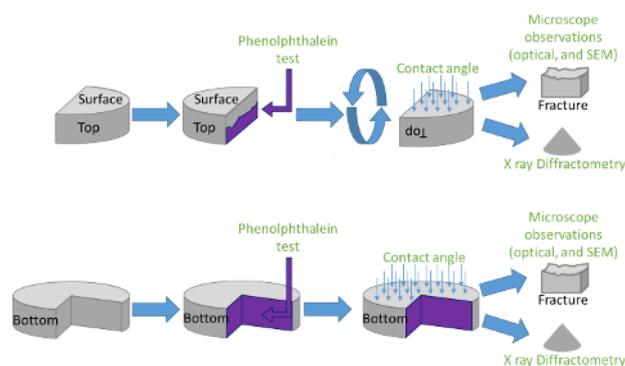


Figure 8. Overview of the final stage of testing.

3.3.1 Carbonation Depth

The depth of carbonation was assessed through two methods. First, following the procedure described in EN 14630 [17] ‘*Products and systems for the protection and repair of concrete structures - Test methods - Determination of carbonation depth in hardened concrete by the phenolphthalein method*’, and then by petrographic methods.

3.3.2 Contact Angle

Determination of static contact angle was determined following a modified version of the procedure described in EN 15802 [18] ‘*Conservation of cultural property - Test methods - Determination of static contact angle*’. Measurements were carried out using a Krüss DSA25E and DSA100E at LRMH and the GCI, respectively, with both laboratories using a 5 µL drop size, and Krüss ‘Advance’ software to carry out image analyses. A first measurement of the contact angle was measured 0-5 seconds after the drop deposition, then a second at 10-15 seconds.

The contact angle is determined by the equation:

$$\theta = 2 \cdot \tan^{-1}(2h/d) \quad (3)$$

Where:

- θ is the contact angle, in degrees;
- h is the drop height, in mm;
- d is the diameter of the surface of the drop in contact with the material, in mm.

3.3.3 Capillary Absorption

Capillary absorption was determined in accordance with EN 15801 [19] ‘*Conservation of cultural property - Test methods. Determination of water absorption by capillarity*’. Prior to testing, the samples were dried at 40°C and the sides sealed with adhesive tape or paraffin film to prevent water penetration.

The amount of water absorbed was calculated using the expression:

$$M_i/S = A(t_i)^{0.5} \quad (4)$$

Where:

- M_i is the mass of water absorbed at time ‘ t_i ’, in

- ρ_w is the density of water, in kg/m³;
- A is the coefficient of capillary absorption, in kg/(m².s^{0.5});
- S is the sample surface area in contact with water, in m²;
- t_i is the time, in seconds.

3.3.4 Density and Porosity Accessible to Water

Measurements of the density and porosity accessible to water were measured following a modified procedure of that described in NF P 18-459 [20] ‘Concrete - Testing hardened concrete - Testing porosity and density’. In many cases, the samples in the study were smaller than those required by the standard.

The bulk density of the sample is determined by the equation:

$$D_B = [M_{od}/(M_{ssd} - M_w)] \times \rho_w \quad (5)$$

Where:

- M_{od} is the oven-dried sample mass, in kg;
- M_{ssd} is the saturated-surface-dry mass of the sample, in kg;
- M_w is the apparent mass of the immersed specimen, in kg;
- ρ_w is the density of water, at 20°C, taken as 998 kg/m³.

The porosity of sample, ε (expressed as a % to the nearest 0.1%) is determined by the equation:

$$\varepsilon = (M_{ssd} - M_{od})/(M_{ssd} - M_w) \quad (6)$$

3.3.5 Ultrasonic Pulse Velocity

Ultrasonic Pulse Velocity (UPV) measurements were carried out in accordance with a modified version of the procedure described in EN 12504-4 [21] ‘Testing concrete - Part 4: Determination of ultrasonic pulse velocity’ using a Ginger-CEBTP AU2000 (60 kHz). In the case of shallow repairs, there was not enough material to carry out UPV.

The ultrasonic pulse velocity is calculated using the formula:

$$V = L/T \quad (7)$$

Where:

- V is pulse velocity, in km/s, expressed to the nearest 0.01 km/s;
- L is the path length, in mm;
- T is the time taken by the pulse to pass through the samples, in μ s.

The dynamic modulus of elasticity could then be calculated using the formula:

$$E = [(1+\nu)(1-2\nu)]/(1-\nu) \times D_B \times c_l^2 \times 10^{-9} \quad (8)$$

Where:

- E is the dynamic modulus of elasticity of the material (GPa);

- ν is the Poisson’s ratio of the material, 0.20 for concrete;
- D_B is the bulk density of the sample, in kg/m³;
- c_l is the ultrasonic pulse velocity in the material, in m/s.

3.3.6 X-Ray Diffractometry

X-ray diffractometry (XRD) was carried out on samples 2-5 cm³ in volume. The matrix and the aggregates were separated as much as possible using a smooth attrition with a pestle in a mortar followed by a sieving through a 100 μ m mesh. The powder passing through was assumed to be the matrix. The fraction remaining in the 100 μ m mesh sieve was also ground to a powder passing through a 100 μ m mesh sieve. Both fractions (matrix rich and aggregate rich) were analysed using a Bruker D8 Advance diffractometer (France) and Rigaku MiniFlex 600 (USA) at standard conditions of: 40 kV, 40 mA, angular range 2 θ covered from 5 to 64°, and with an acquisition time of one second per 0.02°.

3.3.7 Microscopy

Observations were carried out on fractures and cross-sections from both the top and bottom surfaces of the sample, including the surface as it was exposed to the external environment. The samples were placed in a \varnothing 40 mm mould and impregnated with a two-component epoxy resin and red dye, and, after hardening, cut and polished on a Saphir 520 automatic polishing machine using increasingly fine grit polishing discs. Polishing was performed with diamond powders and using ethanol as a lubricant to avoid hydration.

Initial observations were undertaken with a VHX-5000 Series 3D microscope, before moving to a more detailed study with a JEOL IT300 scanning electron microscope with an X-type Oxford Xmax 50n probe (SEM-EDS) which allowed chemical analyses to be carried out. Analyses and chemical mapping were performed using AZtec analysis software.

Petrographic analyses were carried out on thin sections in accordance with ASTM C856-18a ‘Standard Practice for Petrographic Examination of Hardened Concrete’ [22] in a variety of observation modes. Emphasis was placed on observations made on and around the interface between the original substrate and the repair material.

3.4 Externally Contracted Laboratory Testing

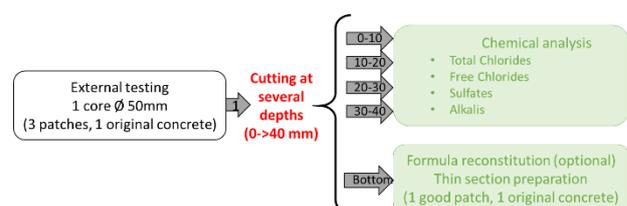


Figure 9. Summary of external testing protocol

3.4.1 Chemical Analyses

Chemical analyses were performed on powdered samples from four-depths, ground to < 125 µm and dried at 80 °C. Chemical analyses were carried out using the following methods, with results expressed as a percentage of cement content:

- Chloride content was determined by potentiometric titration (Method B) in accordance with EN 14629 [23] after nitric acid dissolution and water dissolution, with results expressed as “total” and “free” chlorides according to the AFREM method [24];
- Sulfate content was determined by ionic chromatography after nitric acid dissolution;
- Alkali content was determined by ionic chromatography after nitric acid dissolution;
- Insoluble residue was determined to be that which remained following loss-on-ignition at 1000°C after filtration of the solution obtained after nitric acid dissolution;
- Elementary chemical analyses of elements Ca, Si, Al, Mg, Fe, K, Na, P, Cr, Ti, Sr and Mn were determined by Inductively Coupled Plasma (ICP-AES), after dissolving the samples in a nitric acid solution.

3.4.2 Thermogravimetric & Differential Thermal Analysis

Thermogravimetric (TGA) and differential thermal (DTA) analyses were carried out under nitrogen atmosphere from 20 °C to 1000 °C on powdered samples (< 125 µm) to determine the loss-on-ignition (LOI) of the material, the free water content and chemically bound water content, and the carbonate content.

3.4.3 Material Composition

The material composition was determined using the ‘Calcul Minéraux LCPC’ method and in-house software at the external laboratory and utilizing the results of previous tests and petrographic examinations. This analysis was only conducted if research found little or no information on the compositions of the original concrete or the repair material used, or if there was evidence that the specification was not followed.

The cement content is determined from the equation:

$$C = (s \times D_B) / S \quad (9)$$

Where:

- C is the cement content, in kg/m³;
- s is the soluble silica determined in the sample, in %;
- D_B is the bulk density of the sample, in kg/m³;
- S is the theoretical soluble silica of the binder, in %.

The water content is determined from the equation:

$$W_t = (D_{ssd} - D_B) + (W_b \times D_B) - E - W_a \quad (10)$$

Where:

- W_t is the total (mixing) water content, in kg/m³;
- D_{ssd} is the saturated-surface-dry density, in kg/m³;
- W_b is the mass of chemically bound water, in %;
- E is the entrained air, considered to be saturated by water, in kg/m³;
- W_a is the amount of water absorbed by aggregates, in kg/m³.

4 Conclusion

Within the frame of the international project PEPS, an assessment methodology was developed, dedicated to the evaluation of patch repairs on historic concrete structures. This methodology gathers standards and approaches from three different countries. It also considers the difficulty of sampling scheduled monuments and listed buildings, which require an approach of minimal invasion that limits damage to the original fabric, and the diversity of typical patching techniques.

The methodology was applied to a series of historic concrete structures in three countries – England, France, and USA – in order to understand the different repair approaches applied in each country and the reasons for their success or failure

The results of this vast campaign of measurements and analysis will be presented in further papers, with the final goal of producing practical guidelines towards best practices for the patch repair of culturally significant concrete structures.

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