

# Performance evaluation of patch repairs on historic concrete structures (PEPS): Preliminary results from a selection of French case studies.

Myriam Bouichou<sup>1,2</sup>, Jean Ducasse-Lapeyrousse<sup>1,2,3</sup>, Elisabeth Marie-Victoire<sup>1,2</sup> and Mirah Rakarabo<sup>1,2</sup>

<sup>1</sup>Laboratoire de Recherche des Monuments Historiques (LRMH), Ministère de la Culture, 29 rue de Paris, 77420 Champs-sur-Marne, France

<sup>2</sup>Sorbonne Universités, Centre de Recherche sur la Conservation (CRC, UAR 3224), Museum national d'Histoire naturelle, Ministère de la Culture, CNRS; CP21, 36 rue Geoffroy-Saint-Hilaire, 75005 Paris, France

<sup>3</sup>Comue Paris Est Sup, 6-8 avenue Blaise-Pascal Cité Descartes - Champs-sur-Marne 77455 Marne-la-Vallée, France

**Abstract.** Within the frame of the international research project PEPS, 'Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS)', dedicated to the durability of patch repairs in the context of culturally significant structure, a series of repaired monuments was examined in detail. Thus, the operational phases of the project are composed of *in situ* tests and laboratory analysis on samples performed on a selection of representative historic concrete structures in the three countries who are partners in the project: United States of America, United Kingdom and France. In this paper, cases studies and some results obtained on three of the five French sites will be presented: Le Raincy church built by Auguste Perret between 1920 and 1924, and Rezé housing unit and Jaoul houses built by Le Corbusier respectively in 1955 and in 1953. The assessment methodology followed is the one developed between the three institutions partners on the PEPS project: the Getty Conservation Institute (GCI), Historic England (HE) and Laboratory of Research in Historical Monuments (LRMH). All the selected French sites were repaired several decades ago. For Le Raincy church and the Jaoul houses, the conservation campaign of 1991 was considered, while for Rezé housing unit it was the 1995-1997 campaign. All the case study structures have different construction dates and concrete compositions. Various repair materials and application techniques were used. The conditions of exposure differ from one site to another. All these variations make the evaluation highly complex but also fully instructive, and able to meet the objectives of the project: producing practical guidance helpful for companies and conservators repairing historic concrete.

## 1 Introduction

Concrete is now considered as a heritage material in its own right, throughout the world. In France, the exponential growth in the number of historical monuments made of concrete since the 1990s evidences clearly this new trend. In 2021, there were 950 historical monuments in concrete in France. A survey conducted within the framework of the European project REDMONEST on a panel of French monuments in concrete showed that 19% were degraded, 13% very degraded and 6% endangered [1].

Faced with the main pathology of historic concrete, which is corrosion of the reinforcement, the traditional repair technique is patching, which consists of removing the damaged concrete around the reinforcement and replacing it with a new repair mortar or concrete. The European CONREPNET project, in which the LRMH was involved, showed that in 50% of the cases of "classic" reinforced concrete structures (civil engineering, engineering structures, etc.), patch repairs failed, sometimes within a very short period of time and with a maximum durability evaluated at 10 years. This observation is even more alarming for historical concrete,

as the associated losses of original material are sometimes considerable which is in contradiction with the ethics of monument restoration. In addition, in recent years, materials and techniques for the conservation of heritage concrete have evolved with the introduction of notions of physico-chemical and aesthetical compatibility for patch repairing.

In order to better understand the origins of the durability deficit of some of the repairs, but also to compare the conservation practices of historic concrete on an international scale, the project PEPS (Performance Evaluation Of Patch Repairs On Historic Concrete Structures) was initiated in 2018. The project federates 3 teams: the Getty Conservation Institute of Los Angeles (GCI), the Historic Buildings and Monuments Commission for England (HE) and the Laboratory of Research on Historical Monuments (LRMH) and is a continuation of the Conserving modern architecture initiative, for which the GCI had already solicited concrete experts in 2013 and 2014, among which is the LRMH concrete department. The PEPS project is based on experience feedback from a panel of conservation works carried out on historic monuments in the three

partner countries: France, the United Kingdom and the United States [2].

The aim of the project is to identify the reasons for failure or success and to develop criteria for more sustainable patch repairs. Thus, the identification of the causes of the disorders should lead to optimisation of restoration/repair strategies and practices and address the heritage and economic issues that they represent in the particular context of historic monuments.

The project includes three phases. Firstly, a bibliographical study was carried out on the issue of repair compatibility for historic concrete [3]. Then, the project required the development of an accurate analytical protocol common to the three partner institutions [4]. Thus, the evaluation of patch repairs requires characterising the intrinsic properties of the materials (original concrete and repair materials) and putting them into perspective with the archival data collected on the different conservation phases of the monuments of the panel. The problems of durability and compatibility of repairs with ancient concrete must consider the interdependence of certain properties, the implementation of repairs, the environment (climate, contaminants, etc.), and aesthetic considerations, essential to historic monuments.

The extensive protocol of analyses was developed [4] to allow the evaluation of a series of performances such as aesthetic or mechanical, but also transfer properties and corrosion characterization of the reinforcements, both *in situ* and in the laboratory. From the more in-depth laboratory analyses, the composition of the original concrete and repair materials, the characterisation of the pathologies, and the concentration profiles of various pollutants should be assessed.

The final analysis protocol was therefore divided into three steps : a preliminary archival study, a first preliminary set of on-site observations and characterizations on original concrete and patch repairs (phase II), and a final series of more in depth assessments (Phase III), on site and in the laboratory on samples collected on the monuments of the panel.

The first results of this three-step evaluation will be presented in this paper for three French representative historical monuments: Notre-Dame de la Consolation church in Le Raincy, the Jaoul houses in Neuilly-sur-Seine, both in Paris area, and the Rezé residential unit near Nantes.

## 2 Step one of Phase II: Archival study

The historical survey has consisted of researching information on the construction and the conservation campaigns for each case study.

### 2.1 Notre-Dame du Raincy church

Notre-Dame de La Consolation church of Le Raincy (Fig 1) was built from May 1922 to June 1923 by the brothers Auguste and Gustave Perret, at the initiative of the priest of Le Raincy, Father Félix Nègre. It is composed of a nave with 5 bays, covered with a vault, and a bell tower. Its

self-supporting structure is in reinforced concrete, and prefabricated reinforced concrete panels form the facades. The bell tower, with a square plan, presents a series of stools with a pyramidal progression. Its supporting structure, composed on the first stools of four columns of reinforced concrete at each angle, is connected by a series of reinforced concrete frames. The last frame supports the spire culminating at 42.15 m.

This often so-called “Sainte-Chapelle of reinforced concrete” is considered as the first “modern” church in France. The building was listed as a historical monument on June 29, 1966.

According to 2018 the study of the architects Ms. François Lacoste, Wandrille Thieulin, and Bernard Bauchet and to the diagnosis of GCI [5], three conservation operations were carried out on the bell tower:

- In 1960, before the classification as historical of the church in 1966, a first repair work of the degraded bell tower was financed by the parish,
- Between 1989 and 1991, a second series of conservation operations of the bell tower was undertaken by Jacques Lavedan, Chief architect of historical monuments.
- From 1992 to 1995, repair work was carried out on the east and south-west concrete/glass screen wall by Jacques Lavedan.
- In 1996, The north façade was restored by Benjamin Mouton, Chief architect of historical monuments.

If there is no information on the 1960 repairs, more data could be collected from the 1991 work. Thus, in 1991, after the removal of the deteriorated concrete, and stripping of the corroded steel reinforcement, the repairs were realised with a clearly identified repairing concrete design: 400 kg of cement CPJ 32.5R (clinker with slag), 800 kg of 5/15 rolled gravel, 400 kg of sand 0-6, 400 l of water with synthetic resin diluted to 20%. The repairs were cast using elastomer-coated wooden forms. Some repairs, which were probably too smooth, were bush-hammered at the request of the architect. The edges of the repairs were also bush-hammered to ensure their continuity with the original concrete. Since 1995, periodic purging was carried out on the bell tower for safety issues due to concrete spalling, but without any additional repairs. The diagnosis performed in 2018 showed that only 2% of the spalling on the bell tower concerned the repairs from the 1991 repair work.

## 2.2 The Jaoul houses



**Figure 1** Notre-Dame du Raincy church, first examinations of the bell tower

The Jaoul houses (Fig2) were built from 1953 to 1955 by the famous architect Le Corbusier, in association with the architects André Wogensky, German Samper and Jacques Michel [6,7]. The houses were designed to accommodate two families: those of André Jaoul and his son Michel. They consist of two buildings: House A on the street side and House B on the garden side. Both are rectangular shaped (16 m by 6.90 m) and located perpendicularly to each other. The construction system of the two houses is identical. The facades are made of reinforced rough concrete beams and brick load-bearing walls. Privately owned, Jaoul Houses were listed as Historical Monuments on June 29, 1966.

According to the architect Claudia Devaux, in charge of their last restoration in 2019, since the completion of their construction in 1955, only one repair operation was performed in 1991. The latest was led by Jacques Michel, architect and former collaborator of Le Corbusier and site manager in charge during the construction of the houses. On the facades, this work consisted mainly of restoration of the concrete. In the renovation permit, it is indicated: «Identical repair of the raw concrete : approximately 30%, after finishing, high-pressure washing of the whole to standardize the textures». The on-site observations and photos of the architect Claudia Devaux indicate that concrete was removed to a thickness of two to three centimetres to reach the reinforcement. Wooden formwork was then installed according to the original drawings. During the restoration work of 2019, 72% of the total removal was realised on the 1991 patch repairs. 28% of this 1991 patch repairs were removed in 2019.



**Fig. 2** The Jaoul houses in Neuilly-sur-Seine, view of the B House.

## 2.3 Rezé housing unit

Rezé housing unit designed by the famous architect Le Corbusier, was built between 1953 and 1955 for “La Maison Familiale”, a cooperative housing company founded in Nantes in 1911, as part of the reconstruction of the city, very affected by the Second World War [8]. The design of this housing unit gathers among the main principles of Le Corbusier: human-scale architecture (“the modulator”) and architecture of air and light (open houses with morning and evening sun). This so-called “radiant house”, comprising 294 apartments, differs from the Marseille model in that there is no shopping street, the scope of the program being limited by the modest budget of “low-income housing.”

Differing from those of Marseille Housing unit, the ground floor pilotis in Rezé are pillars-walls, arranged at each span, and whose edges are alternately tilted inward and outward, in the shape of a “V” or an “M”.

From 1995 to 1997, a documented restoration campaign was conducted on the pilotis [9]. The patch repairs realized at that time were integrated in the testing sites of the project. The available documentation refers to the following steps of the conservation work:

- Concrete removal and exposure of reinforcing steels.
- Cleaning of the steels with metal brush.
- Replacement of some steels with galvanized steel stirrups Ø 8 HA 500.
- Passivation of steels with a commercial product, combining a bonding primer and a corrosion protection cement-based slurry.
- Products mentioned for the repair of the pilotis are quick-setting fibered repair mortar, with a finishing coat made of a waterproofing micro-mortar (hydraulic binder based) and a synthetic resin to fix the sand grains.
- Marking of formwork board joints.

The main information collected from the historical study is synthesized in Table 1.



**Fig. 3** East facade of the Rezé housing unit. Pilotis and loggias.

### 3 Step two of Phase II: First on-site observations and trials

In Notre-Dame du Raincy church, the first on-site observations revealed that the 1991 repairs were very well conserved. Only a few of them showed debonding or cracks at the interface with the original concrete. However, the adjacent concrete showed numerous spalls at the interface (Fig 4 ). In addition, the patch repairs did not match with the colour and texture of the ancient concrete, and were highly visible.

For the Jaoul Houses, the aesthetic matching was almost perfect. The repairs could be distinguished when carefully observed, as they were slightly thicker than the adjacent ancient concrete. Although most of the repairs were still in place, detailed patch observations revealed numerous dislocations, cracks, and spalls, mainly located on the repairs and very occasionally on the adjacent ancient concrete. The evaluation of the cover depth showed low and heterogeneous cover depths (from 25 to 55 mm for the A House). The superficial hardness measured with a rebound hammer was higher for the original adjacent concrete than for the patch repair, whereas there was no difference in the scratch tests. Hydrophobic treatment was not revealed by water spraying.

On Rezé housing unit, the first observations of the 1995 repairs evidenced numerous degradations. Spalling, delamination, cracks, in the repair, at the interface, or in the adjacent ancient concrete were recurrently observed on the pilotis. The aesthetic performance was not good either, with very different textures and colours from those of the ancient concrete (Fig. ). The cover depth was very heterogeneous, and sometimes very low, from 10 to 65 mm. The ancient concrete in the adjacent area was harder than the finishing of the repaired areas, according to rebound hammer and scratch tests.

All data, observations and results gathered in phase II tests are summarised in Table 1. For each site, as agreed in the testing protocol elaborated [4], ten representative patch repairs were selected to perform phase II tests. On five of them, additional tests were carried out: non destructive and destructive testing followed by sampling for laboratory analyses. For each patch, decay mapping was realized (an example is given in Fig 11).



**Fig. 4** Notre-Dame de la Consolation church in Le Raincy, View of the area around patch 5, with a spalling in the ancient concrete (light area) adjacent to the repairs (slightly darker areas).



**Fig. 5.** The Jaoul houses in Neuilly-sur-Seine, spalling on a patch repair (second wood framework vertically from the left) and on the concrete, view of the B House.

### 4 Phase III: Detailed diagnosis with on-site characterisations and laboratory analyses

A series of tests were implemented in the three French sites, following the protocol elaborated [4]. For reasons of timing and logistics, some of the tests are not yet performed and some others couldn't be carried out.

Thus, for the on-site testing, due to access difficulties (no scaffolding), only the pull-off tests could be carried

out for Notre-Dame du Raincy church, and the corrosion diagnosis could not be performed in the Jaoul houses.



**Fig. 6** Rezé housing unit. V-shaped pile with spalling in the edge repair of the patch repaired area.

## 4.1 On-site testing

### 4.1.1 Colorimetry

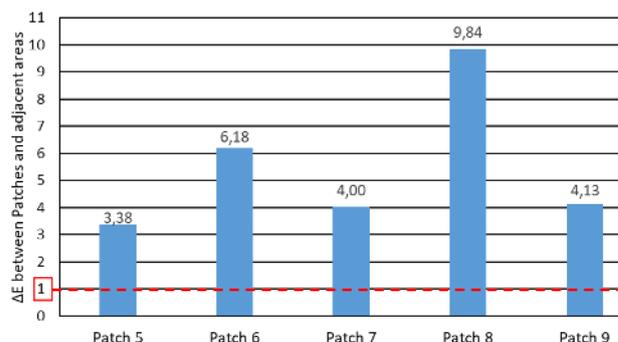
Colour measurements were performed with a Konica Minolta CR-410 colorimeter with D65 CIE standard illuminant, 2° CIE standard colorimetric observer angle, and measurement area of  $\varnothing$  50 mm [4]. To quantify the colour difference between the average colour of a patch repair and the average colour of its adjacent parent concrete the differences in colour,  $\Delta E$ , were calculated using the following formula:

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

For Rezé housing unit (Fig. 1), when considering a  $\Delta E$  of 1 for colour differentiation perceptible by the human eye, all patch repairs showed significant colour differences with the adjacent ancient concrete, with very heterogeneous values, varying between 3.38 and 9.84.

For Jaoul houses, the  $\Delta E$  values mainly ranged between 1 and 3, with a maximum of 7.

The colour measurements in Notre-Dame du Raincy will be performed in May 2022.



**Fig. 7.**  $\Delta E$  between the patch repairs and the concrete in the adjacent area according to the patch reference in Rezé housing unit.

### 4.1.2 Initial water absorption

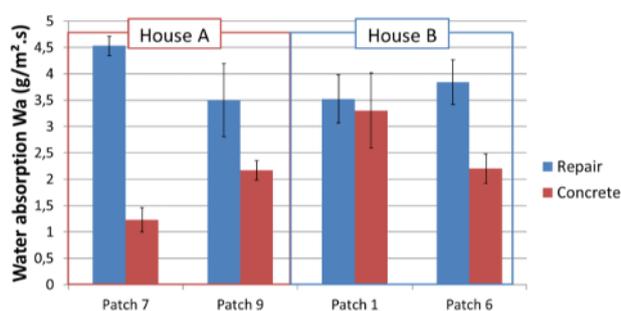
Initial water absorption was determined using the so-called *Sponge Test* with three measurements per area [4].

In Jaoul houses, significant differences were noted between the patch repairs and the adjacent ancient concrete for three of the four patch repairs investigated (Fig. ), with values ranging between 3.5 and 4.5  $g/m^2.s$  for the repair and between 1.2 and 3.3  $g/m^2.s$  for the ancient concrete.

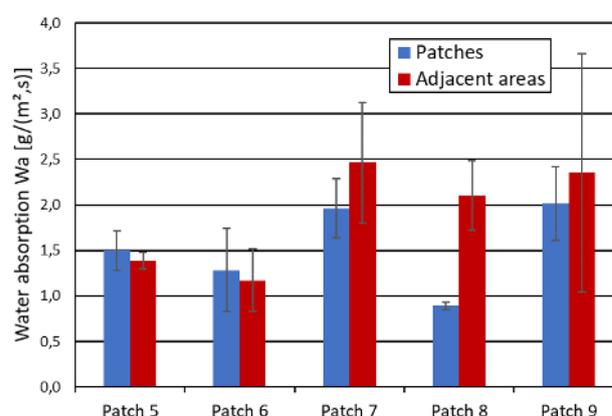
For Rezé Housing unit, water absorption values for the repaired areas varied between 1  $g/m^2.s$  and 2  $g/m^2.s$ , while for the ancient adjacent concrete they ranged between 1.2  $g/m^2.s$  and 2.4  $g/m^2.s$ . It is to be noted that the results were very scattered, with high standard deviations, so that no clear differences between the patches and the adjacent ancient concrete could be evidenced except for one patch (Fig. ). The latest (Patch 8) was significantly less absorbent than the adjacent ancient concrete. To explain this dispersion of results it is important to underline that water absorption can be very affected by micro cracking or surface faults even if the tests are performed on apparently sound zones.

**Table 1.** Main information, dates, general observations and main results of Phase II testing concerning the three French sites and their studied conservation campaigns. Ø = not yet realized

	Cases studies	Notre-Dame du Raincy church	Jaoul houses	Rez� housing unit
Historical information collected during phase I	Construction period	1920-1924	1953-1955	1953-1955
	Date of studied conservation campaign	1991	1991	1995-1997
	Repair materials	Bonding primer and ad hoc repair concrete	Like for, Like mortar, wood prints	Commercial ready to use mortar with fibres covered by a micro-mortar waterproofing
	Surface finishing	Casting with elastomer-coated wooden forms. Some repairs were bush-hammered	Pressure water cleaning at the end of the patch work for texture homogenization	Finishing coat with sand grains. Formwork board joints printing
Visual assessment and first testing during the phase II	General Aesthetic performance	Colour and texture of the repair do not match with the parent concrete	Colour and texture match very well with the parent concrete	Colour and texture of the repair do not match with the parent concrete
	General technical performance	Very good on the repair, but mainly bad on the adjacent area	Mainly good on the adjacent area and fair on the repair	Mainly bad on the adjacent area and on the repair
	Main deteriorations	Spalling on the adjacent original concrete, very punctually cracks in the interface and delamination in the repair	Cracks on the interface and on the repair, delamination, spalling and scaling mainly on the repair, a few on concrete	Delamination and spalling mainly located at the interface concrete/repair, cracks on repair and interface on the adjacent area
	Cover depth	Ø	From 25 to 55 mm (House A) From 20 to 40 mm (House B)	From 10 to 65 mm
	Superficial hardness / Rebound hammer	Ø	Concrete harder than repair Concrete 38±3 Repair 32±3	Concrete harder than repair 41±5 Repair 31±5
	Scratch tests	Ø	Similar hardness between concrete and patch	Concrete on the adjacent area harder than the patches' finishing
	Hydrophobic surface tests	Ø	No hydrophobic treatment	Hydrophobic treatment



**Fig. 8.** Contact sponge water absorption test results for several patch repairs of Jaoul houses A and B, both on the repaired zones (blue) and on the ancient concrete (red).



**Fig. 9.** Contact sponge water absorption test results for several patch repairs of Rez  housing unit, on both the repaired zones (blue) and on the original concrete (red).

#### 4.1.3 Bond strength of repair (Pull-off tests)

The results of the pull-off tests of the three French sites are presented in table 2. The tests were performed with standardized equipment and according to EN 1504 which indicates minimum values respectively of 0.8 MPa for mortars classified R1 and R2, 1.5 MPa and 2 Mpa for mortars classified R3 and R4. The location of the failure

is also very informative (adhesive failure, cohesive failure...).

For Notre-Dame du Raincy church, an average bond strength of 0.40 Mpa was measured, with failures mainly observed at the interface between the patch and the ancient concrete. This low average value should be taken with caution for two reasons: first, the thickness of the repairs was quite important; and second, because the tests were carried out on the columns, thus on curved surfaces, which can easily generate misalignment during the traction.

For the Jaoul houses, very low values were measured, with an average bond strength of 0.2 MPa, and with failures mainly located at the concrete/repair interface.

For Rezé housing unit, an average value of 0.46 Mpa was evaluated, but the majority of the failures occurred in the adhesive layer certainly because of a polymerisation problem induced by very low temperatures when the measurements were performed. This could indicate that the bond strength values of the repair material might be higher than this average value of 0.46 MPa.

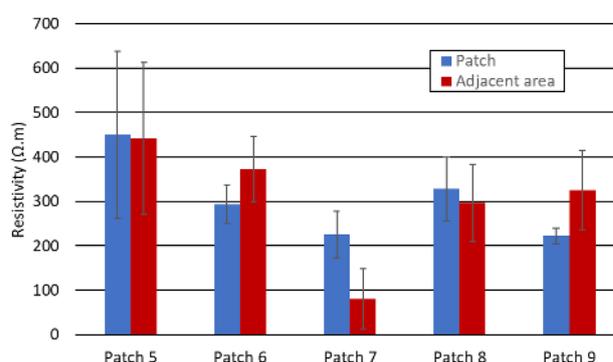
#### 4.1.4 Electrochemical diagnosis

The corrosion diagnosis consisted of resistivity and potential mapping, and corrosion rate measurements. So far, only the Rezé Housing unit was tested.

The resistivity measurements were performed using the Wenner method with a Resipod<sup>®</sup> and are gathered in Figure Fig. . Except for the adjacent ancient concrete of patch 7, all the resistivity values ranged between 200 and 450  $\Omega.m$ , which according to the RILEM Recommendation [10], can be considered as high and representative of a negligible risk of corrosion. As the standard deviations are noticeable, except for patch 7 whose resistivity is significantly lower than that of the adjacent concrete, no clear difference could be evidenced between the repair material and the ancient concrete. For patch 7, the resistivity measured in the adjacent concrete is indicative of a high risk of corrosion (<100  $\Omega.m$ ).

**Table 2.** Results of bond strength for each site. Y = Cohesion failure in the adhesive layer. A/B = Adhesion failure between the substrate and the first layer. B = Cohesion failure in the first layer.

Cases studies	Notre-Dame du Raincy church	Jaoul houses	Rezé housing unit
Patch reference	Patch 1	Patch 1	Patch 5
Bond strength (MPa)	0.38	0.26 Mpa	0.39 Mpa
Type of failure	A/B	A/B	Y
Patch reference	Patch 2	Patch 7	Patch 6
Bond strength (MPa)	0.49	0.16 Mpa	0.48
Type of failure	A/B	A/B	Y
Patch reference /	Patch 3	Patch 8	Patch 9
Bond strength (MPa)	0.32	0.18	0.53
Type of failure	A/B	A/B or B	Y
Mean of bond strength (MPa)	0.40±0.08	0.20±0.05	0.46±0.07



**Fig. 10.** Resistivity assessed with a Resipod<sup>®</sup> on five patch repairs of Rezé housing unit. Measurements were performed in the repair material (blue) and in the ancient concrete in adjacent areas (red).

The corrosion current densities, calculated from the polarization resistances measured with a Gecor10<sup>®</sup> on the repair patches and on the adjacent concrete, are detailed in the following figure (Fig. )

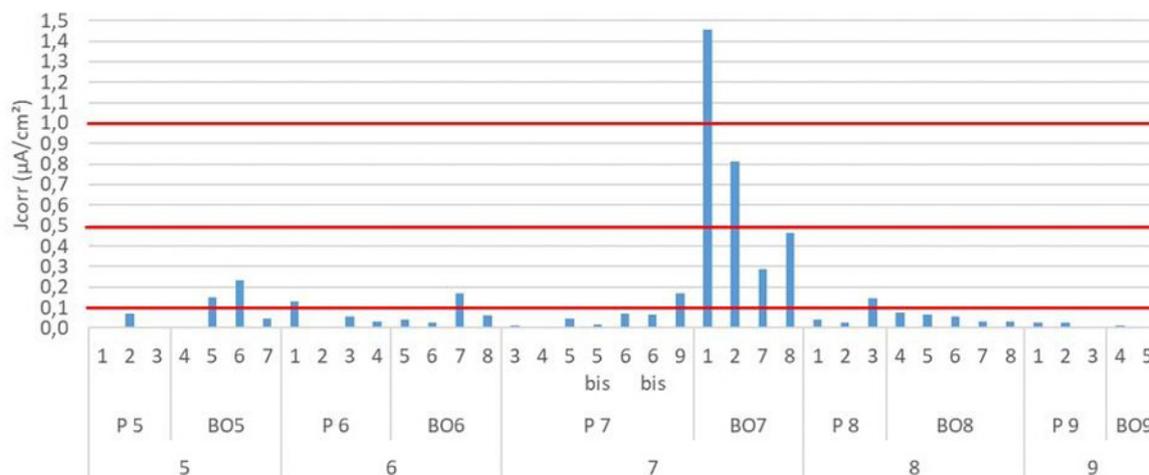
For most of the patches, corrosion current densities under 0.1  $\mu A.cm^2$  were measured, which correspond to negligible corrosion rates according to the RILEM Recommendation [12]. For patches 6, 7 and 8, three measured values were slightly above the 0.1  $\mu A.cm^2$  threshold corresponding to a low corrosion rate.

In the concrete areas adjacent to the patches, the corrosion current densities generally varied from 0.007  $\mu A.cm^2$  to 0.234  $\mu A.cm^2$ , with an average value of 0.07  $\mu A.cm^2$ . These values correspond to negligible (under 0.1  $\mu A.cm^2$ ) to low corrosion rates (between 0.1  $\mu A.cm^2$  and 0.5  $\mu A.cm^2$ ) according to the RILEM Recommendation [12]. But for patch 7, in line with the resistivity results, the corrosion seems more active in the concrete area adjacent to the patch, with values higher than 0.5  $\mu A.cm^2$ .

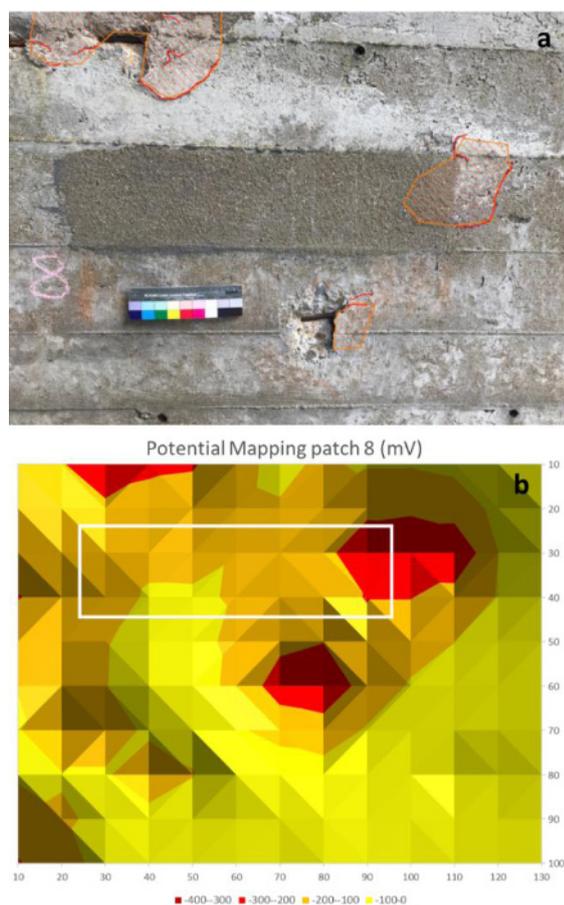
Potential mapping was performed versus a Copper-Copper sulphate reference electrode and analysed according to the RILEM recommendation [11] which indicates that not only the potential values but also

noticeable gradients should be researched to identify zones presenting high corrosion probability. The degradation and potential mapping for patch 8 are gathered in Figure Fig. . The potential map of patch 8 (Fig. b) shows a fairly high gradient in its upper right corner,

which corresponds to visibly developing spalling due to the swelling of the corroding reinforcement underneath. High gradients were also evidenced in the adjacent concrete, in correlation with spalling and cracking of the concrete.



**Fig. 11.** Corrosion current density measured on the patch repairs of Rezé housing unit (P= Patch, BO= adjacent Original Concrete). The red lines indicate the RILEM thresholds for corrosion rates (0-0.1µA/cm<sup>2</sup> = negligible corrosion, 0.1-0.5µA/cm<sup>2</sup> = low corrosion, 0.5-1µA/cm<sup>2</sup> = moderate corrosion, >1µA/cm<sup>2</sup>= high corrosion).



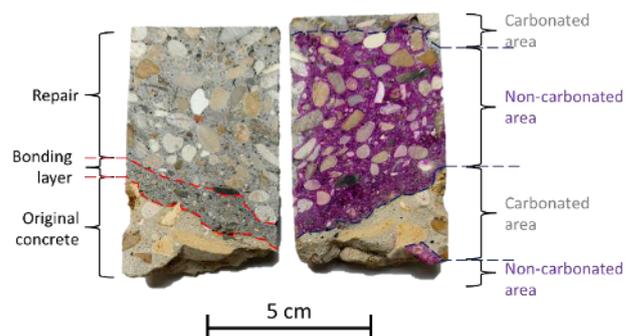
**Fig. 12.** The decay (a) and potential mapping (b) of patch 8, of Rezé housing unit. In the degradation mapping, the cracks are represented in red and the delamination in orange. The most electronegative potentials (mV vs Cu/CuSO<sub>4</sub> reference electrode) appear in red in the map. The contours of the patch are highlighted in bold white lines on the potential map.

#### 4.2 Opening inspection and sampling

The inspection procedure has not yet been carried out for Notre-Dame du Raincy church due to accessibility issues (no scaffolding), but they will be performed in May 2022. However, cores could be sampled from a basket and evidenced repair thicknesses up to 8 cm, with a double layer (Fig. ). The colour difference between the original concrete and the repair materials could be very well distinguished. Differences in aggregate size were also noticed.

In Jaoul houses, the repair thicknesses were lower (2-3cm). The repairs were single layered, with brushless steels, and the presence of a green layer on the surface of the steel and sometimes on the concrete too. This green layer probably corresponds to a passivating product (Fig. ).

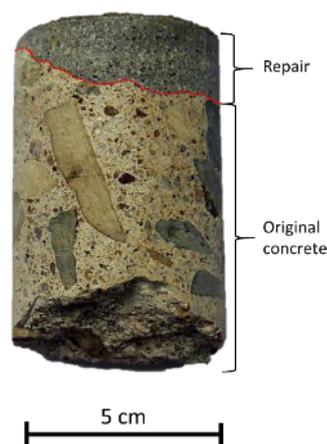
At Rezé Housing unit, inspection and sampling showed that the repair thicknesses were also very low, less than 2 cm (Fig. ). The repair was double-layered, with a mortar applied in limited areas around the reinforcement, and a thin coating covering both repaired and unrepaired areas.



**Fig. 13.** Core of patch repair 1 in Notre-Dame du Raincy church.



**Fig. 14.** Inspection of a patch repair in Jaoul houses.



**Fig. 15.** Core of patch repair 9 on Rezé housing unit.

#### 4.2 Laboratory analysis

The preliminary results of the Phase III laboratory analysis [13,14] are given in Table 3. The contact angle, capillary absorption, ultrasonic pulse velocity, X-Ray diffractometry, and the microscopy observations remain to be achieved (by the end of summer 2022).

Concerning the water porosity, the values were very different between the original concrete and the repair materials, whatever the site: the original concrete was more porous than the repair material for Notre-Dame du Raincy church whereas it was less porous for Jaoul houses and Rezé housing unit. This might be attributed either to concrete design (different water and cement contents...) or to implementation conditions.

For the total chloride content, expressed in relation to the mass of the cement, for all the sites it was lower than the 0.40% threshold for rebar corrosion specified in the concrete standard NF EN 206/CN.

Concerning the total equivalent alkali content (acid-soluble), expressed in  $\text{kg/m}^3$  of concrete, the values were low to medium and moderate. No significant variation was observed as a function of the depth of analysis.

For the sulphate content, expressed in relation to the mass of the cement, for all the sites, it was low or moderate in the repair materials. However, for the ancient concrete, a higher content was always noticed for the surface or the subsurface zones, in relation to urban pollution.

The carbonation depth of the ancient concretes, although heterogeneous, exhibited quite high values whatever the site (up to 60 mm for Rezé housing unit). Contrarily, the repair materials showed low carbonation depths, except for Jaoul houses, probably in connection with their high porosity.

Finally, dealing with the mechanical performance, the dynamic modulus of elasticity measured in the Notre-Dame du Raincy church showed that the repair material was more rigid than the original concrete. Contrarily, in Rezé housing unit, the repair material was less rigid than the original concrete.

## 5 Conclusions

Although preliminary and to be completed, the first set of results obtained on the three French sites examined within the PEPS project allows drawing first conclusions on the durability of almost 30-year-old conservation campaigns.

For Notre-Dame de la Consolation church in Le Raincy, the preliminary results showed that the original concrete was deeply carbonated, over at least 2.5 cm and up to 5.5 cm. sulphate contamination was also evidenced on both the surface and subsurface. The repair material was less porous than the original concrete. Little degradation was observed on the patches, whereas the majority of the degraded areas were noted in the original concrete at the repairing interface. Indeed, in 2018 only 2% of the spalling on the bell tower concerned the repairs of the 1991 conservation campaign. This could be correlated to the higher rigidity of the repair material compared to the original concrete. However, based on these results, the conclusion for this site is that the overall durability of the patch repairs of this conservation work is quite good after 30 years, but the aesthetic matching was not totally achieved.

For the Jaoul houses, there is a wide panel from good to bad patches, with generally very low performances of the repair mortar, lower than that of the ancient concrete (hardness, permeability and porosity). The bond was also very poor. A high carbonation depth was noticed for both the concrete and the patch repairs. The visual observation revealed that the implementation of the repair in 1991 was not compliant with recommendations (concrete not removed from the rebars on their entire circumference, passivation product applied both on the rebars and the concrete...). During the conservation campaign in 2019,

72% of the removed surface concerned the 1991 patches. Based on these results, the conclusion for this site is that a good aesthetical compatibility was evidenced, but with very low mechanical performance for some patches, after a period of 30 years.

Concerning the Rezé housing unit, a clear problem of aesthetic compatibility was evidenced, the repair material being very different from the original concrete. The concrete removal seemed very superficial in some patches. Corrosion occurred in some patches but mainly in the adjacent areas and at the interface with the original concrete. The finishing coating appeared more hydrophobic than the original concrete, which could be one of the factors explaining the more active corrosion in the adjacent area in the original concrete, water penetration in the material was clearly affecting the corrosion processes. The large carbonation depth in the original material (up to 60 mm) compared to the repair material (uncarbonated) can be another important parameter explaining the more active corrosion in the adjacent concrete areas. Based on these results, the conclusion for this site is that the 90's repair campaign shows poor performances after a period of 26 years. However, the evaluation of a conservation campaign is much more complex, because beyond the durability of the repair material itself, the condition of the adjacent area i.e., the historic concrete to be preserved has to be considered.

In Notre-Dame du Raincy church, repairs showed good durability but the adjacent concrete areas directly in contact with the repair exhibited some spalling. Contrarily, the 2019-conservation campaign achieved in Jaoul houses mainly concerned the 1991 repairs as the original concrete remained mainly in good condition. Further scheduled assessments on the French sites and data-sharing with the other countries partners of the PEPS project should help to identify the conservation campaigns leading to both durable patch repairs and satisfactory preservation of the original concrete. However, these first results already provided a lot of information on the reasons for failure or for success of a patch repair campaign and they will help to establish guidance for historic concrete repairing best practices.

## References

1. E. Marie-Victoire, M. Bouichou, T. Congar, R. Blanchard, Concrete cultural heritage in France: inventory and state of conservation, in: *Concrete Repair, Rehabilitation and Retrofitting IV: Proceedings of the 4th International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICRRR-4)*, Leipzig, Germany, (2015).
2. A.P.A. Gonçalves, S. Macdonald, É. Marie-Victoire, M. Bouichou, C. Wood, Performance of patch repairs on historic concrete structures: a preliminary assessment, in: *MATEC Web of Conferences*, EDP Sciences, (2019), p. 07001. <https://doi.org/10.1051/mateconf/201928907001>

3. J. Ducasse-Lapeyrusse, É. Marie-Victoire, M. Bouichou, A.P. Arato Gonçalves, S. Wilkie, S. Macdonald, N. Lauder, D. Farrell, P. Gaudette, A. Harrer, Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): a bibliographic review of patch repair durability, in: *Proceedings of Concrete Solutions, 8th International Conference on Concrete Repair*, CRC Press, Leeds, (2022).
4. S. Wilkie, J. Ducasse-Lapeyrusse, A.P. Arato Gonçalves, S. Macdonald, É. Marie-Victoire, M. Bouichou, N. Lauder, D. Farrell, P. Gaudette, A. Harrer, Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS): a bibliographic review of patch repair durability, in: *Proceedings of Concrete Solutions, 8th International Conference on Concrete Repair*, CRC Press, Leeds, (2022).
5. F. Lacoste, W. Thieulin, B. Bauchet, *Restauration du clocher et des verrières sud de Notre-Dame de la Consolation, Diagnostic*, (2018).
6. C. Devaux, DDA Devaux & Devaux Architectes, *Etude préalable à la restauration, Maisons Jaoul, Le Corbusier, Neuilly-sur-Seine*, (2017).
7. Base POP-Mérimée, Maisons Jaoul notice n° PA00088131, p. (2022).
8. Base POP-Mérimée, Maison radieuse de Rezé notice n° PA00108783, p. (2022).
9. M. Ferauge, R. Medrea, *La Maison Radieuse, Restauration des façades, Diagnostic*, (2016).
10. R. Polder, C. Andrade, B. Elsener, Ø. Vennesland, J. Gulikers, R. Weidert, M. Raupach, Recommendations of RILEM TC 154-EMC: Electrochemical techniques for measuring metallic corrosion Test methods for on site measurement of resistivity of concrete, *Materials and Structures*. **33**, pp. 603–611 (2000).
11. Bernhard Elsener, BERNHARD ELSENER, Recommendations of RILEM TC 154-EMC: Electrochemical techniques for measuring metallic corrosion Half-cell potential measurements - Potential mapping on reinforced concrete structures, *Materials and Structures*. **36**, pp. 461–471 (2003). <https://doi.org/10.1617/13718>.
12. RILEM TC-154-EMC, Recommendations of RILEM TC-154-EMC: “Electrochemical techniques for measuring metallic corrosion” Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarization resistance method, p. (2004). <https://doi.org/10.1617/13952>.
13. S. Gwinner, T. Lenormand, A. Ammouche, *Caractérisation des bétons et mortiers des façades des Maisons Jaoul, rue de Longchamp, Neuilly-sur-Seine (92)*, LERM, (2018).
14. H. Jourdan, A. Ammouche, *Chemical analyses and characterisation of concrete and mortar repairs. Maison Radieuse de Rezé (44), Eglise Notre-Dame du Raincy (93)*, LERM, (2021).

**Table 3.** Data obtained from the laboratory analyses of phase III.

Cases studies	Notre-Dame du Raincy church		Jaoul houses				Rezé housing unit	
	Concrete	Repair	House A		House B		Concrete	Repair
			Concrete	Repair	Concrete	Repair		
Type of binder	CEM I	Portland slag cement CEM II	Portland slag cement CEM II	Portland slag cement CEMIII	Portland slag cement CEM II	Portland slag cement CEMIII	CEM II/ B-S	CEM II A-M ( S-D)
Aggregate type	Limestone and siliceous	Limestone and siliceous	Limestone Silicate and quartz sand	Limestone and silicate sand	Limestone Silicate and quartz sand	Limestone and silicate sand	Siliceous aggregate	Mainly siliceous, few limestone
Cement content (kg/m <sup>3</sup> )	410	365	390	545	285	510	320	325
Open water porosity (%)	19.9	15.4	17.80	22.2	16.2	20	12.4	16.5
Water content (kg/m <sup>3</sup> )	220	170	245	255	200	255	135	210
W/C	0.54	0.47	0.65	0.45	0.7	0.5	0.42	0.65
Total chloride content ( % versus mass of cement)	Low (<0.22%) (no gradient in the profile)	Low (<0.17%) no gradient in the profile	Low (<0.07%), higher for the surface 0.13%	Low (<0.18%) no gradient in the profile	Low (<0.07%) no gradient in the profile	Low (<0.16%) no gradient in the profile	Medium (0.35% from 30 to 40 mm)	Low (<0.24%) no gradient in the profile
Total Alkali content Na <sub>2</sub> O <sub>eq</sub> (kg/m <sup>3</sup> )	Approx. 2 no gradient in the profile	Approx. 3 no gradient in the profile	Approx. 3 no gradient in the profile	Approx.4.5 no gradient in the profile	Approx.2.5 no gradient in the profile	Approx.5.5 no gradient in the profile	Approx.5 no gradient in the profile	Approx.5 no gradient in the profile
Sulphate content (% versus mass of cement)	Low in the concrete (<2%) Higher for the surface (0-20mm) 6%	Moderate (<3.11%) (no gradient in the profile)	Low (<3.26%) Higher for the surface (0-15mm) 4.43%	Low (<3.5%) (no gradient in the profile)	Low (<3.19%) Higher for the surface (0-15mm) 4.3%	Low (<2.5%) (no gradient in the profile)	Low (<3.19%) Higher for the surface (0-10mm) 3.89%	High, from 4.3 to 5.5 % (surface) no profile
Carbonation depth (mm)	Mean 43 mm From 25 mm to 55 mm	Mean 10 mm (from 2 mm to 22 mm)	Mean 25 mm (from 10 mm to 35 mm)	Mean 27 mm (patches 7 and 8)	Mean 20 mm (from 5 mm to 30 mm)	57 mm (patch 1)	Mean 35 mm From 25 mm to 60 mm	Mean 0 mm
Dynamic modulus of elasticity (GPa)	24.9	36.7	-	-	-	-	41.9	25.9