Performance evaluation of patch repairs on historic concrete structures (PEPS): preliminary results from an American case study

Simeon Wilkie[1*], *Ana Paula* Arato Gonçalves[1], *Paul* Gaudette[2], *Ann* Harrer[3]

[1]Getty Conservation Institute, 1200 Getty Center Drive, Suite 700, Los Angeles, CA, USA
[2]Wiss, Janney, Elstner Associates, Chicago, Illinois, United States
[3]Wiss, Janney, Elstner Associates, Los Angeles, California, United States

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 analyses performed on both the original substrate and previous patch repairs. In this paper, preliminary results from the Phase II & III in-situ assessments of a single case study in the United States of America are presented, and the differences in aesthetic and technical performance between repairs from three different intervention campaigns are discussed.

1 Introduction

The project 'Performance Evaluation of Patch Repairs on Historic Concrete Structures' (PEPS) is evaluating case studies in France, England and the United States to provide practical guidance through better understanding of the parameters for successful repair of culturally significant exposed concrete, and identifying appropriate methods to assess patch repairs for historic concrete. The selected case studies have been repaired in the past with the intent of conserving the historic and/or aesthetic values that the concrete contributes to each site. These sites are of various ages, have a variety of concrete finishes, and represent different types of materials and techniques, both in terms or their original construction and the repair [1]. The inclusion of case studies from three different countries allowed for the assessment of a broader variation in approaches to this complex category of concrete repair. This project is a partnership between Getty Conservation Institute (GCI), Historic England (HE) and the Laboratoire de Recherche des Monuments Historiques (LRMH), who are also joined by expert consultants from Rowan Technologies (England) and Wiss, Janney, Elstner Associates (USA).

The two operational phases for this project followed the completion of Phase I, which included development of the research proposal and of the assessment methodology, and selection of potential case studies. The operational phases consist of an initial preliminary assessment in a larger number of sites (Phase II) and a detailed assessment of a select number of case studies (Phase III). The preliminary assessment used visual condition assessment, historical research, documentation, and limited non-destructive evaluation (NDE) techniques to identify types of repairs and develop an initial understanding of their performance. The detailed assessment utilized in-situ and laboratory analyses aimed at answering questions on the characterization of repair materials and techniques, and technical and aesthetic performance of the repairs. The detailed assessment is further described in another paper presented in the conference.

This paper presents preliminary results from the Phase II & III in-situ assessments for a case study in the United States, identified by case study number: USA03. This building has aesthetically significant precast reinforced concrete elements on the facades which had to be repaired multiple times due to reoccurring reinforcement corrosion. Each of the three repair campaigns identified utilized different materials and techniques illustrating various attempts at reaching the desired technical and aesthetic performance.

* Corresponding author: swilkie@getty.edu

2 Background

2.1 Case Study USA03

USA03 was built in the 1960s and is exposed to rain and freezing (XF1) and cyclic wet and dry carbonation conditions (XC4) as described in EN 1992-1-1 [2]. This two-story institutional building has a cast-in-place reinforced concrete structure with facades made of masonry, architectural precast reinforced concrete panels, and aluminium frame windows. Even though the building is not listed, it is considered architecturally significant, and the precast concrete elements, in particular, contribute to the aesthetic value of this site. However, these precast concrete elements have a long history of deterioration related to reinforcement corrosion, which has led to multiple repair campaigns in the past. Given the aesthetic prominence of the precast concrete, the repairs have tried to match the aesthetic of the original with various degrees of success.

The architectural precast concrete panels are made of white angular coarse aggregates and white cement paste. The coarse aggregate is exposed on the surfaces of the panels. The panels surveyed in this research span the full height of the facade and appear in two different widths approximately 3 feet (914 mm) or 5 feet (1524 mm) in width at the top, and they taper into slender columns measuring 9 ½ inches (241 mm) in width. These panels measure 4 ½ inches (115 mm) in depth with a raised perimeter edge that increases depth by 3 inches (76 mm). They were installed in different building facades and are fully exposed to the environment with no protective roof overhang.

The panels surveyed for the PEPS project were chosen for the concentration of multiple repair vintages. Reinforcement corrosion most often occurs on the raised perimeter edge (rib), which measures 2 ½ inches (64 mm) in width and has a 5/8 inch (16 mm) diameter steel reinforcement bar located at its center. The slender design of the rib has meant that the reinforcement has little more than 1 inch (25 mm) cover on three sides and the slightest misplacement during fabrication resulted in reduced concrete cover in many locations. The challenge of placement of the reinforcement in the curved ribs combined with the exposed nature and the open pores from the texture of the surface has left the concrete in these locations quite susceptible to carbonation and reinforcement corrosion.

These panels were first inspected (Phase II) in June 2019 following the PEPS protocol for visual inspection and using a sounding technique to detect unsound and delaminated concrete. A second inspection (Phase III) was conducted in November 2021, which included a more comprehensive set of non-destructive evaluation techniques and sampling for laboratory analysis.

A total of three different repair campaigns were identified among the repairs assessed. Each repair campaign was assigned a letter as an identifier: A, B, and C. Only the most recent one (A), completed in 2017, has a known date. B and C consist of repair campaigns completed prior to 2017.

2.2 Background on Repairs

The project team had access to a 2016 condition assessment report, 2017 repair design drawings, a description of the work and materials specified, and access to the professionals that developed the repair solution. The project team was told there was no documentation on the repairs installed prior to 2016 investigation. However, the 2017 repair process was well documented.

The 2016 report revealed the following conditions had been observed on the precast panels: delamination and spalling of concrete with evidence of reinforcement corrosion, and previous repairs. The previous repairs varied in aesthetic proximity to the original concrete and also in technical performance. These repairs used different types of coarse aggregates and binders, but they were typically shallow and did not extend behind the reinforcement. Some were showing signs of deterioration similar to the original concrete, others were sound. The deterioration and repairs observed were located on the ribs of the panels.

The report described laboratory studies of samples and included the results from petrographic analysis, depths of carbonation, and chloride content measurement. Petrographic analysis of samples from original concrete identified white Portland cement, crushed quartzite aggregate and rounded quartz sand as fine aggregate. Chloride content was measured in three samples of original concrete removed from the top of the precast panels and revealed chloride contents above the recommended limit.

The repairs carried out in 2017, designated 'campaign A' in this paper, were completed following the 2016 condition assessment, and the professionals involved in this repair campaign, from investigation, repair design, to construction phases, were considered extremely experienced in concrete repair, and have significant experience in concrete conservation. The scope of work for the precast panels included cleaning of panels, repair of deteriorated concrete and replacement of repairs that were performing poorly (technically and aesthetically), and application of a water-resistant treatment to reduce further corrosion. The repairs were carried out following best practice guidelines on concrete repair [3, 4, 5] and concrete conservation [6], and the final solutions for cleaning and repairing were developed based on trials and mock-ups.

The repair process involved the following techniques that were first performed in mock-ups:

- Cleaning the original concrete with warm water, mild detergent, and a soft brush, following trials to determine the least aggressive effective system;
- Concrete removal by saw-cutting the perimeter to at least 2 inches (50 mm) beyond the deteriorated area, chipping away concrete with a light hammer (≤ 15 lbs) to a depth of at least 3/4 inch (20 mm) behind the reinforcement, then cleaning of the substrate with abrasive blasting while protecting adjacent original concrete;

- Cleaning of the steel reinforcement to grey metal (SSPC-SP10) by abrasive blasting;
- Cleaning of substrate with high pressure compressed air;
- Application of two coats of corrosion inhibiting zinc-rich epoxy primer to reinforcement;
- Installation of plywood formwork, with a retarder applied on the formwork surface, prior to pouring the repair mix;
- Poured custom designed, cementitious pre-bagged concrete;
- Formwork removed after 24 hours of curing, and the surface hand brushed to expose the aggregate to match the adjacent original concrete;
- Removal/replacement or modification of any repairs that deviated from the approved mock-ups, were unsound or did not match the adjacent original concrete;
- Application of a breathable water repellent clear sealer to all concrete.

3 Findings on Repairs of Case Study USA03

In June 2019, the project team made an initial assessment of six repairs from campaign A, and three repairs from campaign B.

In November 2021, the project team returned to the site for further NDE and sampling. This work focused on two campaign A repairs, two campaign B repairs, and one campaign C repair (a repair campaign that had not been included in the Phase II first inspection). An initial visual inspection revealed that campaign A repairs retained good aesthetic and technical performances, but repairs from campaigns B and C had deteriorated.

3.1 Repair Campaign A

3.1.1. Phase II Assessment

Campaign A repairs mostly showed good aesthetic and technical performances. The repairs had colour and texture that appeared very close to the original, and with both cement paste and exposed aggregates that appear similar to the original. Only one repair deviated slightly from the original profile, this repair was located on the curved edge where the panel tapers into a column. All repair edges appeared to have been sawcut and had sufficient depth to reach behind the reinforcement. All repairs were sound, with no cracks or other signs of deterioration.

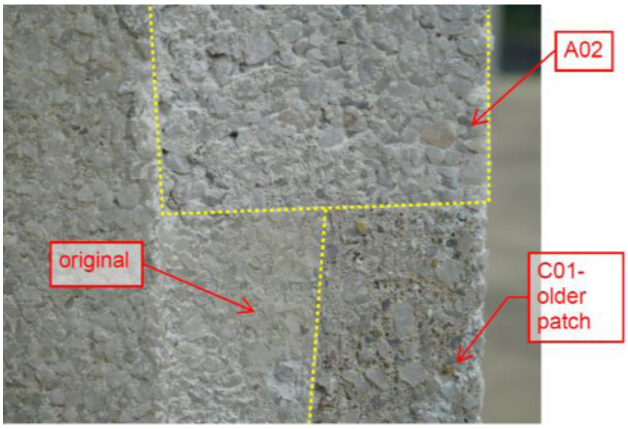

Figure 1. Intersection of repair A02, the original concrete, and repair C01.

3.1.2. Phase III Assessment

The campaign A repairs showed no signs of deterioration when the team returned to conduct the Phase III assessment in 2021. However, in some adjacent areas where previous repairs had been carried out, there were clear signs that corrosion was going on in the repairs from campaigns B and C that were not visible during the 2019 assessment. It is unclear whether this is an example incipient anode effect [4], or merely an inevitable outcome due to the quality of the previous repairs.

Coring at the bond line between A02 and the original concrete (Figure 2) revealed that the concrete was well consolidated, bonded, and with no air voids or signs of segregation. In fact, the interface between the materials within the core hole was barely perceptible.

Figure 2. Core at bond line of repair A02 and original concrete.

An inspection opening of repair A08 (Figure 3) revealed that the reinforcement remained in good condition and the zinc-rich epoxy primer coating was fully intact, with no indication the repair techniques applied deviated from those documents and previously described.

Figure 3. Inspection opening of reinforcement within a patch from the most recent repair campaign (A08).

From a visual perspective, the repairs from campaign A appear to be the closest aesthetic match, with colour, texture and profile that appear similar to the adjacent original concrete. However, colorimetric data taken on site (Table 1) shows that there is a clear difference in colour between the patches and the original concrete.

While there are no specific requirements for matching concrete, and limited data regarding the variability of concrete colour, typical descriptions of ΔE relating to the perception of colour by a standard observer are as follows [7]:

- $0 < \Delta E < 1$ observer does not notice the difference;
- $1 < \Delta E < 2$ only experienced observer can notice the difference;
- $2 < \Delta E < 3.5$ unexperienced observer also notices the difference;
- $3.5 < \Delta E < 5$ clear difference in colour is noticed;
- $5 \leq \Delta E$ observer notices two different colours.

Table 1. Summary of colorimetric differences between repairs from campaign A and the adjacent original substrate.

Repair	ΔE between patch and adjacent concrete when both dry	ΔE between patch and adjacent concrete when both wet
A02	4.56	4.62
A08	3.78	4.09
B01	2.79	3.42
B03	2.10	5.19
C01	6.97	8.52

Based on this colorimetric data, the patches from repair campaign A show a clear difference in colour to the original concrete when both are dry and when both are wet. The reason for this difference may be explained by examining digital microscope images taken on site. Figure 4 shows an image of repair A02. When compared to the original concrete (Figure 5), there are clear differences in the matrix and aggregates.

While petrographic analyses are yet to be completed on samples of the repair materials, the microscopy carried out on site appears to show fine aggregates that are more angular than those found on the surface of the original concrete, with some darker aggregates and possibly with a finer grading. However, the excess of cement paste makes this difficult to compare without petrographic analyses of a cross-section.

While the excess of the WPC paste is visible both under the microscope and on close visual inspection of the repairs (Figure 1, Figure 6), the campaign A repairs are still relatively young, having only been completed in 2017, and it is likely that the excess paste will erode slowly over time as part of the natural weathering process. As previously mentioned, when the interface between the materials within the core hole was examined, it was barely perceptible as the two materials had such a good visual match.

Figure 4. Digital microscope image of repair A02 *in situ*, ≈ 55x magnification.

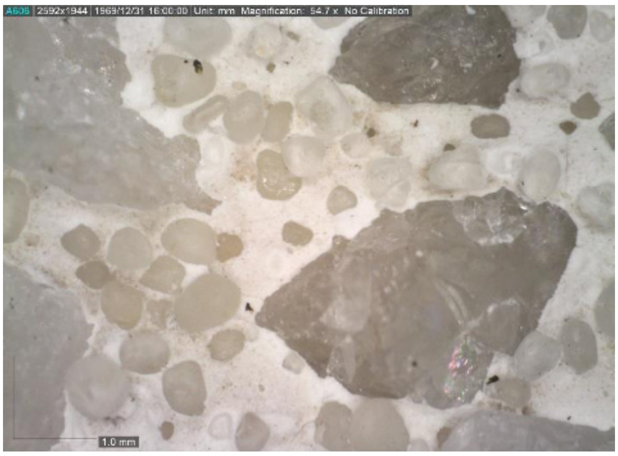

Figure 5. Digital microscope image of the original concrete *in situ*, ≈ 55x magnification.

3.2 Repair Campaign B

3.2.1. Phase II Assessment

Campaign B repairs showed fair aesthetic and technical performances. The colour and profile of the repairs were close to the original, but the texture looked very different on close inspection. The difference in texture was due to a larger proportion of fine round aggregates exposed on the surface, while the original concrete has a larger proportion of angled medium sized aggregates. These repairs had irregular edges and did not extend behind the reinforcement. One of these repairs sounded hollow and showed a few linear cracks around the border, but no sign of imminent failure. Based on a visual assessment, it is most likely that the repairs from campaign B were hand-applied mortar repairs, and the positioning of the aggregates suggests they were likely post applied by pressing into the surface of the repair as it set. As a result, these repairs have a much smoother surface texture that does not match the original concrete.

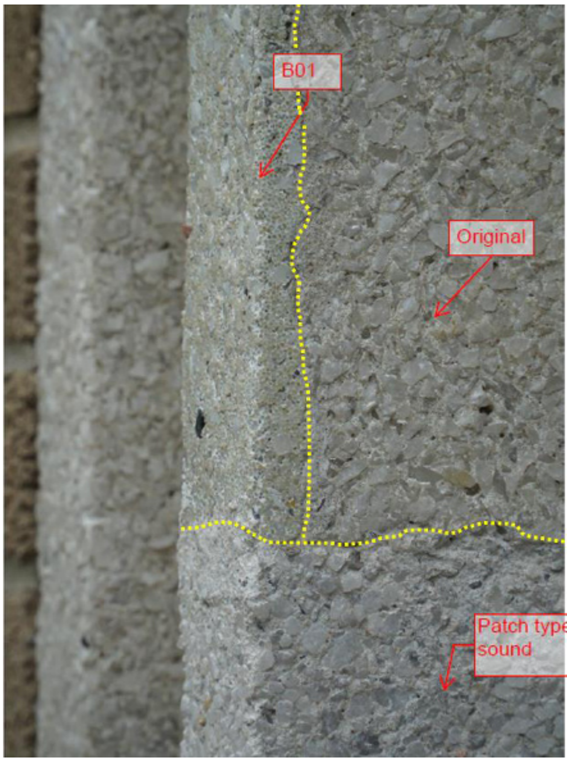

Figure 6. Intersection of repair B01, the original concrete, and a repair from campaign A.

3.2.2. Phase III Assessment

B01, which showed minor cracks and had delamination detected by sounding in 2019, showed more prominent cracking in 2021. One crack of particular concern, located in the top portion of the repair, progressed onto the original concrete, and was accompanied by small rust deposits.

Careful removal of this repair revealed a feathered edge and confirmed that the repair did not extend behind the reinforcement, and that corrosion was occurring.

Figure 7. Repair B01 showing significant cracking and rust staining from reinforcement corrosion (right) and the reinforcement following removal of the de-bonded repair (left).

It also exposed the reinforcement, revealing it had been coated during repair. However, this coating was only applied to the front face of the reinforcement – not the full circumference of the bar – and it was clear that it had been applied carelessly as it was also found on the substrate around the reinforcement.

B03 showed similar conditions as in 2019 – it was sound, with no visible signs of deterioration. However, an inspection opening revealed initial stages of reinforcement corrosion. As with B01, repair B03 also had the same careless application of a coating on the reinforcement, feathered edges, and insufficient depth to reach behind the reinforcement (Figure 8). As such, it is unlikely that the reinforcement was sufficiently cleaned during the repair process.

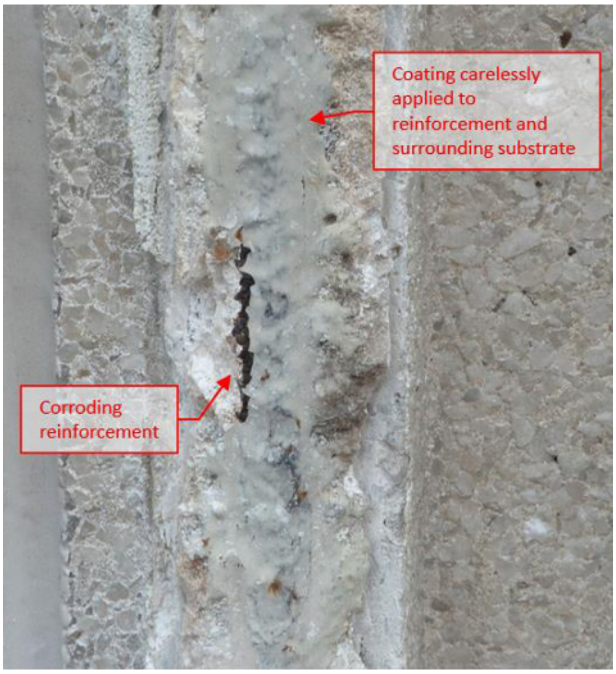

Figure 8. Inspection opening of repair B03 showing poorly applied coating to reinforcement and ongoing corrosion.

From an aesthetic perspective, the repairs from this campaign had mixed performance. On one hand, the colorimetric data shows that, when both the repair and the original are dry, these repairs were the closest in colour to the original – though even an unexperienced observer would be able to tell the difference in colour. When viewed under the digital microscope (Figure 9), the use of WPC is clearly visible and shape and colour of the fine aggregates seem similar. However, the fine aggregate in the repairs is noticeably larger than in the original. Additionally, the application of the aggregates to the surface, which was likely done during the setting of the repair, has resulted in a high concentration of the fine aggregates sitting on top of the surface, rather than being exposed from the surface. These repairs also lack any exposed coarse aggregates and this has led to a significant difference in texture between the repairs from campaign B and the original concrete.

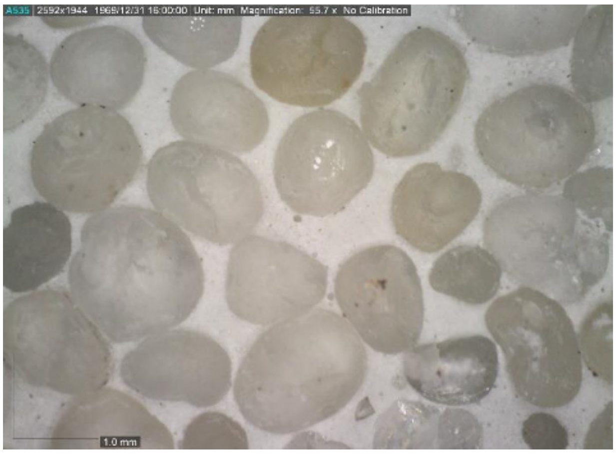

Figure 9. Digital microscope image of repair B03 *in situ*, ≈ 55x magnification.

3.3 Repair Campaign C

3.3.1. Phase II Assessment

The repair from campaign C was not assessed in detail during the Phase II visit and was only assessed as an adjacent area to a campaign A repair that was assessed (A02). It was noted that repair C01 did not match the cement paste colour of the original, but had similar texture, profile, and exposed aggregates. The edges appeared to have been sawcut and have sufficient depth to reach behind the reinforcement. No signs of deterioration were visible during this survey in 2019. Based on the depth of repair and the exposed aggregate finish, it is likely that this repair was carried using a form-and-pour approach, with some form of abrasion used to remove the formed face of cement paste and expose the aggregate.

3.3.2. Phase III Assessment

Repair C01 showed visible signs of deterioration, which had not been detected in 2019. Linear cracks were present on the front and right side of the repair running parallel to the reinforcement and sounding of the repair detected delamination. An inspection opening confirmed that the repair was deep enough to reach behind the reinforcement, and it was revealed that the reinforcement had been coated but, despite this, reinforcement corrosion was ongoing.

Figure 10. Repair C01 showing significant cracking of the repair (left) and the reinforcement following removal of the failed repair (right).

Removal of core samples on the border between repair and original concrete revealed poor consolidation of the repair material and large voids at the interface with the substrate. While laboratory and petrographic analyses of the core samples have yet to be completed, phenolphthalein solution applied in situ to the core hole and inspection opening suggests that the repair material may be entirely carbonated, and this is likely to be the main cause of reinforcement corrosion in repair C01.

Figure 11. Core at bond line of repair C01 and original substrate.

As previously mentioned, it was noted during the initial visual inspection that the colour of C01 did not match the colour of the original, but the repair had similar texture, profile, and exposed aggregates. Colorimetric measurements (Table 1) taken on site confirm a significant difference in colour between the repair and the surrounding substrate. In this case, the colorimetric measurements confirmed visual observations: C01 was a much poorer colour match than any of the repairs surveyed from the A or B repair campaigns.

Figure 12. Core at bond line of repair C01 and original substrate following the application of phenolphthalein solution.

Due to the colour of the matrix, it was initially assumed that ordinary Portland cement (OPC) had been used instead of WPC, and that this was the cause of the colour difference. However, images taken on site with a digital microscope suggest this is not the case – the cement paste appears to be WPC. The microscope images reveal the matrix binds a high proportion of very fine angular aggregates, some of which are considerably darker than that used in the original concrete. When viewed from a distance, this gives the illusion that the cement paste is darker than it actually is.

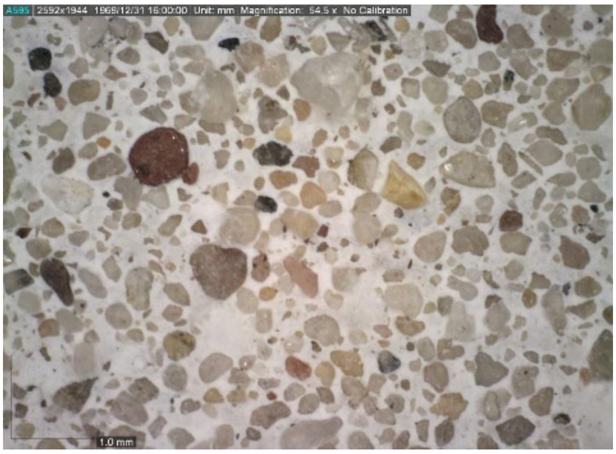

Figure 13. Digital microscope image of repair C01 *in situ*, ≈ 55x magnification.

4 Conclusions

This paper presents preliminary results from two phases of site assessments carried out at a case study in the USA. The structure, built in the 1960s, is considered architecturally significant and has previously had a series of repair campaigns carried out. This paper assesses the technical and aesthetic performances of patch repairs from three of these campaigns. Each of these campaigns adopted a different approach to the repair process, and each achieved a different level of technical and aesthetic performance as a result.

This case study highlights that despite the availability of guidance on concrete repair [3, 4, 5], basic good practice is not always followed on site and this can result in repairs which have poor technical performance and fail prematurely. Furthermore, it highlights the need for experienced professionals in this type of work and the importance of disseminating this knowledge to building owners and stewards who are responsible for hiring contractors to work and approving the final repairs.

The final results of this research will contribute in filling the current need for guidance on concrete conservation best practice which supplements that which is already available [8, 9, 6, 10, 11].

References

1. A. P. Arato Gonçalves, et al., *Performance of patch repairs on historic concrete structures: a preliminary assessment*, 07001, MATEC Web of Conferences, **289** (2019)
2. British Standards Institution, *BS EN 1992-1-1:2004+A1:2014, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*, BSI: London (2014)
3. American Concrete Institute, *ACI 546.3R-14. Guide to Materials Selection for Concrete Repair*, ACI: Farmington Hills (2014a)
4. American Concrete Institute, *ACI 546R-14. Guide to Concrete Repair*, ACI: Farmington Hills (2014b)
5. American Concrete Institute, *ACI 563-18. Specifications for Repair of Concrete in Buildings*, ACI: Farmington Hills (2018)
6. P. Gaudette and D. Slaton, *Preservation Brief 15: Preservation of Historic Concrete*, National Park Service, U.S. Department of the Interior: Washington D.C. (2007)
7. W. Mokrzycki and M. Tatol, *Color difference Delta E - A survey*, Machine Graphics & Vision International Journal, **20**, 4, pp. 383–411 (2011)
8. D. Odgers (ed.), *Practical Building Conservation: Concrete*, London: Ashgate/English Heritage, (2012)
9. D. Urquhart, *Historic Concrete in Scotland Part 3: maintenance and repair of historic concrete structures*, Historic Scotland: Edinburgh (2014)
10. S. Macdonald and A. P. Arato Gonçalves, *Conservation Principles for Concrete of Cultural Significance*, Getty Conservation Institute: Los Angeles (2020)
11. A. Harrer, P. Gaudette and D. Slaton, *Approach to Preservation of Historic Concrete*, Concrete Repair Bulletin, pp. 12-17, March/April (2020)