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Performance evaluation of patch repairs on historic concrete structures (PEPS): the evolution of conservation repairs on the Historic England Phase II test sites and PEPS Phase II results

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Abstract. Historically, little effort had been made to match patch repairs to culturally significant reinforced concrete structures so that they are effective and sustain the aesthetic values of the structure. The collaborative research project, Performance Evaluation of Patch Repairs on Historic Concrete Structures (PEPS), being undertaken by Getty Conservation Institute (GCI), Historic England (HE) and the Laboratoire de Recherche des Monuments Historiques (LRMH), seeks to address this problem. Through its advice on grant-aided projects, Historic England has tried to achieve effective like-for-like repairs over the last 20 years. The ten English sites selected for the PEPs Phase II non-destructive testing (NDT) includes some of the buildings and structures where this repair work was carried out. Data on site location, specification of repair, environmental conditions, test results and tentative conclusions from this phase of the research is presented in this paper. Five of the sites will be subject to further NDT and destructive testing and sampling as part of Phase III.

1 Introduction and background to PEPS Phase II

There have been many studies on the performance criteria for concrete patch repairs, but few that focus on the long-term performance of patch repairs carried out using like-for-like materials that are designed to sustain the aesthetic value of culturally significant concrete structures. This is an increasing worldwide problem as more concrete buildings are recognised for their architectural and historical value and are being protected. To address this issue, the Getty Conservation Institute (GCI), Historic England (HE) and the Laboratoire de Recherche des Monuments Historiques (LRMH) started a collaborative research project, 'Performance Evaluation of Patch Repairs on Historic Concrete Structures' (PEPS), in 2018. The PEPS project aims to determine whether patch repairs using like-for-like materials are more successful in matching the host concrete and perform as effectively as alternative proprietary materials.

The research is being carried out in four phases:

- Phase I Project development
- Phase II Preliminary assessment
- Phase III Detailed diagnostic assessment
- Phase IV Synthesis & conclusions

The assessment methodology includes a variety of traditional and non-traditional non-destructive, mechanical, chemical, and electro-chemical characterization and diagnostic techniques. An overview of the methodology is provided in the 2019 Concrete Solutions paper *Performance of patch repairs on historic concrete structures: (PEPS) a preliminary assessment* [1].

This paper describes the Phase II preliminary assessment carried out by Historic England at ten sites in England. These sites are all designated structures that are either listed (as buildings of architectural or historical importance) [2] or scheduled (as scheduled monuments) [3]. Within this legislation, the building's fabric (the materials used to build it) and the contribution that this makes to aesthetic values forms a very important part of the structures' cultural significance [4].

The aim of Phase II was to examine the technical performance of past conservation-based repairs [5] where matching and compatibility of material, minimum intervention, the role of craftsmanship and practical knowledge are important considerations in repair decisions [6].

The Phase II assessment only used non-destructive testing (NDT) techniques. It looked for indications of ongoing corrosion of the reinforcement. The testing was designed to understand how the repair patches had performed both physically (e.g. adherence to the parent concrete) and aesthetically (blended in with the parent concrete and allowing normal weathering and biological growth to become established).

Most of the Phase II patches tested were prepared on a like-for-like basis, using the same concrete constituents that were used for the original mix, and had been undertaken with input from Historic England . Some proprietary polymer-modified trial patch repairs were also tested in Phase II. The availability of first-hand

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knowledge and documentation of the repairs to be tested was a key consideration in selecting the sites for study.

The assessment methodology adopted in each phase of research was developed collaboratively with all project partners. Ten patch repairs were tested on up to ten sites in each of the partner countries. The ten English research sites are quite varied: they have concrete of different ages, are subject to a range of environmental and weather conditions and are found in both urban and rural situations. Three were also close to the sea where corrosion of embedded steel reinforcements, due to chloride ingress, is far more severe.

Phase III, with fabric removal, will provide a more thorough assessment of the performance of a repair including information on whether embedded steel reinforcements have been adequately passivated (prevented from corroding) by the repair process [7]. One objective is to see if the so called 'incipient anode' effect (accelerated corrosion of reinforcement at or around the edge of a patch repair) is affecting the long-term performance of repair patches on any of the sites. Phase III is currently in progress on five of the ten Historic England sites and this is scheduled for completion by the end of 2022.

Phase IV will complete the work with a detailed assessment and comparison of results between different sites in England and with those of the other project partners' sites in France and the USA.

Historic England's consultant on concrete for over twenty years, Dr David Farrell, led the Phase II on-site assessments. He had been directly involved with many of the sites when they were originally repaired, so this was extremely helpful in understanding their detailing and performance. Images taken before, during and after repairs were readily accessible. For other sites, detailed notes, specifications and operation and maintenance (O&M) manuals were sourced from the architects or building managers to assist with the test work. Older repairs, which had been exposed for longer, were felt to give a clearer assessment of a repair's effectiveness. However, some of the older repair materials (principally commercial repair mortars) had been superseded by newer versions or the manufacturer was no longer in business, so the performance data was therefore not as relevant.

1.1 Urban Sites

There were six urban sites situated in the suburbs of major cities in England:

- Church of St Paul, Bow Common, London, built 1958-1960 (listed Grade II)
- Church of St Thomas More, Sheldon, Birmingham, built 1968-1970 (listed Grade II)
- Alexandra Road Estate, London, built in the 1970s (listed Grade II*)
- The National Theatre, London, built 1976-1977 (listed Grade II*)
- Dudley Zoo, near Birmingham, built between 1935-1937 (6 structures listed at Grade II* or Grade II)
- A large residential development in the north built in the early 1960s (listed Grade II*)

The environment in urban sites is today relatively clean as the burning of coal for heating and industrial power (and the emission of acidic gases) is generally a thing of the past. However, the environment is still subject to some pollution from car exhausts – principally nitrous oxide (N_2O).

1.2 Rural Sites

Church of St John and St Mary Magdalene, Goldthorpe, South Yorkshire, built 1914-16 (listed Grade II)

This was the only rural site. However, this does not tell the full story as Goldthorpe was originally a mining town with three deep pits, a coking plant and coal burning from the surrounding houses. The highly acidic sulphurous and hydrogen chloride gases emitted from the coking plant and coal burning reacted with the alkaline concrete of the church and eventually resulted in corrosion of the embedded steel reinforcements. Goldthorpe today has a very clean and pollution free environment.

1.3 Marine Sites

All the PEPS Phase II research sites which are situated close to the coast are scheduled monuments:

- The right battery at Landguard Fort, Felixstowe (Suffolk), built around 1938. Only 50m away from the sea
- The Listening Mirrors, Dungeness (Kent), built in the late 1920s-30s. Distance from the sea is around 2000m
- Tynemouth Priory and Castle coastal battery, South Tynemouth (Tyne and Wear), built between 1880-1945. Situated on a cliff 100m from the sea.

These have been subject to various levels of chloride contamination from sea-borne rainfall and marine aerosols. Generally, the closer the concrete is to the sea, the higher the level of corrosion that may be expected on embedded steel reinforcement when the chlorides migrate into the concrete. Repair of damaged areas is also a problem if chlorides are present in the concrete matrix around the embedded steel.

2 On-site testing

The Phase II testing was carried out in 2019 at ten English sites on ten patches per site. These were selected to cover a range of three different conditions - "good", "bad" and "fair". The on-site tests were carried out using NDT methods and high-quality photographic images to assess the repairs.

The NDTs included:

- Visual assessments for shrinkage, cracking, crazing and other surface defects as well as rust staining
- Hammer tapping to check for hollowness or de-bonding of the back of the repair from the parent concrete

- Schmidt hammer testing of parent and patch concrete for their comparative strengths
- Cover meter assessment of the thickness of concrete cover over embedded steel reinforcements within and around the outside of the patches
- Spraying the surfaces of both the patch and parent material with water to see if it was absorbed or ran off
- Scratching the surfaces of both the patch and parent concretes to give an approximate assessment of their hardness
- Photography to capture surface texture and colour match between the parent and patch concrete

High quality and large capacity (DNG and TIFF files) images were taken using a professional digital camera and a colour passport to enable the colours of the images to be compared with other research images. These images will also be used in future years to assess the longer-term performance of the repairs.

3 Polymer-modified and mixed repairs in urban areas

Dr Farrell had not been directly involved in the specification of commercial patch repairs to any of the concrete buildings investigated in Phase II so information about these repairs has mainly come from O&M manuals issued after the work was completed or notes from the building managers. The one exception is some of the poor 'mixed build-up' repairs reported in 3.3, where the contractor ignored the outline repair specification.

3.1 1990s polymer-modified repairs

At the Alexandra Road Estate (an extensive housing development dating from the 1970s), repairs were needed after only 25 years because of the low cover to the steel reinforcement when the estate was built and subsequent corrosion. Many areas of corroding steel stained the white concrete surfaces. Approximately 11,000 patches had been placed during a repair contract between 1997 and 2001. When Historic England was first involved in this site in 2001, information on the specification of the commercial products used for the repairs was sought, but unfortunately data sheets were no longer available. The repairs were specified as being 3mm thick, but this was later increased to 6mm, still thin but dictated by the workmanship of the original construction.

Figure 1 shows how the patch repairs appeared during the Phase II assessment in 2019. They had not coloured down to blend with the parent concrete, nor did they allow biological growth to establish. Shrinkage cracks were evident around the edges as well as cracking and crazing within the patches. The patches contained no large aggregate to match with the parent concrete and the texture was also different. In some patches, steel was found to be corroding and hollowness was also detected. The Phase II tests showed that the cover to the steel was often only a few millimetres deep and sometimes it was breaking through the top surface. The patch surfaces repelled water suggesting that they were early polymer-modified mortars.

Figure 1. Typical 1997 polymer modified mortar repairs on the Alexandra Road Housing Estate in London. The estimated 11,000 thin patches had shrunk and cracked, and the polymer type surfaces had failed to allow normal algae and mould growth to become established.

3.2 2010 polymer-modified repairs

The second Phase II assessment site where polymer-modified mortar repairs were tested was on a large residential development in the north of England which had been subject to repair between 2009-11. Again, the exact repair material could not be positively identified because, although the specification stipulated a specific product, it also stated that a similar product could be substituted. The owners had no information on which had actually been used but it was certainly a polymer-modified repair mortar which had been painted with a grey coating to try and unify the appearance of the patched concrete.

Many of the patches showed defects including cracking, crazing, poor texture and match to the parent concrete as well as ongoing corrosion of steel reinforcement with shallow cover; an example is shown in Figure 2. Cover meter readings indicated that the steel within the patch had only a few mm cover but hammer tapping showed that most patches were still bonded to the parent material. The repairs did not contain any large aggregate to match with the original concrete and the texture was poor. Both the parent and patch surfaces absorbed water suggesting that this polymer modified mortar was different to the one used in 1997 on the Alexandra Road estate.

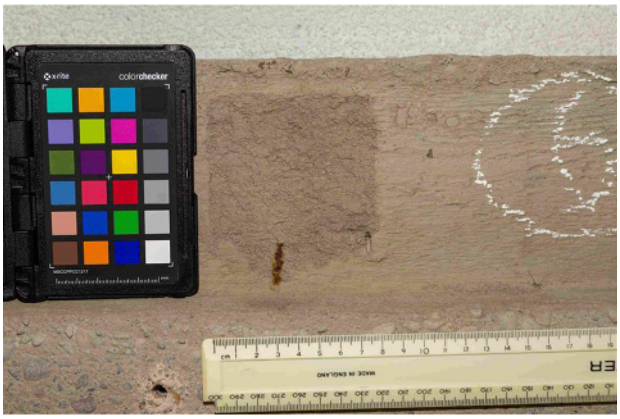

Figure 2. Typical modern (2010) polymer-modified shallow repair patch from the Phase I repairs at a block of residential flats – this showed a poor surface finish which had been unified with the parent by coatings. Ongoing corrosion of embedded steel was noted in many of the patches.

3.3 Mixed build-up repairs

At the National Theatre in London, Dr Farrell had been called in by the building owners to assess damage to the board-marked white concrete and to provide an outline specification for repairs using like-for-like materials. This work was carried out in 2013 and started with test panels and trialling repair mixes to match the parent concrete. The first few small like-for-like repairs were carried out successfully and an example is shown in Figure 3. The contractor then deviated from the outline specification and filled some of the breakouts with an initial layer of polymer-modified repair mortar followed by a like-for-like mortar mix for the outer layer. The results were poor and showed cracking and crazing, as well as hollowness when tapped with a hammer, indicating that the outer like-for-like mortar had not bonded with the inner polymer-modified repair mortar, Figure 4.

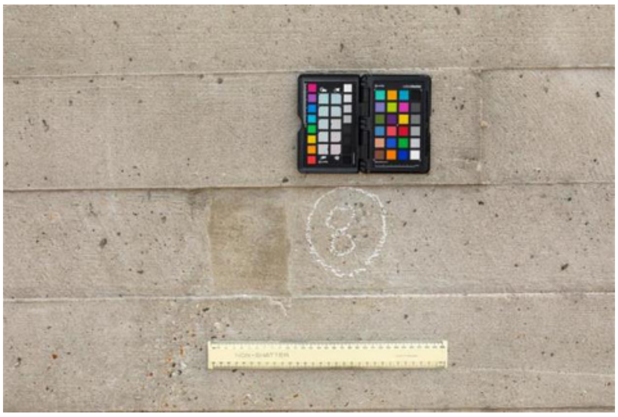

Figure 3. Small like-for-like mortar patch repair at the National Theatre (most probably over some form of redundant wall fixing) which showed reasonably good colour and texture to the parent concrete after 6 years exposure.

Figure 4. This repair patch at the National Theatre had been made using a polymer modified repair mortar with a thin like-for-like mortar layer (12mm) on top in 2013. Some 6 years later it was showing cracking and crazing to the outer layer

4 Like-for-like repairs in urban areas

The first Historic England trials into the specification and application of like-for-like patch and large-scale repairs to concrete structures were carried out at the Alexandra Road Estate in 2001 [8].

The managers of the estate were disappointed by the poor aesthetics and performance of the ‘light coloured’ 1997 commercial patch repairs which were mainly square or rectangular in section. The contractors had been paid for the size or ‘area of each repair’ and so repairs were made using straight lines so that they could be easily measured, plus a square cut repair is standard repair practice and “feather edged” repairs are discouraged. However, breaking open some of the 1997 polymer-modified repairs showed that only about 1% of the patch repair area had been subject to corrosion. The size of the repairs could therefore have been much smaller.

The very first trials involved breaking out some of the failing 1997 polymer-modified patch repairs and replacing them with simple cement mortar repairs in an attempt to match the colour of the existing. The earliest repairs used soft sand and later ones used sharp sand, but neither included any large aggregates, so this was not a true like-for-like (concrete) repair.

Initial results were not particularly good, mainly because the 1997 breakouts were only 6mm deep. The other problem was producing a successful board-marked finish to the patch repairs. A hand roller with a bark finish was used but this resulted in poor surface marking and also tended to pull the thin repairs out from the breakout. Achieving a surface finish and texture to match the adjacent parent concrete was also a problem.

At this time, full scale repairs were also carried out in 2001 to the early reinforced-concrete parish church of St John and St Mary Magdalene in Goldthorpe, South Yorkshire by a commercial repair company (Concrete Repairs Ltd) [9].

Trials, patch repairs and larger-scale repairs using mainly like-for-like concrete mixes have been carried out at a number of other English sites since 2001. Monitoring of the performance of the repairs from each of these has improved the conservation industry's understanding of like-for-like repairs which has benefitted other projects [10]. Examples are given in this paper of the application and performance of patch repairs from two of the Tecton-designed buildings at Dudley Zoo and St Thomas More church in Sheldon [11].

4.1 Early trial repairs and assessment

Figure 5. Like-for-like concrete trial repair from 2001 at the Alexandra Road Estate showing reasonable weathering which supported mould and algal growth after 5 years. The board-marked surface finish was poorly made using a bark grained roller which tended to pull shallow repairs out.

An example of one of the early 2001 like-for-like patch repairs at Alexandra Road was tested in 2019 as part of the PEPS Phase II assessment and is shown in Figure 5. This 2001 patch repair replaced an earlier 1997 commercial repair. When the 1997 repair was chopped out, it showed that there were only two small areas of steel within the large area covered by the patch repair. The repair mortar used was a 1:3 mix of white Portland cement (WPC): silver sand. The patch repair was a maximum of 10mm deep, and a surface roller had been used to provide the board marks to the surface. The outer surface of the patch had slowly weathered (neutralising the alkaline cementitious component and washing sand particles out) and this increased the porosity and allowed biological growth to become established within around 8 years. The repair was fully intact and showed no cracking or shrinkage after 18 years exposure although the surface texture and finish to the repair was considered to be poor. However, it did illustrate that unmodified cement mortar repairs were possible and they could provide a reasonable life. Some of the other thin 2001 trial repairs showed cracking, crazing and sometimes shrinkage, mainly due to their inadequate thickness.

The Alexandra Road Estate has been used for other concrete repair trials over the past 20 years and in 2006 one of these was to test the possibility of using pre-cast (slip) repairs. There were two main reasons for trialling these. Firstly, the preparation, placing, finishing and protection of like-for-like concrete within a patch can be a relatively lengthy process if carried out properly using methods employed by masons. Much of this work is avoided by using pre-prepared slips which can be mass-produced to a high standard in the workshop. On site, the damaged area simply needs to be cut out to an adequate depth which preferably means behind the steel reinforcement and finished with a dovetail arrangement so that the pre-cast slips are locked in. A very mobile cement grout is then pumped in to fill behind the reinforcements and any voids and joints.

Secondly, pre-cast slips can obviate vandalism problems which are common on the estate and mean that it can be difficult to protect wet concrete patches while they cure.

A third benefit of using pre-cast slips is that they could result in financial savings especially if a great many patches were required.

Concrete generally shrinks by up to 0.1% when it sets depending upon the composition, water content and drying conditions. Two sets of pre-cast slips were prepared (one used three individual repair panels and the other slip comprised a larger panel simulating three strips of board-marked concrete) and handed to a contractor to insert into the prepared recess. The face of the joint was temporarily filled before applying the grout. In this case lime mortar was specified as grout to fix the panels in place and this was introduced via a clay 'bird's nest' and allowed to flow down the sides of the slips and fill the back of the repair to fix it to the substrate concrete. The panels were assessed in 2019 after 13 years' exposure, Figure 6. Hammer tapping indicated hollowness at the back of both repairs and also slight shrinkage around the edges of all the panels. The bright white lime mortar which had been used for the grout made the repairs stand out against the parent concrete. It was clear that the main problem was associated with the workmanship required for this type of patch repair. The standard of workmanship from qualified stonemasons is generally better for all aspects of the work, than that of less-skilled concrete repair workers.

Figure 6. These pre-cast like-for-like concrete panel repairs were installed at the Alexandra Road Estate in November 2006. When they were assessed in 2019, they exhibited hollowness behind the panels and the white grout surround stood out.

4.2 2001 large-scale repairs and assessment

Full scale repairs were carried out to St John and St Mary Magdalene, Goldthorpe by Concrete Repairs Ltd in 2001.

The early 1914-1916 concrete had suffered attack from acidic gases resulting from coal mining, operation of a coking plant and also coal combustion in the town. The gases had attacked the alkaline components of the concrete and migrated into the concrete to initiate corrosion of the steel reinforcement. By 2001, the surface of the parent concrete had a yellow colouration. A major repair project was carried out to the church, which included significant repairs and replacement of concrete to the outer walls. Test slabs of different mixes were produced and left outside for a period of one month to assess their texture and final colour. The only additives to the repair mix were a dye (to bring the colour of the repair mix similar to the yellowed parent concrete) and also a waterproofing agent – believed to be styrene butadiene rubber (SBR). This addition enables the water:cement ratio to be lowered closer to 0.4 and also provided a more workable repair concrete, with better adhesion.

Figure 7. Like-for-like patch repair above a door at St John and St Mary Magdalene church in Goldthorpe. The repair had been made using an identical mix to the original concrete with a yellow dye to match to the parent; the surfaces had been brushed after setting to blend in with the parent concrete.

Figure 8. A large-scale patch repair at St John and St Mary Magdalene church which exhibited cracking, and which had also failed to be surface brushed after setting. Hammer trapping indicated hollowness behind.

Most of the repairs were still in very good condition when assessed in 2019 and an example is shown in Figure 7. The colour and texture match of the patch (above the door) to the parent was very close and the patches had almost fully blended in. The shuttering had been removed before the concrete had fully set and the surfaces brushed to remove some of the cementitious layer (while it was still soft) to reveal the aggregate – so called pre-weathering. However, one or two of the repairs were poor and an example is shown in Figure 8. This very large patch (almost 2m^2) showed significant hollowness and delamination when tapped with a hammer and significant cracking and shrinkage were evident around the edges. Strangely, the surface of the patch had not been brushed (unlike all the other repair patches) and this suggested that the normal project manager may not have been in charge when this patch had been applied. Possibly workmanship may have been an issue when some of this repair work was carried out.

4.3 2015 large-scale and patch repairs and assessment

Further large-scale and patch repair projects have been carried out since 2001 and some of these have been included in the PEPs assessment project and been subject to the Phase II work.

Between 2014 and 2016, a major repair and conservation project was carried out on some of the structures designed by The Tecton Group at Dudley Zoo [12]. Dr Farrell was involved with the initial assessment of the concrete in 2012 and prepared outline specifications for repairs. These was then used to prepare a detailed specification and apply for funding for the work. Dudley Zoo's management established their own concrete repair department and - with their architects and engineers - carried out the repairs to five of the structures. The repairs were mainly carried out using like-for-like repair concrete to match the original although commercial 'lightweight' repair mortars were used on some of the underside surfaces and soffits.

Most of the repairs were still in a good condition when assessed in 2019 although a few showed some defects. The biggest repair project was carried out at the bear ravine which had been in a very poor state and required significant repairs in 2014. Five years later, cracks were evident as well as shrinkage and moss growth (Figure 9), although most of these coincided with relatively thin repairs at parapets and balustrades. Another explanation may be that the repair concrete had too high a water: cement ratio or that the repairs were allowed to dry out too fast. It is hoped that the Phase III assessment will be able to confirm why this had occurred and will inform future repairs.

The final Tecton structure to be repaired was the meerkat enclosure in 2015. The in-house workforce had become more experienced since the work started and more time was given to the repair of this structure. No defects were found in 2019 and the repairs were all in very good condition. Figure 10 shows an example where a large section of capping to the wall had been replaced. The like-for-like concrete repair provided a good match to the parent concrete, including in terms of colour and surface finish (it had been brushed after setting). The surfaces had started to weather after four years' exposure which had enabled biological growth to establish and begin matching the existing.

Figure 9. Dudley Zoo - cracks noted to a repaired parapet wall of the prow to the bear ravine, Dudley Zoo. Note also the moss growth established in fine shrinkage cracks to the upper balustrade rail.

Figure 10. Replacement section of concrete capping to the meerkat enclosure at Dudley Zoo made using like-for-like concrete and with surface finishing to match the parent concrete in 2015. This had weathered and had established algal and mould growth within four years.

Further like-for-like patch repairs were carried out at the church of St Thomas More in Sheldon in 2015. Dr Farrell was involved with the initial assessment of the concrete and provided outline specifications for the like-for-like repairs. The appointed contractor started by preparing a slab library using different mixes of sands, cements and aggregates together with different surface finishes. The slabs were held against each elevation and different concrete surfaces on the building and the best match agreed. Many different patch repairs were carried out to the church and when they were inspected in 2019, they were all found to be in good condition. An example of a small patch repair is shown in Figure 11. The surface finish of the repairs to match the parent concrete was good although the new concrete had yet to weather sufficiently to allow biological growth to establish.

Patch repairs were also carried out by Concrete Repairs Ltd in 2015 at the church of St Paul at Bow Common in London. Some repairs were done using a like-for-like concrete repair mix and others using a polymer-modified repair mortar. Both had performed well when assessed in 2019.

Figure 11. St Thomas More church, Sheldon – showing a typical patch repair made using like-for-like materials and brushed after setting to match the parent in 2015. This new concrete was still weathering in 2019 prior to establishing algal and mould growth.

5 Like-for-like repairs in marine areas

Three of the Phase II test sites were located in marine areas; considered to be the most severe for reinforced concrete due to the effect of chlorides. The most severe zone is the splash zone where concrete is regularly washed by tidal sea water and oxygen is plentiful. The next-most severe zone is within 100m of the sea and where marine aerosols (from the sea) are regularly deposited on concrete surfaces.

5.1 Reinforced concrete

Trial like-for-like patch repairs were carried out at the listening mirrors, Dungeness, in 2005. Located around 2km from the sea, high levels of chlorides had been identified in the concrete from the marine aerosols. Dr Farrell was directly involved with these trial repairs and also with ongoing monitoring which he established afterwards and which continued to 2017. The installation and performance of these particular patch repairs has influenced the methodology of all like-for-like repairs that Historic England has been involved with since 2005. This work at the listening mirrors was very wide-ranging and as well as the patch repairs included trials of two different cathodic protection systems, coatings applied to corroding steel reinforcements, migratory corrosion inhibitors (MCIs), surface finishes and cleaning.

Patch repairs were made to the concrete to the rear of the reinforced-concrete structure known as the 200-foot parabolic wall. The work was carried out to a very high standard. The damaged concrete was broken out, rough sawn boards were fixed across the breakouts and sealed at the edges to form shuttering to contain the repair. A 'letterbox' was formed at the top of the shuttering. In this arrangement, the top board of the shuttering is hinged at along its lower edge so it can be dropped down to allow filling of the void behind and compaction of the repair mix by vibration. Once filled level with the bottom of the 'letterbox', the final 'lift' is completed by ramming in a slightly stiffer concrete mix, and the hinged board is folded back up to contain it while it sets. A close like-for-like repair mix was prepared using white Portland cement, local sand and flint aggregates which were readily available locally. The moulds were filled, and the repairs vibrated to remove any trapped air. The boards that held in the repairs were removed after 24 hours (before the concrete was fully set) and the concrete surfaces pre-weathered by rubbing with hessian cloth to remove surface cement and expose the aggregate. The results from the patch repairs were very successful with all repairs closely matching the parent concrete in texture and colour. These patch repairs slowly started to weather over the years and a view of one of them in 2019 is shown in Figure 12.

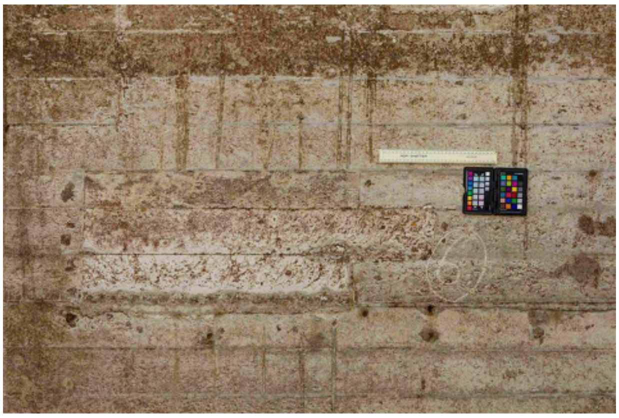

Figure 12. Typical patch repair using a like-for-like mix to the board-marked concrete on the Listening Mirrors after 14 years exposure. This showed good weathering with mould, algal and even red lichen growth on the new surfaces.

Of the ten patch repairs at the listening mirrors, nine were found to be in good condition after 14 years exposure. However, one of them revealed fine cracks during an inspection in 2018. On reviewing record photographs, it was noted that the cracks lined up with a large vertical steel reinforcing bar which had been fully cleaned of corrosion product (rust) using very high-pressure water jetting (4,200psi), Figures 13 and 14. It was also clear that all the other nine patch repairs had been fitted with new steel reinforcement and the old corroding steel cut out and removed. It is possible that the cracks might either be due to the incipient anode effect (where steel just outside the patch repair starts to corrode as a direct result of the repair) or that there were still some chlorides, or just corrosion product, remaining on the steel surfaces which had allowed the process of corrosion to continue. It is hoped that the Phase III assessment will confirm what is affecting this particular patch repair.

Figure 13. A section of damaged concrete buttress at the Listening Mirrors which had been broken open, all steel cleaned and suitably repaired using a like-for-like mix with board-marked shutters – image taken in 2005.

Figure 14. Image of the same repair taken in 2019 showing the weathered repair with lichen and moss growth now fully established. However, this patch was now exhibiting cracking suggesting ongoing corrosion of the underlying steel bars.

The next marine site to be investigated was Landguard Fort. Full scale repairs were carried out to the reinforced concrete to the right battery at Landguard Fort in 2011.The right battery is approximately 50m from the sea and the concrete is therefore subject to severe environmental conditions from the marine aerosols. The patch repairs were made by a large civil engineering company using like-for-like materials to match the parent concrete incorporating flint from the shoreline. The board-marked finish was replicated by simply pressing the repair concrete into the breakouts using rough sawn boards (with exposed grain) with a suitable formwork oil acting as the release agent. This procedure for re-creating the board-marked finish appeared to have been quite effective.

Many of the repairs (approximately 35%) were failing and an example is shown in Figure 15. The O&M manual for the repairs stated that the repair mix did not contain any sand; being only cement and large aggregate (mainly flint). The repair mix therefore contained an excess of cement. Many of the repair patches showed calcite leakage from the bottom of the patches indicating that unreacted calcium hydroxide had leached out. Some of the patches showed cracking and delamination and the cover meter survey indicated that this was associated with the presence of steel reinforcement behind. The suggestion is that some of the embedded steel reinforcement was continuing to suffer from on-going corrosion even after the repairs had been made. However, not all were subject to corrosion. Some of the repairs which do not directly face the sea were still in a reasonable condition and not subject to defects when assessed.

Figure 15. Patch repair using a like-for-like mix at Landguard Fort which was failing after 8 years. This appeared to be related to ongoing corrosion of the embedded steel. Note also lime leaching from the base of the repair due to excessive cement used in the repair mix.

5.2 Bulk (non-reinforced) concrete

The final marine site which was assessed for the Phase II work was at Tynemouth Priory and Castle coastal battery. The concrete dates from the 1880s to the 1940s and the vast majority of it had been formed using non-reinforced (bulk) concrete. The battery is located on a cliff top and only 100m from the sea so chlorides would be expected to be a factor in the deterioration of reinforced concrete. Instead, damage here to the bulk concrete was either due to subsidence, deterioration of the various layers of concrete (it had been applied in layers), rainwater ingress and movement or mechanical damage. Scrap merchants (who were invited in to remove scrap metal after the end of the 2nd World War) had physically ripped out the guns and fittings.

A large number of large scale and patch repairs were carried out in 2009 after Dr Farrell had carried out a full assessment of the site and prepared outline repair specifications. He also oversaw the repairs.

Nine of the ten patches assessed had performed well over the past ten years. The tenth was damaged because the defective area that it has been used to repair had continued to suffer structural movement, rather than because of an inherent failure in the repair material or workmanship . An example of one of the patch repairs which had been made over a damaged corner of concrete is shown in Figure 16. This damage was probably caused by careless removal of metalwork after the War. Plain plywood shutters were prepared, and external

Figure 16. Patch repair of the concrete corner at Tynemouth Priory and Castle coastal battery using a like-for-like concrete mix with plain shutters and using external supports. The surface was abraded after setting to match to the parent and this patch had almost fully blended in after 10 years.

wooden supports were used to fix the shutters in place. The specified like-for-like concrete repair mix was poured in at the top and a poker used to vibrate it. The shuttering was struck early, and the surfaces of the repair brushed using mechanical abrasion to reveal some of the aggregate to match the parent. The patch surfaces have weathered over the past 10 years and now support biological growth.

6 Discussion

6.1 Polymer-modified and mixed repairs

The PEPS Phase II testing of the performance of the commercial polymer modified repair mortars was important as these materials have often been used to repair large concrete heritage structures. More recently, these types of mortars are sometimes applied with large aggregate added in an attempt to better match the parent concrete without having to coat it afterwards. This testing was also important as some of the repairs on sites in France and the USA have used commercial polymer-modified repair mortars. The English results should be directly comparable to those of our research partners.

The results from some of the later repair patches at the National Theatre were disappointing. The results showed that the early small like-for-like repairs had both a good colour and texture match to the parent and were still in a good condition after six years. However, some of the later ones, where the contractor started to mix a commercial polymer-modified repair base layer with a like-for-like mortar top layer were poor. This is not particularly surprising as polymer-modified repair mortars have excellent adhesion to ordinary cementitious concrete and can be applied in very thin layers, whereas like-for-like cementitious concrete repairs have a much lower adhesion and need to be applied as thicker layers. Like-for-like concrete repairs have very poor adhesion to polymer modified mortar surfaces and the mixing of these two different materials is not recommended.

6.2 Like-for-like repairs in urban areas

The Phase II testing of the performance of like-for-like mortar and concrete repairs is of most interest to the heritage industry in England. It has been an evolutionary process which today means that these types of repairs can be used with confidence. Patch repairs using ordinary cementitious concrete had a poor reputation prior to 2001 and there were many reports of it delaminating as corrosion of embedded steel continued. Prior to 2001 the importance of preparation and attention to detail had not been understood. It was subsequently realised that the embedded steel reinforcement needed to be suitably treated (passivated to prevent ongoing corrosion) prior to the concrete being repaired. This meant fully cleaning the corroded steel surfaces (to remove as much rust as possible) and then applying a like-for-like concrete repair mix (similar to that used when new reinforced concrete is cast), which re-creates a high-alkalinity environment to re-passivate the steel. Breakouts of the area to be repaired also need to be relatively deep (and go behind the reinforcement) and have undercut edges to help retain the repair material and reduce risk of cracking.

The early 2001 trials at the Alexandra Road Estate showed that it was possible to use a repair mortar (without large aggregate) to fill shallow breakouts (around 6mm deep) although some of these were found to suffer from shrinkage and cracking. It was soon realised that the repair needed to be deeper (typically greater than 25mm) and the mix needed large aggregates which were similar to the parent concrete. Typical large aggregate sizes may be between 10 to 15mm. Using shutters (rough-sawn boards for board-marked concrete or plywood for fair-faced concrete) to contain the repair and pokers to vibrate the mix was found to be the best method as opposed to hand placing it. Pre-weathering of the repairs (by removing some of the surface cement and reveal the large aggregate) was best carried out by removing shuttering before the repairs had fully cured (typically 24 hours depending upon environmental conditions) and hand finishing the outer surface using muslin cloths, hand brushes or mechanical wire brushing. Retarding agents may also be acceptable to slow down the setting of the exposed repair concrete to give more time to improve post-set finishing.

Matching the colour of the repairs to the parent concrete was initially thought to be critical to achieving a satisfactory match. Dyes were ruled out unless the parent concrete had been heavily stained. Colours of repair concrete were usually altered by changing the mix (white or ordinary Portland cement and different colours of sands). However, patch repairs eventually weather (typically after 5 to 15 years) and the outer alkaline surfaces become neutralised and grains of sand are washed out which increases the porosity and stimulates biological growth - algal, mould, lichen and sometimes moss - on the surfaces. If the repairs are initially lighter in colour to the parent, this often dulls down as biological growth becomes established.

The full-scale repairs by a commercial company at the parish church in Goldthorpe showed that good performance was possible for like-for-like repairs and that the aesthetics could be improved by matching the repairs to the parent concrete. Dye was added to the repair concrete mix to match the yellow parent concrete. The assessment of the repairs in 2019 showed that a few of them exhibited cracking, shrinkage and delamination from the substrate and were starting to fail. The Phase II tests showed that there were marked differences in the finishing of the 'failing' repairs and that of the good repairs, suggesting that the problem may be due to workmanship issues. The Phase III testing will hopefully confirm if this is the reason for the failures.

The trials using the pre-cast slips were initially considered to be a cheaper way forward as they could potentially have been made on a production-line basis in a workshop and brought to site to be grouted into suitable cut-outs. However, the trial showed that on-site workmanship was an issue and this type of repair would perhaps have only been economic if there were a significant number of similar repairs to carry out.

Further patch and full-scale repairs have been carried out at several other historic concrete buildings and structures since the work was done at Alexandra Road and the vast majority are still in a good condition. The many smaller patch repairs carried out at the church in Sheldon were found to be in very good condition after four years with no defects identified. The repairs to four of the Tecton structures at Dudley Zoo were good, although a few of the earlier repairs were starting to show shrinkage cracks where they had been applied thinly. The Phase III testing should confirm why this is happening and allow further improvement for like-for-like concrete repairs in future years.

6.3 Like-for-like repairs in marine areas

The three marine sites that were assessed for the Phase II tests showed interesting results as they represent accelerated weathering for reinforced concrete repairs. The site with the repair patches in the worst condition was Landguard Fort. Approximately 35% of the repairs showed defects after only eight years. There are a number of possibilities as to why this has happened. The coastal battery is located only 50m from the sea and is therefore in a very corrosive environment for the reinforcing steel. The repair mixes reportedly did not contain sand and showed calcite leakage from many of the patches. The patch may not now be sufficiently alkaline to passivate the steel. The embedded steel may not have been suitably cleaned of corrosion product prior to the repair (poor workmanship) which could have allowed it to continue corroding. The remaining concrete surrounding the steel may still have high levels of chlorides remaining which could then initiate further corrosion. The Phase II results were unable to prove what was responsible and it is hoped that the Phase III test results will be able to provide the answer.

The like-for-like repair patches carried out at the listening mirrors were still in an excellent condition after 14 years' exposure, apart from one which showed fine cracks aligning with the main steel reinforcements. Nine out of the ten patch repairs had been fitted with new replacement steel prior to the repairs being placed, the only one which retained the original (but cleaned) steel was the patch which now showed fine cracking. Again, it is hoped that the Phase III work will provide the answer as to why this patch is now starting to fail.

The final marine site that was subjected to the Phase II tests was at Tynemouth coastal battery. This site is only 100m from the sea and is highly exposed. All the repair patches examined had been made to non-reinforced (bulk) concrete and all patches were still in an excellent condition after ten years' exposure. This indicates that it is the presence of the embedded steel reinforcement which is the major factor in the deterioration of patch repairs in marine structures and possibly other areas.

7 Tentative conclusions

The following tentative conclusions may be drawn from this work. However, these conclusions can only be confirmed by the Phase III work.

- Repairs to damaged concrete can be successfully achieved using like-for-like concrete but the breakouts need to be relatively deep and undercut or dovetailed to improve the retention of the patch in the breakout.
- The aesthetics of repaired concrete surfaces can be improved by trialling the repair mixes and carrying out work on the surfaces of the patches to better match the parent material.
- The research has confirmed our understanding that the presence of corroding steel in reinforced concrete is the major factor to overcome in achieving a suitable long-life patch repair. This problem is more severe in marine environments due to the highly corrosive environment.
- Workmanship appears to be an issue, possibly because non-conservation aware concrete repair workers are not as highly trained or are possibly less motivated compared to experienced stone masons.
- Repairs using commercial polymer-modified repairs mortars should be avoided for heritage buildings and structures if possible.

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