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TECTON BUILDINGS, DUDLEY ZOO

Traditional Repair Schemes for Reinforced Concrete Structures

RTL Report No: 1119-01

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For the attention of:

Dudley Zoo
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LOTTERY FUNDED

1. Introduction and Background

A group of thirteen reinforced concrete structures were built in the period 1935 to 1937 at Dudley Zoo by the Tecton Partnership, led by Berthold Lubetkin. The 'Tecton buildings' are historically important and six of them have been listed Grade II and six are listed Grade II*; the thirteenth building (the penguin pool) has since been demolished. The general condition of some of the reinforced concrete structures is poor and little maintenance or repair has been carried out since the late 1980s. Dudley Zoo Group (DZG) is now working in close partnership with Dudley MBC and other authorities to integrate the historic centre of the town with Dudley Zoo, the medieval Castle and other attractions.

Makers Industrial Ltd carried out major refurbishments on a few of the concrete structures in the late 1980s. They reportedly used modern (polymer modified) concrete materials to repair the historic reinforced concrete. These repairs are now starting to fail. The use of different materials for repairing historic listed structures is not encouraged by the conservation industry unless it is the only way to save a structure from demolition. Different materials often have different physical properties and the results of using modern polymer-containing materials to repair traditional concrete will often become more apparent with age. For instance, modern concrete repairs can have different thermal expansion coefficients to traditional concrete and eventually cracks can develop or delamination can occur.

Repairs carried out using traditional materials (like-for-like) and traditional techniques have always been encouraged for historic structures but this has been difficult for reinforced concrete, as methods had not previously been developed for this purpose. However, over the past fifteen years or so English Heritage has been pioneering the use of traditional concrete materials (using standard cements, sands and aggregates to match the original) and application techniques for repairing historic concrete structures.

DZG commissioned Halcrow Group to undertake a condition report of the Tecton buildings in 2006. The report showed that extensive repairs were required to all twelve buildings. It has now been recognised that concrete repairs to the Tecton buildings will be an ongoing project and that further monitoring and maintenance will be required during their lives.

DZG has been successful in obtaining a Phase 1 HLF grant for the development of repair procedures, together with budget costs, for the conservation of four of the reinforced concrete Tecton buildings at Dudley Zoo. The buildings comprise the Bear Ravine, the adjacent Kiosk, the Entrance Structure and the Station Café. It is envisaged that the repairs will take place during the Phase 2 grant. DZG subsequently requested that Rowan Technologies Ltd (RTL) carry out an overall assessment of the condition of the reinforced concrete used for the four buildings and provide outline repair materials and procedures for conserving them on a like-for-like basis. The intention is that these repair strategies will be used with the existing condition reports and a structural survey and that the subsequent conservation repair work will be developed and put out to competitive tender.

The RTL work involved an assessment of the strength of the concrete, measurements of the depth of concrete cover to the reinforcements and measurements of the carbonation depth in sample areas of the buildings. The concrete was also sampled for chloride and sulphate to assess if it had been contaminated either when it was originally poured or during its life. These results should enable the primary reasons for the deterioration of the concrete to become established. One building was to be investigated further by taking cores (50mm diameter samples) and having petrographic analysis, cement type/content and other testing carried out on the samples. This should provide additional

evidence as to the cause of the deterioration of the concrete and assess if Alkali Silica Reaction (ASR) had contributed to the damage. The laboratory-based investigative data should enable the composition of the original concrete mix to become established and this would inform future repairs.

2. Objectives

The objectives of this investigative project are as follows:

- To undertake an assessment of why some of the Tectons have suffered from deterioration.
- To carry out a survey of the current damage to the four Tectons – to be read in conjunction with the 2006 Halcrow Group report.
- To recommend repair procedures for traditional repairs to the four Tectons.

3. Condition of the Tectons

General Condition of All Tectons

All but one of the Tecton buildings have been overcoated, in full or parts, using various layers of paints, with the exception of the Reptiliary (now occupied by the Meercats) enclosure which has remained uncoated. The bear ravine has additionally been provided with some form of fairing coating, prior to the paint coatings. The paint coatings have provided a physical barrier, which was presumably intended to prevent deterioration of the concrete over their 75 year lives in addition to brightening up the concrete for visitors. However, these coatings have not entirely prevented the chemical reaction between the environment and the alkaline constituents of the concrete, which has contributed to their deterioration. Note – paint coatings can also trap moisture within the concrete and stop it drying out.

A few individual areas of some of the buildings have been left uncoated and the degree of weathering over their lives was noticeable. The weathering of the uncoated curved roofs of the entrance structure may be compared to the unweathered surface of the underlying adjacent roof curve, Figure 1. The balustrade rails on the Bear Ravine were also uncoated and weathering of the cementitious components of the concrete had left the aggregates exposed, Figure 2.

Visual Assessment of the Selected Four Tectons

A photographic record of the selected four Tectons, together with the on-site test results is given in Appendix A. These images include the compressive strength of the concrete and the concrete cover to the reinforcements.

Bear Ravine – This Tecton was in a very poor condition and showed significant sections of concrete cover delamination and corroding reinforcement. Some of the concrete parapets appeared to have a thin cementitious layer on their surfaces, which might have been applied afterwards to form the characteristic corrugated surface, Figure 3. Much of the concrete was found to have multiple layers of paint that had been applied over their lives. These were exfoliating from the concrete surfaces.

A significant amount of repair has been carried out on this building and many of them are now failing. The parapet walls, balustrade rails and columns were in a particularly poor condition and some of them now require complete replacement. The soffit of the upper platform showed significant corrosion of shallow reinforcements, Figure 4. The parapet wall, balustrade and soffit of the cantilevered balcony, or prow, of the Bear Ravine were found to be in a particularly poor condition, Figure 5. Some of the steel columns supporting the stairs had suffered significant corrosion, with one completely absent and other ones showing severe damage towards their base. Further information is given in Appendix A and a full list of the areas of repair is given in the Halcrow Report.

Kiosk – This Tecton was in a reasonably good condition. The RC roof structure had been uncoated and thick layers of moss were evident on the roof. Rainwater run-off from the roof had occurred at a

particular point and this had dissolved calcium-containing salts from the sides of the concrete and 'weathered' it away. The calcium salts had subsequently 'precipitated out' from the run-off to form both stalactites on the underside of the roof and stalagmites on the path beneath. The underside of the roof showed some damage due to corroding reinforcements, however most damage was associated with the steel pillars where they embed into the roof slab. Corroding reinforcements were clearly evident on the upper surface of the kiosk worktop, due to low cover, Figure 6. Mechanical damage was noted to an adjoining sidewall of the kiosk where some form of fixture had been removed in the past. Serious corrosion damage was also noted at the base of one of the steel pillars that support the roof, Figure 7. Again, further information is given in Appendix A as well as in the Halcrow Report.

Entrance Structure – The entrance structure contains five curved roof sections supported on steel pillars. Some of the steel pillars have suffered from corrosion at their bases. The underside of some of the sinusoidal roofs showed large areas of delamination, due to the low concrete cover and corroding reinforcements.

The Halcrow report had suggested that the five curved roofs had been pre-stressed but on closer inspection there appeared to be no evidence for this. The topsides of the uncoated roofs were well weathered and on first sight appeared to be in a reasonable condition. A few steel reinforcements were visible due to low cover. Some longitudinal cracks were evident on the topside of the roofs. This suggests that the underlying reinforcements are subject to corrosion and volume increase.

The most significant damage was associated with the steel pillars as they passed through the concrete, Figure 8. Expansion of the corroding pillars has resulted in extensive cracking and delamination of the surrounding concrete on both the underside and topside. More information is given in Appendix A and in the Halcrow Report.

Station Café – The station café was found to be in a reasonably good condition. The building has been divided to form the Safari Shop, which is still in a good condition, and the old Night Club which is now closed and which is in a poorer condition. This part of the building is currently being used for storage. Localised areas of the concrete had been damaged by reinforcement corrosion and possibly mechanical damage on the flying edge beam especially, Figure 9. Small areas of delamination were found on the front wall of the building, due to areas of low concrete cover. Inspection was not carried out on the inside of this building. Additional information is given in Appendix A and in the Halcrow Report.

Carbonation and Cover Survey

Carbonation depths are normally established for concrete structures followed by a detailed cover survey so that the two sets of data can be correlated. For instance, if the average carbonation depth is found to be 20mm and the minimum cover is 22mm, then a time estimate can be established to determine when the carbonation front will reach the steel reinforcement, thus allowing corrosion to initiate.

Generally, the 'carbonation front' proceeds into the body of the concrete at a rate which is inversely proportional to its depth:

$$\text{Depth of carbonation} = k \sqrt{t}$$

Where k is the diffusion coefficient and is determined by the quality of the concrete when cast. High quality concrete will have a k of around 2.0, whereas poor quality concrete, which is highly permeable and contains voids, may have a k closer to 3.0. t = time (years) [1].

Measured carbonation depths will vary significantly in a single sample by up to 15mm, mainly due to the presence of aggregates that protect the alkaline cementitious components behind. They also vary considerably around the structure as a whole due to differences in moisture content, porosity, cement content and other factors. The rate of carbonation is highest at a particular moisture level (equivalent to a relative humidity of between 60 to 70%) and hardly occurs in permanently dry concrete or permanently wet concrete. Determining carbonation depths is a destructive process, involving taking core samples or breaking off sections of concrete for testing. This should be minimised for historic concrete structures. However, a cover survey, using an NDT technique, should be more extensive.

Core samples were taken from both a wall of the Bear Ravine, which had been already damaged, and the base of the internal wall in the kiosk to assess the depth of carbonation. The results show that for these unpainted concrete areas the depth of carbonation was between 26 and 40mm – see Appendix A. This implies that any steel reinforcement with cover less than 26mm may be subject to corrosion and that areas of cover up to 40mm may also be at risk of corrosion in the future. The cover survey from the Bear Ravine showed that many areas had cover below 26mm. Using the above formula and inserting a life of 74 years, this gives a diffusion coefficient of 2.7, i.e. relatively poor quality concrete.

The parapet walls of the cantilevered balcony were particularly badly affected and the carbonation would have occurred on both sides of this relatively thin wall. The parapet walls on the upper and lower platforms were also found to be in a similar condition. The circular mushroom headed columns and also the end column walls also showed many areas where the concrete cover was low. This structure is likely to require significant removal and replacement of cover.

The survey of the Kiosk showed that the cover thickness was significantly better with only a few areas showing cover below 26mm, mostly on the counter. This structure should be readily conserved using ‘patch type’ repairs, in addition to other repair work to the steel columns.

The entrance structure showed that many areas on the underside of the curved concrete canopies had low cover and in some places, no cover at all. Many areas of delamination and cracking were evident, especially around the steel pillars as they were cast into the concrete slab. The topside was in a better condition but there was some longitudinal cracking and a small number of reinforcements exposed, both being associated with corrosion of reinforcements lying under the surface due to low cover. These cracks will require opening up and repairing.

The Station Café showed a few areas where the cover was less than 26mm and these were frequently associated with small areas of delamination and corrosion. This structure can probably be conserved using patch repair of the damaged areas.

Strength Testing of Concrete

The strength of the concrete was generally found to be good, especially considering that they were constructed in the late 1930s when quality control may have expected to have been poor – see Appendix A. Only a few isolated areas showed low strength. This indicates that the underlying concrete is still in a good condition. This also confirms that repair of these Tectons using patch and large-scale replacement of the damaged cover concrete is a viable method for their conservation.

Sampling and Laboratory Testing

Core samples of the concrete from both the Bear Ravine and the Kiosk were taken using a 50mm diameter core drill from either damaged areas of the walls or from unobtrusive areas. Drill samples

(0-10mm, 10-20mm and 20-30mm) were also taken from all four structures. The samples were sent to UK Analytical Ltd for analysis. The laboratory results are given in Appendix B.

Chloride Analyses – Chloride concentrations above 0.4% of concrete (or 0.06% by weight of cement) are considered excessive and require special measures to effect repair and repassivation of the steel reinforcements [1]. The results show that only two drill sample analyses (both from the Kiosk) showed values above this level (0.988% and 0.575%). All other chloride analyses were well below this maximum level. The Kiosk results may be associated with a localised area where contamination of the original concrete mix had occurred. The difference in chloride concentrations at different depths of cover indicate that post-contamination of the concrete (typically by marine aerosols or deicing salts) has not occurred.

Sulphate Analyses – Sulphate attack of concrete results from the reaction of excessive concentrations of sulphates (typically above 0.8%) with calcium hydroxide and tricalcium aluminium hydrate which are found in concrete. The resulting reaction products are gypsum and calcium sulphotoaluminate (Ettringite). These reaction products have an increased volume from their starting compounds and this expansion in volume results in cracking and spalling of hardened concrete.

However, cement naturally contains sulphates and the particular cements used in the 1930s may have been expected to result in sulphate concentrations of the concrete of between 0.4 to 0.8%. Modern concretes typically contain sulphate contents of between 0.3 to 0.45%. The results from the drill samples from the four structures showed sulphate concentrations of between 0.45% and 0.83%, i.e. typical of concrete constructions from that era.

Cement Content – Analysis of the cement contents were determined from core samples taken from both the Bear Ravine and the associated Kiosk. The result from the Bear Ravine sample showed a cement content of 14.7%, whereas the result from the Kiosk was only 9.5%. This low cement content could have resulted from poor on-site supervision or possibly the economic use of scarce cement just prior to the war. These mixed results are typical for on-site mixed concrete prior to ready-mixed concrete becoming available later in the century. The low cement content probably contributed to the early deterioration of some of the concrete used for the Tecton buildings.

Water/Cement Content (Bear Ravine and Kiosk) – The same core samples that were used for the cement contents were also used to determine the original water/cement ratio when the concrete was first placed. The measured ratios of 0.69 and 0.70 are typical of concrete, which would have been placed in the 1930s. Today's modern concrete is likely to have a water/cement ratio nearer to 0.4% using ready-mixed concrete and additives to minimise the amount of water required. This high w/c ratio make the concrete more porous and less resistant to attack by both carbonation and chloride.

X-Ray Diffraction Analysis – A view of the different types of aggregates is shown in Figure 10. Much of the aggregate was round, indicating that it was naturally formed and had originated from old river beds (gravel pits) or from deposits from marine environments. However, some of the aggregates were both round and angular indicating that it was derived from crushed stone. It is most probable that it was all derived from locally produced gravel pits (Trent Valley gravels), which are normally located around 1m below the surface in many areas of the Midlands. The larger stones would have subsequently been crushed. The size distribution was between 5 to 25mm in diameter.

The XRD results indicate that the aggregates were mostly quartz (72%) with both feldspar (7%) and chlorite (typical clay components) at around 7%. There were also minor components that are typical of gravel aggregates.

Petrographic Analysis (Bear Ravine) – A full report on the Petrographic results are given in Appendix B. The results show that the coarse aggregates (typically 3 to 10mm) consist mainly of crushed and natural stones (sub-angular to sub-rounded) and well distributed. They were mainly a quartzitic conglomerate containing both mica and chlorite, typical of a greywacke. Well sorted sandstone was also present. This aggregate is typical of that produced by local gravel pits within the Midlands area.

The fine aggregate (typically 0.1 to 1mm) was mainly sand containing quartz, but also particles from the coarse aggregate. The detailed petrographic analysis of the cement paste showed few signs of internal branched cracking and no sign of gel, indicating that alkali-aggregate reaction has not been a problem for the concrete. No evidence was found to indicate that alkali silica reaction (AAR) had been a problem for the concrete.

4. Recommendations for Repair using Traditional Materials

It is recommended that the repair of the four Tecton structures should be carried out as much as possible using traditional repair materials and recently developed methods for conserving concrete structures. An outline for different types of repairs for concrete structures is given in Appendix C. These repair procedures are still in their infancy and further development will be required by the selected contractor for the conservation work on the Tecton structures. It is of critical importance that these repairs are fully documented (methods and materials, complete with images) for future use in the conservation of historic concrete structures. Note – these traditional repairs do not fall within EN1504, which requires that all repair materials used are manufactured in certified factories as compared to on-site batching. For this reason, good quality control will be essential when the repair work is being carried out.

Repairs should mainly involve the use of traditional materials including ordinary Portland cement (OPC), locally produced sands and locally produced gravel (naturally formed and broken) from the Midland area to match the original. These should initially be trialed to produce a slab library - see Appendix C. A full list of the areas and problems of the Tecton structures has already been given in the 2006 Halcrow Group report.

Surface Finish

The vast majority of the concrete for the four selected Tecton structures have been coated with various layers of paint. These coatings might have been applied from new or they might have started applying the coatings in their later lives. If it is assumed that the English Heritage conservation officer and DZG management are in favour of keeping the Tectons with coatings applied, then the surface finish of the repairs do not need any special attention; the repairs can therefore be left with the as-cast finish. It is recommended that the loose and friable coatings from the parent concrete be removed by either mechanical or chemical means and that the Tecton buildings be re-coated once the repairs have been completed.

The main areas of concrete that were found to be uncoated on the four Tectons are the roof structures of both the Kiosk and the Entrance Structure and the balustrade rails on the Bear Ravine. Damage has resulted from failure to coat the roofs and this is considered to be a design fault. It is therefore proposed that the top surfaces of the concrete roofs be cleaned down to remove plant growth, repaired if necessary, and some form of bituminous coating applied to give long term protection to the concrete. The coatings should overlap the edges of the roof slabs and a drip should also be provided. The only area that might require some form of surface preparation is the balustrade rails which are naturally weathered with the aggregates exposed. Repair or replacement of the balustrade rails should

include some form of post-setting abrasion to reveal the aggregates and/or the use of retarders on the shutters to assist this process.

Bear Ravine

This structure requires significant repair. All carbonated concrete down to a depth of 40mm requires removal, either using hammers or hydrojetting. Hydrojetting is recommended as it is likely to be more economic and also effective at removing the carbonated concrete and cleaning up the steel. However, it can be very noisy for the Zoo's residents. Hammers may result in mechanical damage to the underlying concrete structure.

The exposed steel reinforcements will require cleaning to remove the thick layers of corrosion product, but they do not need to be coated as the new alkaline concrete will repassivate the steel surfaces and prevent ongoing corrosion. If small amounts of carbonated concrete are left within the concrete structure the 'alkaline components' from the new concrete will tend to migrate into it and this carbonated concrete will also turn more alkaline. Complete removal of all carbonated concrete is therefore not essential.

The parapet walls and lower walls below the cantilevered balcony have been severely carbonated from both sides and the wall is relatively thin. It is therefore recommended that this be completely replaced. The floors of the balcony (and other floors) are still in a reasonable condition and patch repair should be sufficient for any exposed steel reinforcement. The soffit of the cantilevered balcony and associated support beams are in a very poor condition and this is likely to require complete replacement of the concrete cover. The balcony will require some form of support before any repair work is carried out on it. The concrete cover should be removed and any low-lying reinforcements forced back into the surface.

Repair of horizontal soffit surfaces, using traditional materials, has not yet been developed. Normally this would be carried out on non-historic concrete using modern polymer-modified repair mortars using hand placement (lightweight concrete). Trials and testing using traditional materials and shutters will be required prior to this repair work being initiated. Additional steel cramps (bonded into the concrete) may assist the mechanical bonding of the repair concrete to the existing parent concrete in the soffit areas. One possible option is to use shutters that can be jacked up to push the concrete repair material up into the parent concrete. If this is not possible then some form of modern lightweight concrete with improved adhesive properties may be required for these particular sections. Although this is not 'repair using traditional materials', it may be required in order to save the structure. This repair method will also be required for the soffit of the upper platform on the bear ravine and also the underside of the Entrance Structure roof, which have similar problems.

The right side of the lower platform is in a reasonable good condition and patch repair of the parapet wall and balustrade rail may be satisfactory to extend its life. The six mushroom headed columns and two end column walls require significant repair. Again, cover should be removed down to 40mm, the steel reinforcements cleaned up, shuttering applied around the columns and new concrete applied. The stairwell walls will require some large patch repairs in addition to repairing or replacing steel columns.

The upper platform is not as badly damaged as the lower platform and patch repair of both the parapet walls and balustrade rails may be sufficient to achieve an extended life. The soffit of the upper platform will require repair using the same method as that for the underside of the cantilevered balcony. There are many other areas of the Bear Ravine that will require repair or replacement of the concrete and also repair to metal columns and balustrade posts and reference should be made to the

2006 Halcrow report. After all the repairs have been completed, the complete structure should be suitably painted.

Kiosk

The kiosk is in a reasonably good condition. The depth of carbonation is similar to that of the Bear Ravine but there doesn't appear to be as many areas of low cover, so the damage has not been as severe. The concrete roof has been left uncoated and now supports a thick layer of moss. This area could not be examined and some form of repair may be required. The plant growth requires removal, any repairs carried out and a bituminous coating is suggested – as outlined above. Patch repair will also be required to where the edge of the concrete roof has been weathered away. The underside of the concrete roof showed damage where the steel columns are attached. Again, localised patch repairs may be required. The top of the counter shows exposed steel reinforcements and the cover here needs to be replaced and the steel reinforcements forced back into the concrete. An alternative is to apply a thicker layer of cover to the counter. Localised patch repairs will also be required in other areas of the kiosk and the structure suitably painted.

Entrance Structure

The main areas for repair on the entrance structures are the five sinusoidal reinforced concrete roofs. These do not appear to be pre-stressed and the repair many simply involve opening up the cover associated with the cracks and exposing the low-lying steel reinforcements. A structural engineer's report on the cracking is recommended. The steel will need to be cleaned up and new high-alkalinity cover replaced. Again, it is suggested that a bituminous coating be applied (as detailed earlier) to provide long-term protection to the top surface as it is unlikely that the steel reinforcements could be inserted deeper into the roof slabs.

Repairs are also required on the bottom face of the roof slabs where exposed steel reinforcements are present. The cover needs to be removed and the steel forced back into the concrete roof - if possible. Repair should be similar to that for the soffits – described earlier. Patch repair is also required for the remainder of the concrete and work is also required to the steel support columns, which have suffered from corrosion. Again, the repaired structure should be suitably coated.

Station Café

The station café was not examined in detail, but the work required mainly involves patch repairs to areas of low-lying steel reinforcements followed by a suitable coating afterwards.

References

1. BRE Digest 444 – Part 2, February 2000.

Dr David M. Farrell
Rowan Technologies Ltd
September 2011



Figure 1: The weathering of the uncoated curved roofs of the entrance structure as compared with the unweathered surface of the underlying adjacent roof curve.



Figure 2: Weathering of the cementitious components of the concrete has left the aggregates exposed on the Bear Ravine's balustrade rail.



Figure 3: The corrugated finish was achieved using a thin cementitious layer applied on the base concrete.



Figure 4: The soffit of the upper platform showed significant corrosion of the low-lying reinforcements.



Figure 5: The cantilevered balcony of the Bear Ravine was in a particularly poor condition.



Figure 6: Corroding reinforcements are exposed due to low concrete cover on the Kiosk worktop.



Figure 7: Corrosion damage to the base of a steel pillar within the Kiosk.



Figure 8: Corrosion damage to the underside of the sinusoidal roof of the entrance.



Figure 9: Localised damage to the flying edge beam of the Safari Shop.



Figure 10: An example of the different types of aggregate used in the concrete mix.

APPENDIX A

ON-SITE TEST RESULTS FROM THE TECTONS

The four selected Tectons (Bear Ravine, Kiosk, Entrance Structure and Station Café) were subject to testing in selected areas to determine their current condition and to provide information for conservation.

The initial testing was associated with a visual inspection to determine areas of spalling (which included a hammer survey to assess delamination, ultimately leading to spalling), concrete cover measurements to the reinforcements to gauge the likely life of the unspalled areas, concrete strength testing to determine the underlying condition of the concrete and also selected half-cell mapping to determine if the reinforcements were still subject to ongoing corrosion. Core samples (50mm diameter) were taken from both the Bear Ravine and the Kiosk to provide general data on the depth of carbonation of the concrete cover and also for laboratory analyses (see main report and Appendix B).

The data has been provided both on images of the concrete surfaces (A-1 to A-20) and has also been tabulated in the attached tables. The areas of spalling and delamination (from the hammer testing) are shown on the images.

A Schmidt hammer was used to assess the strength and uniformity of the concrete cover. Measurements were normally taken horizontally on vertical surfaces although vertical measurements were taken both for floors and also for soffits – different graphs are used to convert these results. Five readings were taken in a particular area and the average value calculated. The results were surprising in that the concrete cover showed surprisingly high and consistent results. The concrete strength for the Bear Ravine was generally in the range 40 to 55 N/mm², with the occasional readings down at 26 N/mm². The concrete strength for the Kiosk was generally in the range 38 to 60 N/mm², with one lower reading of 32 N/mm². The concrete strength for the entrance structure was generally in the range 40 to 56 N/mm², with a lower reading of 36 N/mm². The concrete strength for the Station Café was generally in the range 40 to 52 N/mm², with a lower reading of 36 N/mm². A concrete strength of 35 N/mm² is generally taken to differentiate between poor and average quality concrete. Considering that these RC structures were built in the late 1930s when quality control would not have been as good as today's standards, these results are surprisingly good.

Carbonation is due to the action of carbon dioxide and moisture (so called carbonic acid) reacting and neutralising the alkaline constituents of the concrete. The rate of carbonation is initially high on the surface but slows as the reaction gets deeper into the concrete. Typical carbonation depths from the cores taken from both the Bear Ravine and the Kiosk, where the concrete had been uncoated throughout their lives, showed depths of between 32 to 40mm, Figures A-21 and A-22. Note - some 'still-alkaline' areas of concrete have been protected by the presence of large lumps of aggregate. Concrete surfaces which have had paint coatings applied during their lives may be expected to have lower carbonation depths due to the physical barrier presented by the coating.

A micro-covermeter was used to measure the depth of cover to the steel reinforcements. This uses an eddy current technique to detect the steel and report on its depth. This particular instrument is capable of detecting steel to a depth of 120mm. Measurements were only taken on areas that had not yet spalled or delaminated.

Bear Ravine – The floor of the cantilevered balcony showed cover readings of between 30 to 110mm, Figure A-2. Because only a few readings were below 40mm this concrete was still in a reasonably good condition. The balcony wall and parapet showed cover readings of between 16 to 49mm and was subsequently in a very poor condition, Figure A-3. The central staircase wall on the lower platform showed cover readings between 8 and 67mm with a large area of delamination where readings were lowest, Figure A-4. The concrete retaining wall showed cover readings of between 41 to 106mm and this showed no obvious damage, apart from the exfoliating paint coating, Figure A-5. The upper platform parapet (external surface) showed cover readings of between 26 to 52mm and the soffit between 15 to 35mm, Figure A-6. Again, most of the delamination was associated with the areas of low cover. Note the exfoliation of some form a fairing coat that had been applied to the external parapet surface. The upper platform parapet (internal surface) showed cover readings of between 17 to 36mm with significant delamination and exposed reinforcements close to where the low cover was identified, Figure A-7.

The mushroom headed columns showed very low general cover of between 13 to 35mm and delamination and exposed reinforcements in selected areas, Figure A-8. One of the end column walls was assessed and this showed cover readings of between 18 to 44mm and extensive damage, Figure A-9.

Kiosk – The front of the kiosk showed cover meter readings of between 14 to 66mm, but because most of the areas of low cover had been physically protected from rainwater, it is probable that the carbonation front had not yet reached the steel, Figure A-11. The top of the counter showed very low cover of between 12 to 19mm and this showed extensive damage. The edge of the concrete roof on the left hand side had been extensively weathered by rainwater running off the roof at this point. This had resulted in both stalactites on the bottom edge of the roof slab and stalagmites on the floor below. The back of the kiosk showed cover readings between 11 to 40mm, but again, this area had been protected from the weather and was still in a reasonable condition. There were also corrosion related problems with the steel supports holding the roof slab in place.

Entrance Structure – The top surfaces of the curved concrete canopy generally showed cover within the range 13 to 65mm, although some areas showed no cover at all and the exposed reinforcement had corroded, Figure A-14. Longitudinal cracking was evident on the topside surfaces almost certainly associated with ongoing corrosion of the low-lying steel reinforcements. The roof canopies had not been painted and the degree of weathering was quite extensive. The underside of the canopy showed cover between 7 to 28mm and extensive corrosion of the low lying reinforcements, Figure A-15. The concrete around one of the ticket booths showed cover of between 14 to 33mm although no delamination or corrosion was evident due to it being protected from the weather, Figure A-16. Note – condensation frequently

forms on the underside of concrete roofs resulting in an acceleration of carbonation and corrosion.

Station Café – The left side of the nightclub was assessed for cover and this showed readings of between 16 to 109mm, Figure A-18. The areas of low cover were coincident with delamination and corrosion of the steel reinforcements. The right side of the nightclub showed cover readings of between 8 to 40mm and again delamination was evident in the low cover areas, Figure A-19. The shop was similar in that the concrete cover was between 9 to 46mm and damage was associated with the low cover areas.

Finally, natural potentials (half-cells readings) were taken on one of the end column walls of the Bear Ravine and this confirmed that corrosion of the steel reinforcements was ongoing, Figure A-10. Natural potentials between -250mV and -350mV indicate that the steel has a medium risk of ongoing corrosion. And potentials more negative than -350mV indicate a high risk of ongoing corrosion. These results indicate that the corrosion at the base of the column wall is ongoing. Further half-cell mapping was suspended as these results were not particularly helpful for the repair work.

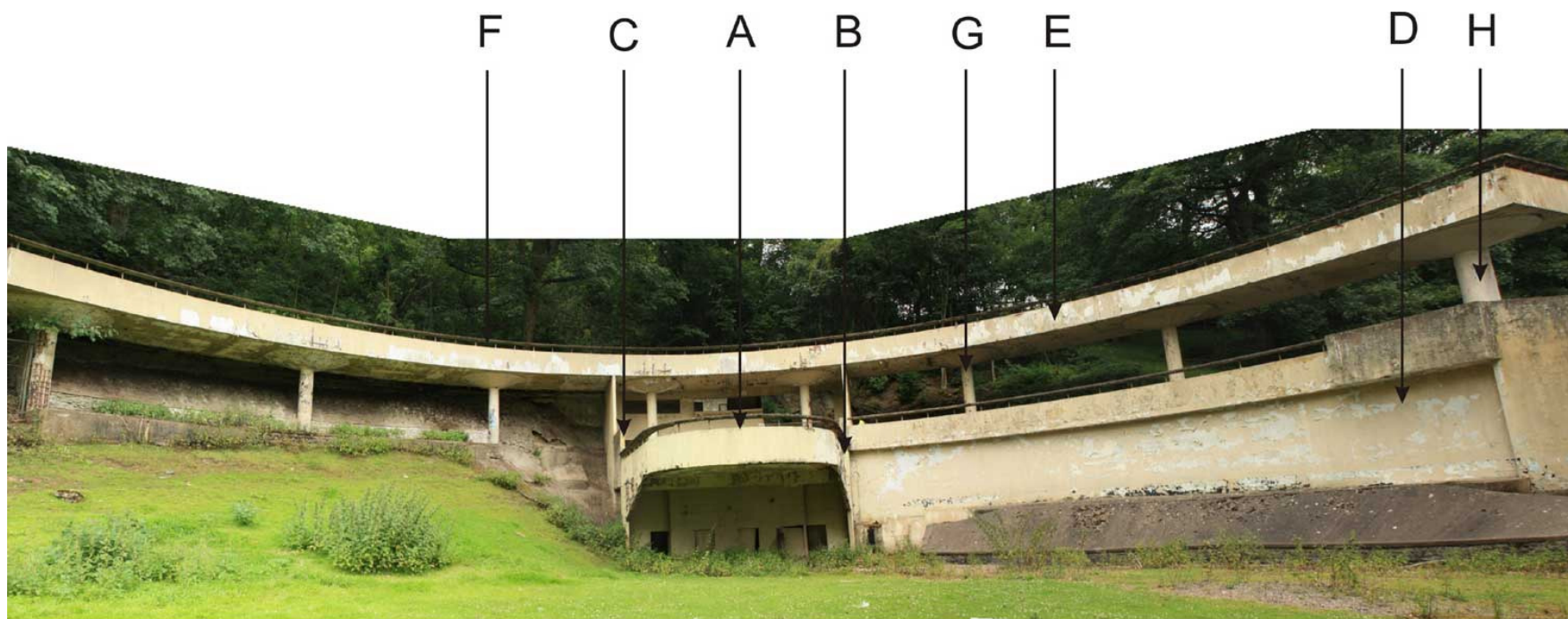


Figure A-1: Overall view of the Bear Ravine

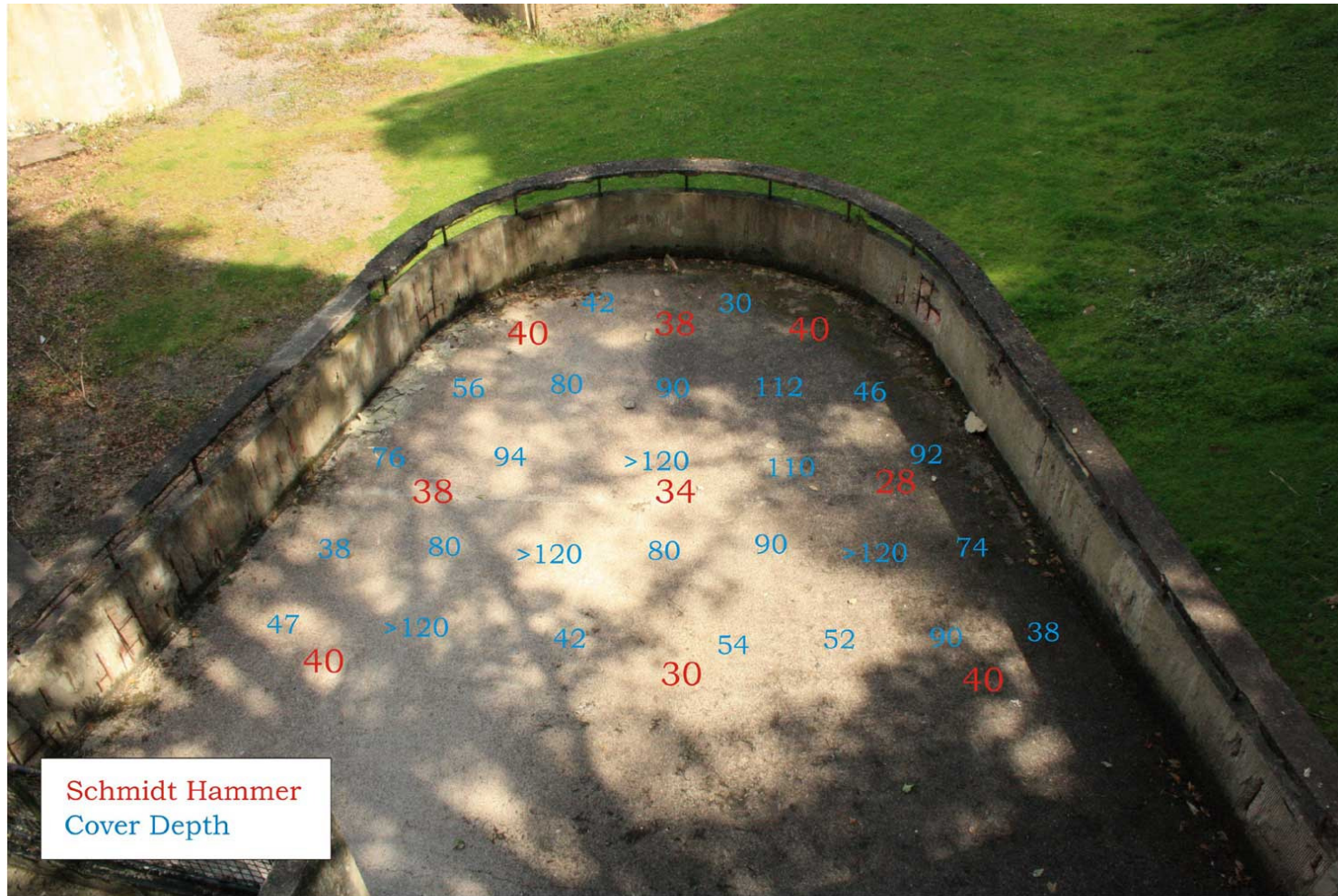


Figure A-2: Cantilevered Balcony Topside (Area A)



Figure A-3: Cantilevered Balcony Wall and Parapet (Area B)

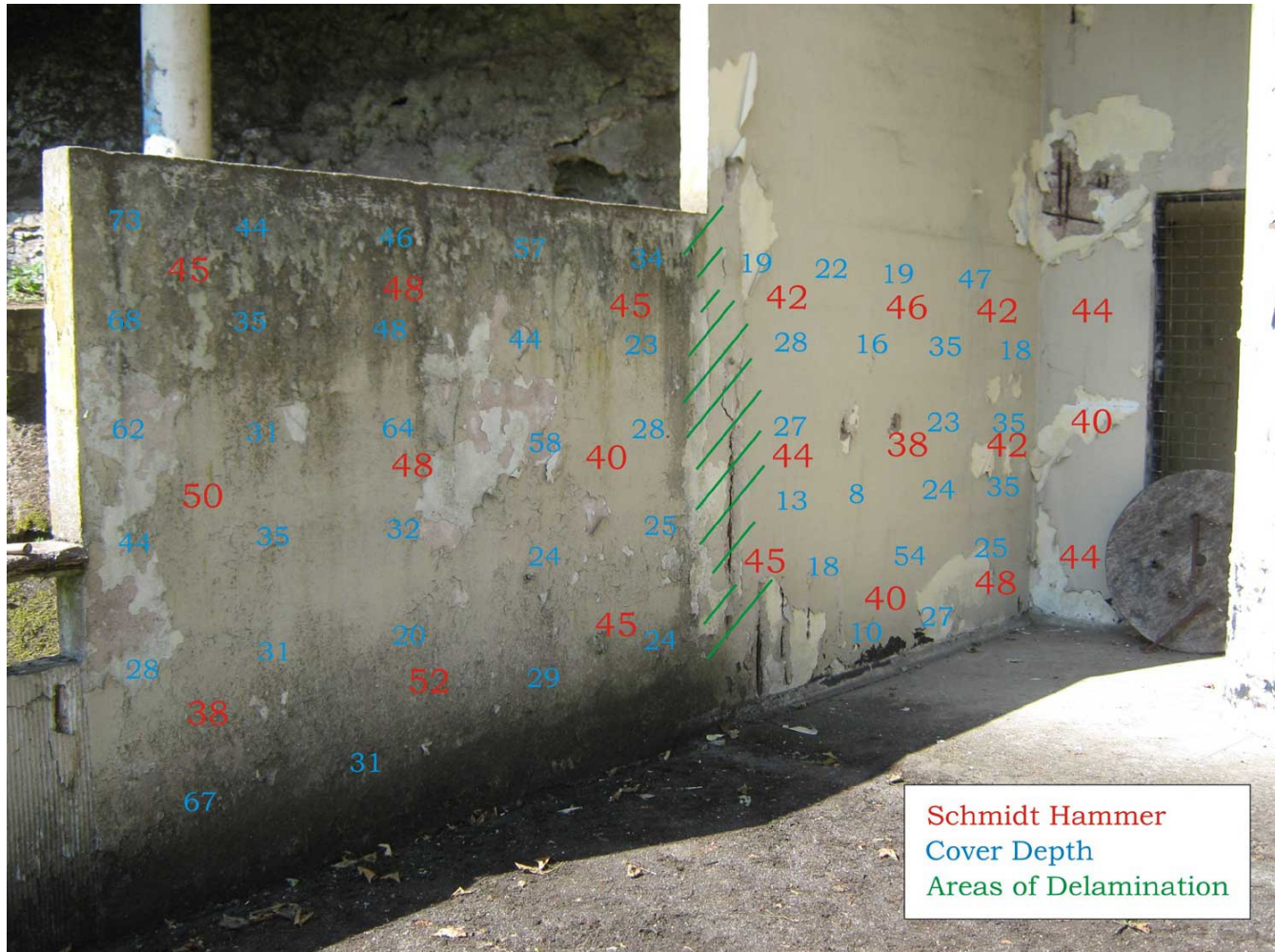


Figure A-4: Central Stairwell Wall - Lower Platform (Area C)



Figure A-5: Concrete Retaining Wall (Area D)



Figure A-6: Upper Platform Parapet and Soffit (Area E)

Schmidt Hammer
Cover Depth

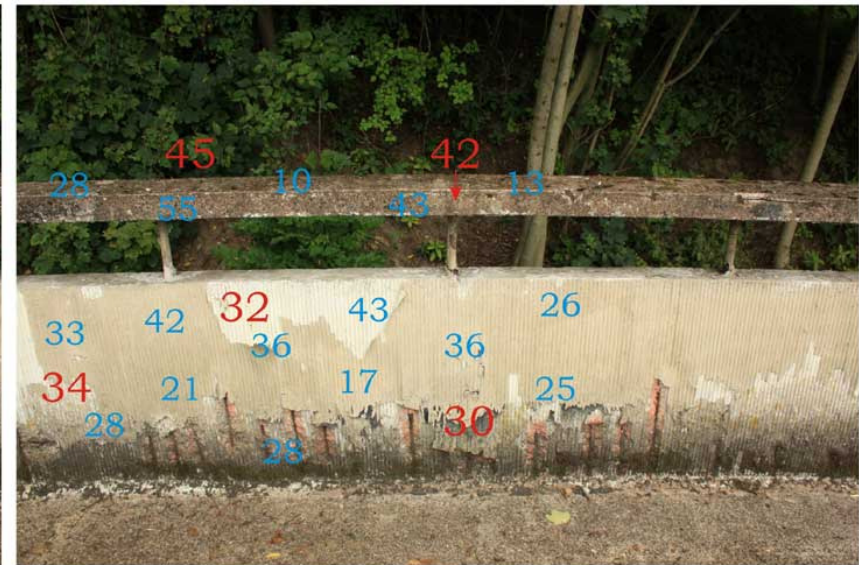
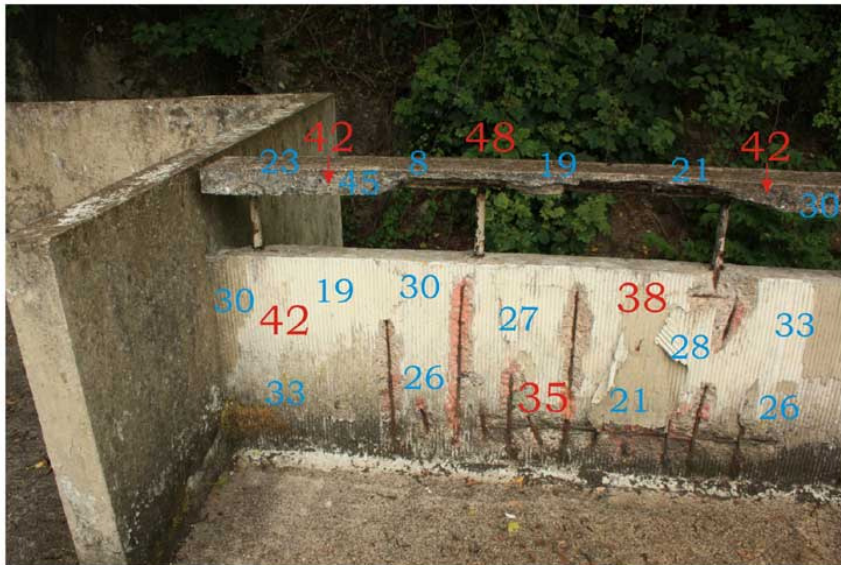


Figure A-7: Upper Platform Internal Parapet (Area F)



Figure A-8: Mushroom Headed Column (Area G)



Figure A-9: End Column Wall (Area H)

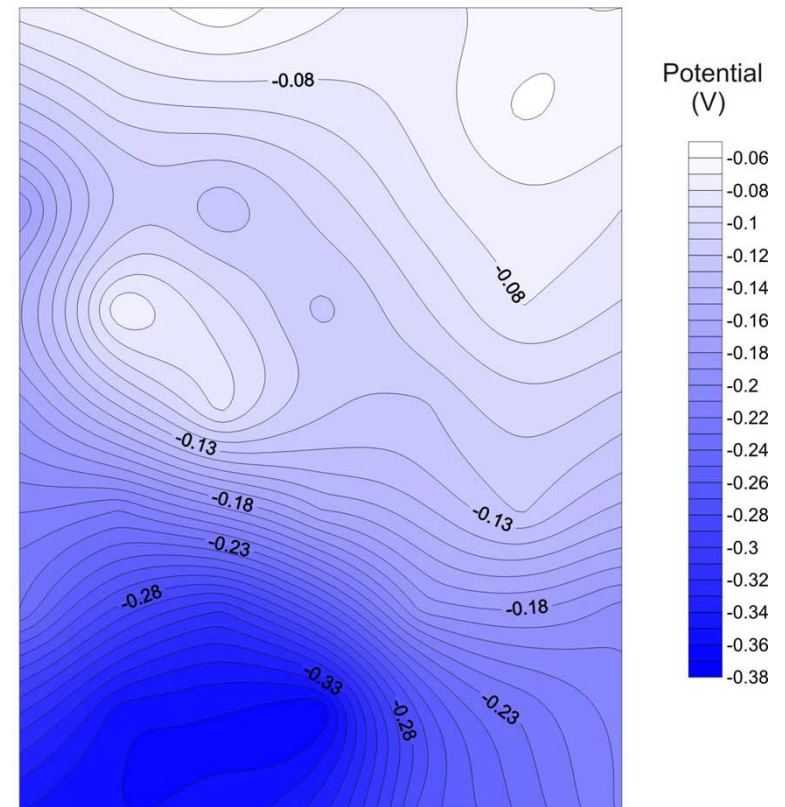
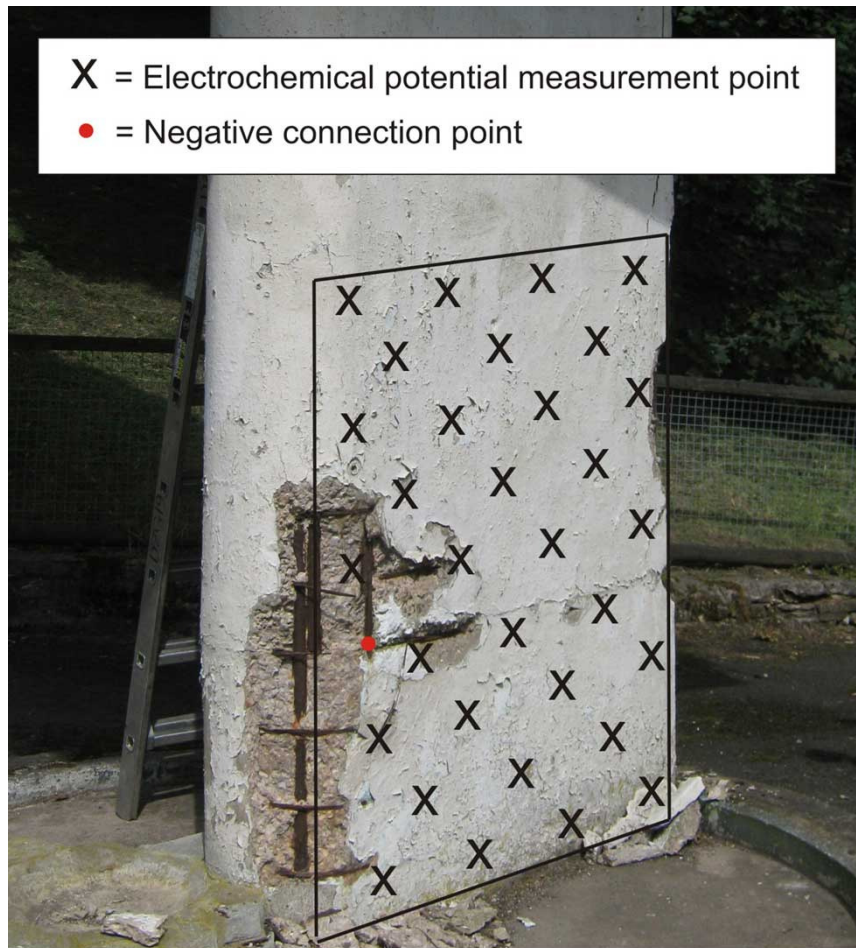


Figure A-10: Natural Potential (half-cell) map of part of Area H



Figure A-11: Front of Kiosk



Figure A-12: Rear of Kiosk



Figure A-13: Overall View of the entrance structure

Schmidt Hammer
Cover Depth
Areas of Delamination

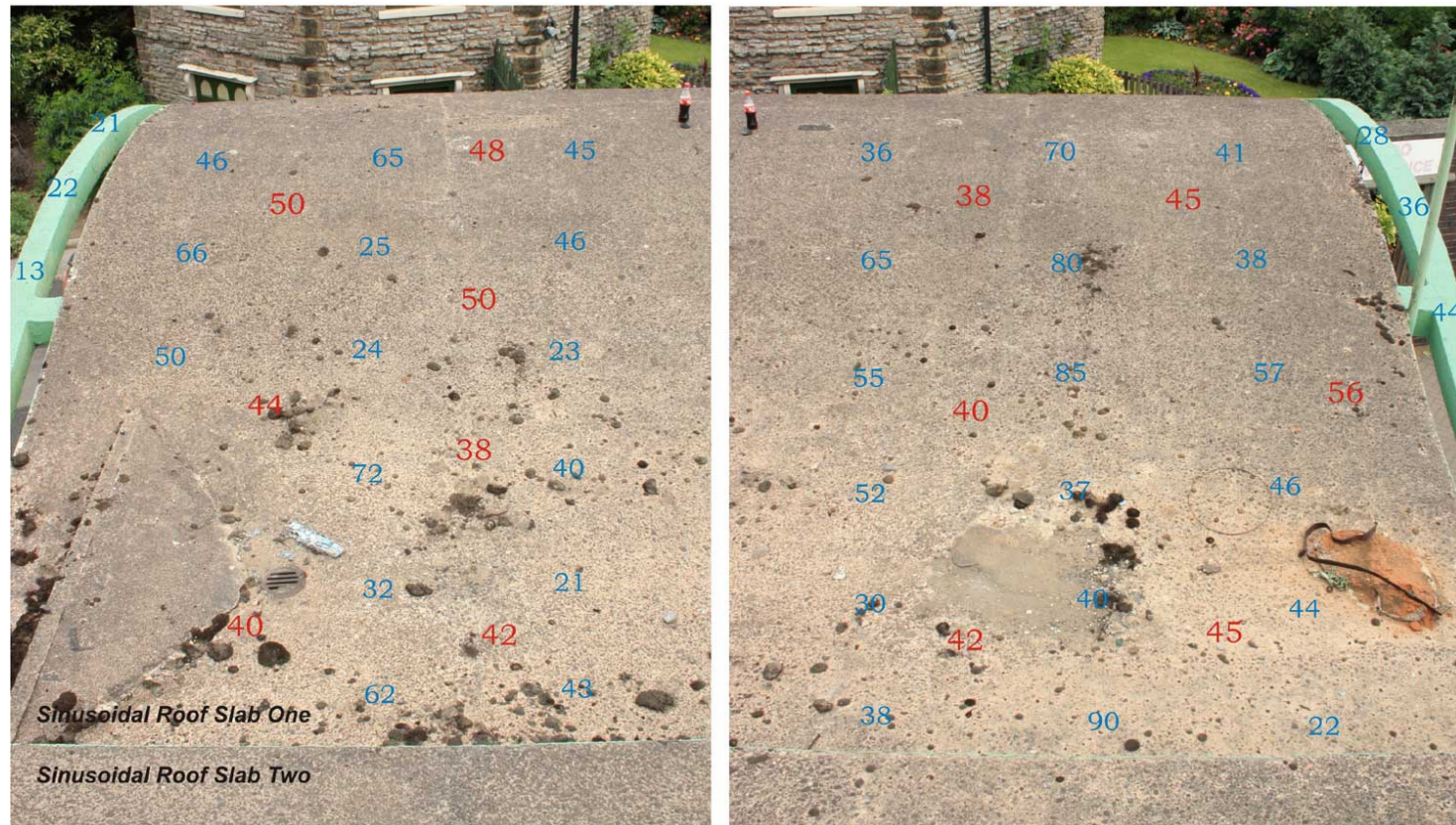


Figure A-14: Entrance topside of curved concrete canopy (Area A)

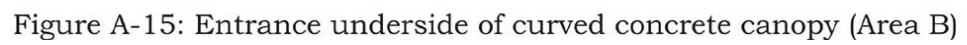


Figure A-15: Entrance underside of curved concrete canopy (Area B)

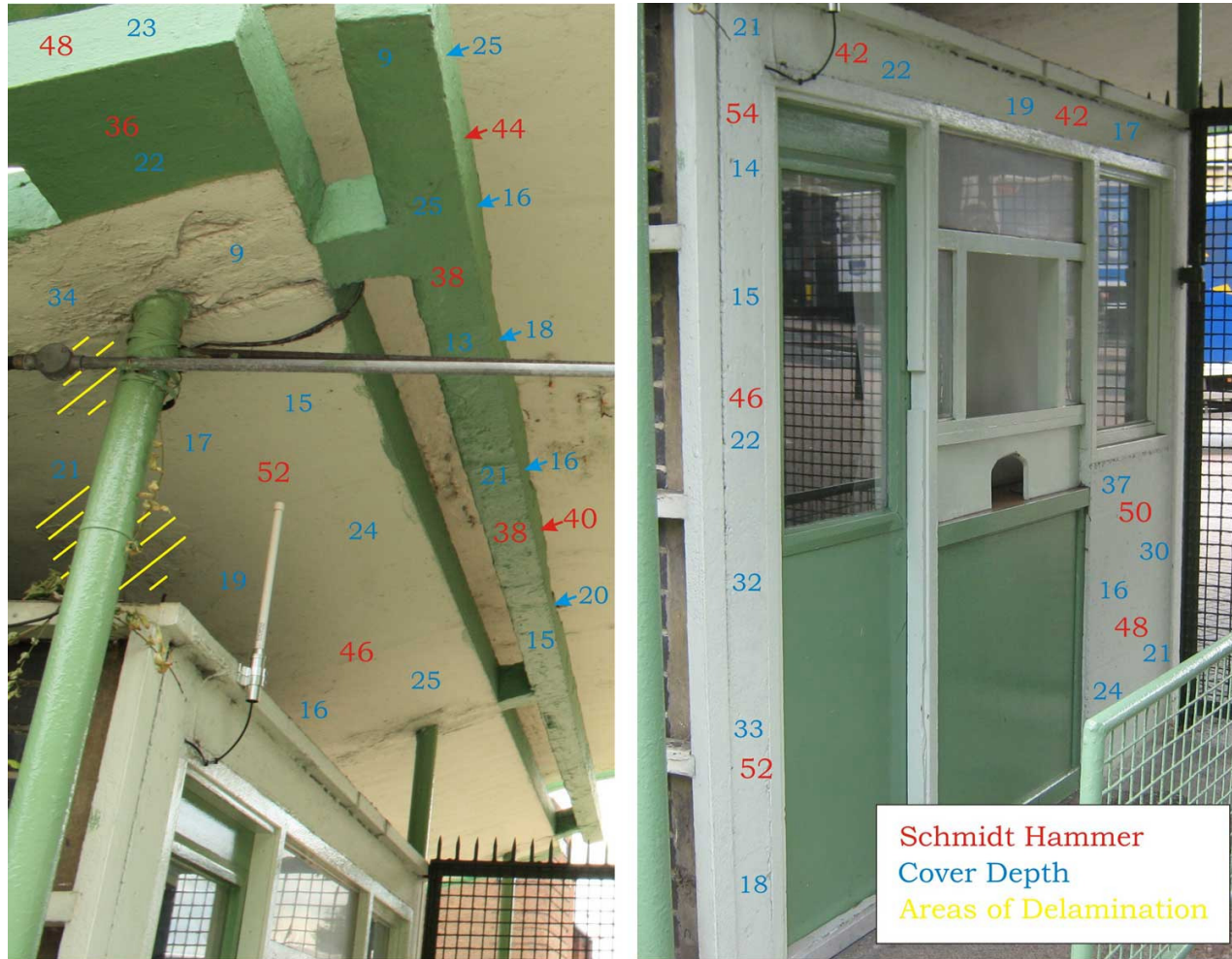


Figure A-16: Entrance underside and booth wall (Areas B and C)

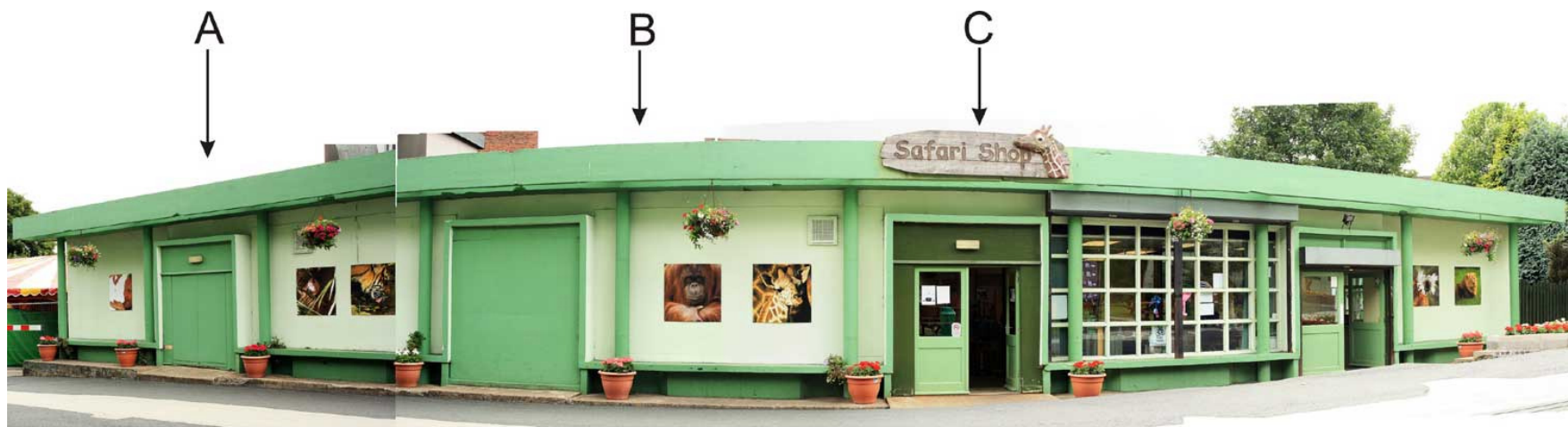


Figure A-17: Overall view of the Station Cafe

Schmidt Hammer
Cover Depth
Areas of Delamination



Figure A-18: Left side of the night club building (Area A)



Figure A-19: Right side of the night club building (Area B)



Figure A-20: Safari shop building (Area C)



Figure A-21: Carbonation testing of two cores taken from the Bear Ravine.



Figure A-22: Carbonation testing of two cores taken from the Kiosk.

BEAR RAVINE

Area A: Cantilevered Balcony

Overall mean cover depth of 66mm (52 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	0	0%
21mm – 40mm	6	11.5%
41mm – 60mm	10	19.2%
61mm – 120mm	36	69.3%

Mean Schmidt Hammer result = 39N/mm^2 (65 readings recorded)

Area B: Cantilevered Balcony Wall and Parapet

Overall mean cover depth of 29mm (45 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	17	38%
21mm – 40mm	18	40%
41mm – 60mm	10	22%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 38N/mm^2 (110 readings recorded)

Area C: Central Stairwell Wall – Cantilevered Platform

Overall mean cover depth of 29mm (67 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	20	29.9%
21mm – 40mm	32	47.8%
41mm – 60mm	15	22.4%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 44N/mm^2 (105 readings recorded)

Area D: Concrete Retaining Wall

Overall mean cover depth of 82mm (39 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	0	0%
21mm – 40mm	1	2.6%
41mm – 60mm	7	17.9%
61mm – 120mm	31	79.5%

Mean Schmidt Hammer result = 44N/mm^2 (45 readings recorded)

Area E: Upper Platform External Parapet and Soffit

Overall mean cover depth of 36mm (44 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	3	6.8%
21mm – 40mm	22	50%
41mm – 60mm	18	40.9%
61mm – 120mm	1	2.2%

Mean Schmidt Hammer result = 38N/mm^2 (55 readings recorded)

Area F: Upper Platform Internal Parapet

Overall mean cover depth of 31mm (63 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	12	19%
21mm – 40mm	38	60.3%
41mm – 60mm	9	14.3%
61mm – 120mm	4	6.4%

Mean Schmidt Hammer result = 39N/mm^2 (60 readings recorded)

Area G: Mushroom Headed Column

Overall mean cover depth of 22mm (42 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	15	35.7%
21mm – 40mm	27	64.3%
41mm – 60mm	0	0%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 46N/mm^2 (95 readings recorded)

Area H: End Column Wall

Overall mean cover depth of 26mm (39 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	8	20.5%
21mm – 40mm	30	77%
41mm – 60mm	1	2.5%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 47N/mm^2 (105 readings recorded)

KIOSK ONE

Main Outer Wall

Overall mean cover depth of 27mm (120 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	31	25.8%
21mm – 40mm	80	66.7%
41mm – 60mm	7	5.8%
61mm – 120mm	2	1.7%

Mean Schmidt Hammer result = 43N/mm² (135 readings recorded)

Roof Slab

Overall mean cover depth of 43mm (39 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	6	15.4%
21mm – 40mm	15	38.5%
41mm – 60mm	12	30.8%
61mm – 120mm	6	15.4%

Mean Schmidt Hammer result = 44N/mm² (35 readings recorded)

Counter Top

Overall mean cover depth of 19mm (17 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	12	70.6%
21mm – 40mm	5	29.4%
41mm – 60mm	0	0%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 47N/mm² (40 readings recorded)

ENTRANCE

(Sinusoidal Roof One Surveyed)

Sinusoidal Roof Topside

Overall mean cover depth of 49mm (75 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	4	5.3%
21mm – 40mm	29	38.7%
41mm – 60mm	21	28%
61mm – 120mm	21	28%

Mean Schmidt Hammer result = 45N/mm^2 (80 readings recorded)

Sinusoidal Roof Frontside

Overall mean cover depth of 22mm (39 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	22	56.4%
21mm – 40mm	13	33.3%
41mm – 60mm	4	10.3%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 45N/mm^2 (30 readings recorded)

Sinusoidal Roof Underside

Overall mean cover depth of 19mm (77 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	38	49.3%
21mm – 40mm	37	48.1%
41mm – 60mm	2	2.6%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 43N/mm^2 (75 readings recorded)

Ticket Cabin Wall

Overall mean cover depth of 26mm (36 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	12	33.3%
21mm – 40mm	21	58.3%
41mm – 60mm	2	5.6%
61mm – 120mm	1	2.7%

Mean Schmidt Hammer result = 49N/mm^2 (30 readings recorded)

SAFARI SHOP

Main Building

Overall mean cover depth of 30.3mm (168 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	47	28%
21mm – 40mm	96	57.1%
41mm – 60mm	15	8.9%
61mm – 120mm	10	6%

Mean Schmidt Hammer result = 47N/mm^2 (190 readings recorded)

Piers

Overall mean cover depth of 23.4mm (35 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	12	34.3%
21mm – 40mm	22	62.9%
41mm – 60mm	1	2.8%
61mm – 120mm	0	0%

Mean Schmidt Hammer result = 42N/mm^2 (75 readings recorded)

Flying Edge Beam

Overall mean cover depth of 33.4mm (128 readings recorded)

Cover Depth Range	Readings Total	% Total
<20mm	17	13.3%
21mm – 40mm	74	57.8%
41mm – 60mm	34	26.6%
61mm – 120mm	3	2.3%

Mean Schmidt Hammer result = 44N/mm^2 (120 readings recorded)

Carbonation Depth Testing (38mm core)

Location	Sample	Carbonation Depth (mm)
Bear Ravine	1	32 – 38
	2	35 – 40
Kiosk	1	32 – 38
	2	26 – 38
	3	33 – 39

APPENDIX B

LABORATORY RESULTS

Core samples of the concrete from both the Bear Ravine and the Kiosk were taken using a 50mm diameter core drill from either damaged areas of the walls or from unobtrusive areas. Drill samples (0-10mm, 10-20mm and 20-30mm) were also taken from all four structures. The core and drill samples were sent to UK Analytical for detailed analyses. The results are contained in this Appendix.



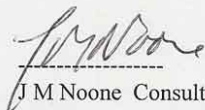
0013

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Whitehall Road
Leeds
LS12 1HE
Telephone: 0113 245 6303
Fax: 0113 245 5975
Email: enquiries@ukanalytical.com
Web: www.ukanalytical.com

TEST CERTIFICATE FOR THE DETERMINATION OF THE SULPHATE
CONTENT OF CONCRETE BY BS1881 : PART 124 : 1988 : 10.3

LABORATORY REFERENCE NO. : 11/18426/1
CLIENT : Rowan Technologies Ltd.
ADDRESS : 216 Church Road, Urmston, Manchester
M41 9DX
REPORT DATE : 28/7/2011
DATE RECEIVED : 14/7/2011
IDENTIFICATION : Dudley Zoo Tecton Buildings
4. Entrance 2-10mm
8. Cafe 2-10mm
12. Bear Ravine 2-10mm
16. Kiosk 2-10mm
TEST METHOD : BS1881 : PART 124 : 1988 : 10.3
(UKA Method No.3)
SAMPLING : Drillings
SAMPLING DATE & PLACE : Samples supplied by client
SAMPLING CERTIFICATE : Not supplied
DESCRIPTION : 4 no. concrete samples
RESULTS :

SAMPLE REFERENCE	% w/w Sulphate (SO ₃) of concrete
4	0.71
8	0.83
12	0.45
16	0.72


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Samples are kept for a period of one month from the report date.

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Web: www.ukanalytical.com

**TEST CERTIFICATE FOR THE DETERMINATION OF THE CHLORIDE
CONTENT OF CONCRETE BY BS1881 : PART 124 : 1988 : 10.2**

LABORATORY REFERENCE NO. : 11/18426/2
CLIENT : Rowan Technologies Ltd.
ADDRESS : 216 Church Road, Urmston, Manchester
M41 9DX
REPORT DATE : 28/7/2011
DATE RECEIVED : 14/7/2011
IDENTIFICATION : Dudley Zoo Tecton Buildings
TEST METHOD : BS1881 : Part 124 : 1988 : 10.2 (UKA
Method No 2)
SAMPLING : Unknown
SAMPLING DATE & PLACE : Samples supplied by client
SAMPLING CERTIFICATE : Not supplied
DESCRIPTION : 12no. Concrete samples
RESULTS :

SAMPLE REFERENCE **% w/w Chloride (Cl) of Concrete**

Entrance	1. 0-10mm	0.117
	2. 10-20mm	0.084
	3. 20-30mm	0.137
Cafe	5. 0-10mm	0.066
	6. 10-20mm	0.041
	7. 20-30mm	0.048
Bear Ravine	9. 0-10mm	0.040
	10. 10-20mm	0.060
	11. 20-30mm	0.033
Kiosk	13. 0-10mm	0.988
	14. 10-20mm	0.363
	15. 20-30mm	0.575


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Samples are kept for a period of one month from the report date.

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TEST CERTIFICATE FOR THE DETERMINATION OF THE CEMENT
CONTENT BY BS1881 : PART 124 : 1988 : 5

LABORATORY REFERENCE NO. : 11/18426/3
CLIENT : Rowan Technologies Ltd.
ADDRESS : 216 Church Road, Urmston, Manchester
M41 9DX
REPORT DATE : 28/7/2011
DATE RECEIVED : 14/7/2011
IDENTIFICATION : Dudley Zoo Tecton Buildings
17. Bear Ravine Core Sample 1
19. Kiosk Core Sample 1
TEST METHOD : BS1881 : PART 124 : 1988 : 5
(UKA Method No.4)
SAMPLING : Unknown
SAMPLING DATE & PLACE : Samples supplied by client
SAMPLING CERTIFICATE : Not supplied
DESCRIPTION : 2 no. concrete samples

RESULTS :

Sample reference	17	19
------------------	----	----

Soluble silica % w/w : (uncorrected)	3.58	1.92
---	------	------

CaO % w/w : (uncorrected)	9.45	6.08
------------------------------	------	------

Cement ex Silica % w/w :	17.72	9.50
Cement ex CaO % w/w :	14.65	9.43

<u>CEMENT CONTENT % w/w</u> :	14.7	9.5
-------------------------------	------	-----

Combined water % w/w :	3.38	2.19
------------------------	------	------

Uncombined water % w/w :	6.75	4.47
--------------------------	------	------

Total water % w/w :	10.13	6.66
---------------------	-------	------

<u>WATER/CEMENT RATIO</u> :	0.69	0.70
-----------------------------	------	------

Insoluble residue % w/w :	73.2	78.0
---------------------------	------	------


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Test certificate for the determination of the cement content of
concrete by BS1881 : Part 124 : 1988 : 5

Report no. : 11/18426/3

Client : Rowan Technologies

Notes :

1. BS1881 : Part 124 : 1988 : 5.9.1 states that where the cement content by the two methods differs by more than 1%, the lower figure is taken.
2. The cement is assumed to be Ordinary Portland Cement with SiO₂ content of 20.2%, and CaO 64.5%
(BS1881 : Part 124 : 1988: Appendix B.)
3. No corrections were made for the soluble silica and calcium oxide contents of the aggregates.
4. The results are reported for the dry sample and are the mean of two determinations.
5. BS1881 (Appendix A) gives a repeatability [r] of 40 kg/m³, and reproducibility [R] of 60 kg/m³ where samples are available for correction. This is approximately equivalent to a repeatability [r] of 15 % w/w, and a reproducibility [R] of 20 % w/w.
6. Sample weight taken for analysis is 2g +/- 0.005g not 5g +/- 0.005g. This lower weight has been validated in-house.

Samples are kept for a period of one month from the report date.

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TEST CERTIFICATE FOR QUALITATIVE ANALYSIS BY X-RAY
DIFFRACTION

LABORATORY REFERENCE NO. : 11/18426/4
CLIENT : Rowan Technologies Ltd.
ADDRESS : 216 Church Road, Urmston, Manchester
M41 9DX
REPORT DATE : 28/7/2011
DATE RECEIVED : 14/7/2011
IDENTIFICATION : Dudley Zoo Tecton Buildings
17. Bear Ravine Core Sample 1
TEST METHOD : Carried out by partner laboratory, Methods
M7, M9 and M30
RESULT :

Sample Reference	17	Approx %
Major phases :	Quartz (SiO ₂)	72.1
(approx.5%)	Alkali Feldspar	7.0
	Chlorite	8.1
Minor phases :	C2S (Ca ₂ SiO ₄)	1.2
(approx.0.5-5%)	Kaolinite (Al ₂ Si ₂ O ₅ (OH) ₄)	0.7
	Mica	3.9
	Portlandite (Ca(OH) ₂)	2.1
	Albite (NaAlSi ₃ O ₅)	4.9

COMMENTS


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Samples are kept for a period of one month from the report date.

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PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE : 11/18426/5
CLIENT : Rowan Technologies Ltd.
ADDRESS : 216 Church Road, Urmston, Manchester
M41 9DX
REPORT DATE : 10/10/2011
DATE RECEIVED : 14/7/2011
IDENTIFICATION : 18 – Core 2 Bear Ravine, Dudley Zoo

TEST METHOD : ASTM C 856-83 (reapproved 1988),
“Petrographic examination of hardened concrete”. This includes visual examination,
microscopic examination of a thin section, x-ray diffraction, and hydrochloric acid
separation.

SAMPLING : Coring

SAMPLING DATE & PLACE : Samples supplied by client.

SAMPLE PREPARATION FOR MICROSCOPY : The core was sliced lengthways,
and vacuum impregnated with a resin containing a blue dye. A thin section was
prepared for examination by transmitted light microscopy using both normal and
polarised light.

VISUAL EXAMINATION :

The sample consisted of a light grey coloured cement matrix, with both crushed and
natural stone aggregate. The aggregate particles were dark grey, green to brown in
colour, sub-angular to sub-rounded and well-distributed.

AGGREGATES

Coarse : Poorly sorted quartzitic conglomerate
containing particles of mica and chlorite (Figures 1 and 2). The material is typical of a
greywacke. Also present is moderately well sorted sandstone (Figure 3).

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited

Fine : Sand containing mainly quartz, but also particles of the coarse aggregate. Figure 4 shows the fine aggregate.

Size Range : Coarse aggregate 3-10mm.
Fine aggregate 0.1-1mm.

Shape & Distribution : Coarse aggregate : Sub-angular to sub-rounded
Fine aggregate : Sub-rounded
Uniform distribution.

Paste :
Colour : Light grey
Hardness : Hard
Lustre : Dull
Admixtures : None
Carbonation : At surface only
Voids : Very few

Cracks : Microcracks are fairly few. These are mostly associated with internal aggregate cracking in both the coarse and fine aggregate, (Figures 5 and 6)

The assessment of evidence for the presence of alkali-aggregate or alkali-silica reaction is based upon the following features:-

1. Branching crack systems originating at suspect aggregate particles.
2. Internal aggregate cracking running both normal and sub-parallel to the cement-aggregate interface.
3. The presence of a reaction rim within the aggregate, either by discolouration of the border or by cracking of the margin with associated gel development.
4. The presence of isotropic gel, extending outwards from the aggregate along crack systems or contained within voids at variable distances from the aggregate.
5. The impregnation of reaction product gel into the cement paste immediately adjacent to the aggregate.

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PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited

The results are presented in the form of a table where the above features are recorded, according to the relative amount affected, assessed on a scale 1-10. This is a subjective assessment and should be regarded as giving an indication only.

Feature no. :-					
1	2	3	4	5	

0	2	0	0	0	

COMMENTS : The cement paste contains very few cracks. The cracking is associated with the aggregate particles, but not with any specific type of aggregate particle. Although some of the cracks are branched, and therefore characteristic of alkali-aggregate reaction, no gel was found.

The sample contains potentially reactive aggregate in the form of a greywacke. No evidence of reaction between the aggregate and the cement paste was noted.

The sample is deemed to be free from ASR.



J M Noone Consultant



Samples are kept for a period of one month from the report date.

Thin sections are kept indefinitely.

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO.: 11/18426/5

CLIENT: Rowan Technologies Limited

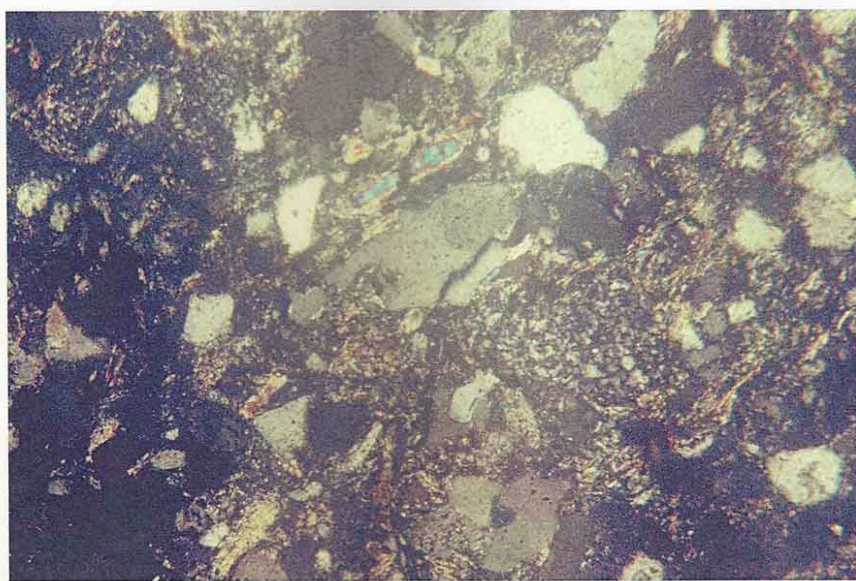


Figure 1 Magnification x140 Crossed Polars

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO.: 11/18426/5

CLIENT: Rowan Technologies Limited

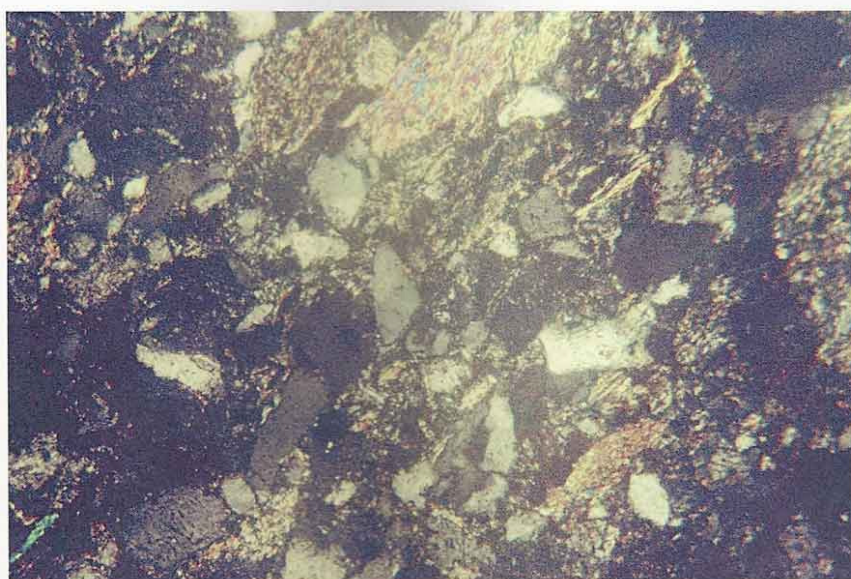


Figure 2 Magnification x140 Crossed Polars

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited



Figure 3 Magnification x140 Crossed Polars

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited



Figure 4 Magnification x140

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited

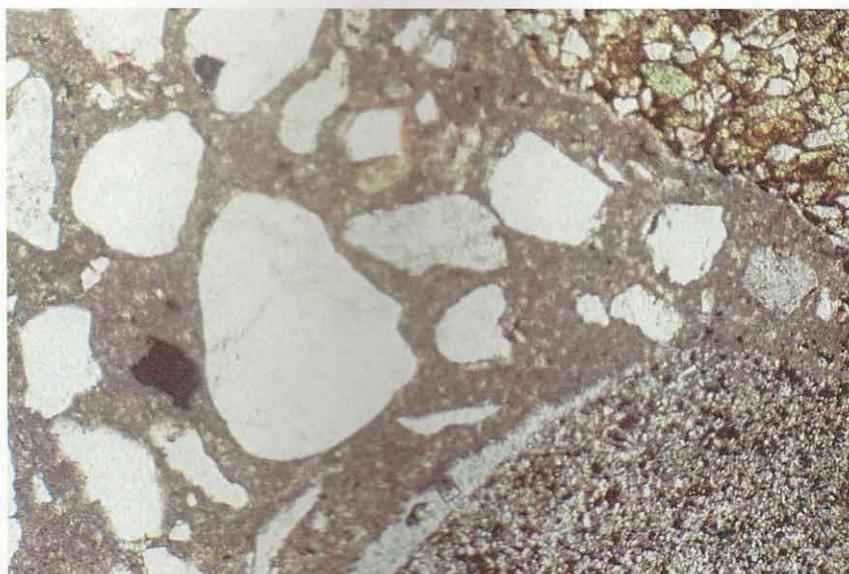


Figure 5 Magnification x60

PETROGRAPHIC EXAMINATION OF CONCRETE BY ASTM C 856

LABORATORY REFERENCE NO. : 11/18426/5

CLIENT : Rowan Technologies Limited



Figure 6 Magnification x60

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APPENDIX C

OUTLINE REPAIR METHODS FOR CONCRETE USING TRADITIONAL MATERIALS

PRELIMINARY WORK

Prior to starting the traditional repairs to historic concrete, it is recommended that a flag library be prepared using different combinations and quantities of the concrete constituents – as indicated from the analysis results. An example of this is shown in Figure C-1. Typically 10 to 20 test flags should be cast using different combinations of cement (OPC and/or white masonry cement), mixtures of sands and different types and sizes of aggregates to match that of the original concrete. Depending upon the damage to the structure, the size of the aggregates may need to be reduced from the parent concrete to accommodate them within thinner repairs. Colour match is best achieved using different combinations of sands, and sometimes even cements. However, colouring agents may be allowed in certain circumstances to assist the match to the original ‘aged’ concrete. The results from the laboratory analyses of the original concrete should provide assistance in selecting the appropriate constituents for the test flags.

If the replacement material is to be used to repair weathered concrete, where the cementitious layer has been eroded back to reveal the aggregates, then retardants should be included within the tests. Retardants are normally applied to the shutters to delay setting so that the cementitious material may be more easily removed early on to expose the aggregate. One side of the flag mould should be coated with a retardant and the other side left alone. The moulds should be broken out early (typically 12 hours) and half of the two sides of the slab (retarded and free) should be wire brushed (or mechanically abraded) to assess if retardants are required. Setting is slower in the colder months and retardants may not be required, whereas in the summer months they may be essential.

The slab library can be used as a visual reference during the course of the repair project so that different types, textures, colours and degrees of weathering can be matched as the work progresses. This is particularly important where the concrete has variable texture and colour around the site and has varying degrees of weathering. In addition, this preliminary work will assist the contractor to establish the optimum repair methods prior to initiating the conservation work.

The other aspect to consider before the repairs are initiated is to assess if the original structure contains design faults, which have resulted in earlier deterioration of the structure than would have been expected. Faults might include concrete roofs without waterproofing or rain run-off features which have not been fitted with a suitable drip. Alterations to listed historic concrete structures are often allowed under these sorts of circumstances.

STARTING OFF THE REPAIRS

Modern concrete repair mortars are manufactured using polymer-containing materials. This significantly improves the adhesion of patch repairs to the original

concrete and also the strength of the repair as compared to traditional concrete repairs. This enables them to be applied in relatively thin layers; for instance to repair delaminated concrete or where the surface has suffered from surface mechanical damage. Repair mortars have different physical properties to the original concrete, such as thermal expansion and contraction and different elastic modulus and they do not contain significant amounts of sizable aggregates. In addition, they do not possess the high alkalinity of cement-based mortars, which readily repassivate corroded steel reinforcements. The result is that the lifetime of repairs using modern concrete mortars is normally limited to one or two decades at best. They also invariably have dissimilar aesthetic properties to the parent concrete and usually require coating of both the repairs and the parent concrete to provide uniformity. For these reasons they are not recommended for historic concrete structures.

Traditional concrete repair materials, using similar constituents to the existing concrete, should have a lifetime similar to that of the structure to be repaired, i.e. many decades or centuries for high quality concrete. However, traditional concrete repair materials do not have the advanced adhesive and cohesive properties as given by modern repair mortars. The adhesion of the traditional repairs to the parent concrete is not as good and this requires additional mechanical methods for bonding the repair patches to the original concrete. For repairs involving reinforced concrete (RC), the presence of steelwork within the concrete breakout assists in the bonding. For bulk (unreinforced) concrete, cramps and ties may be inserted to improve the mechanical bonding of the repair to the original concrete. Drilling into the back and/or sides of the breakout and fixing cramps or ties using an epoxy resin adhesive may accomplish this. For marine environments, the additional reinforcements should be in stainless steel and for more benign environments plain mild steel should suffice. Increasing the depth of the repair patch, dovetailing the sides and roughening the base of the breakout should also provide additional mechanical bonding.

BREAKING OUT THE CONCRETE

Once an area of damaged concrete has been identified it should be marked out and straight lines used to draw it out. A 20mm diameter diamond core drill should be used to mark the corners of the breakout, Figure C-2. These provide relief at these points and reduces the risk of spalling to the arrisses. The depth of the repair areas should be specified as a minimum of 40mm but may be up to 75mm and the base left rough. The edges of the break-outs should be cut using a diamond blade with an undercut of 2 to 4mm and to a depth of 25mm to create a dovetail to improve the mechanical bond of the repair to the parent concrete. The concrete can then be removed using a mechanical breaker - typically 10 to 25kg depending upon the depth of removal. Larger areas may require more severe measures to remove the damaged concrete, such as hydrojetting.

Steel reinforcements with previously low cover (typically less than 15mm) or where they have suffered significant loss-in-section may be cut out and new steel replaced at greater depth. An alternative, if the thickness of the steel is sufficient, is to hammer the reinforcement back deeper into the concrete body. A structural engineer should be consulted prior to this work being initiated. If the structure has been formed from mass concrete, then it is recommended that steel cramps or dowels be inserted to provide improved mechanical bonding, Figure C-3.

The corroded bars should be mechanically cleaned to remove their loose corrosion product but not coated. The high alkalinity of the new concrete repair will effectively re-passivate the corroded steel. This may be compared to modern repair mortars that do not have the high alkalinity that naturally repassivates steel, and therefore require grit blasting of all steel reinforcements and protective coatings to be used.

PREPARING THE SHUTTERS

Concrete repairs should preferably be placed using shutters (wood boards, plywood or metal shutters) similar to that used for the original concrete to create a similar surface appearance, to assist the bonding of the repair to the parent and to enable air pockets and voids to be removed and for the repair to completely fill the mould. However, in some circumstances, such as small patch areas or areas between different levels, hand-placing the concrete may be adequate. A decision should be taken at the time of repair.

The shutters should be cut to size to cover the repair area. For small areas of repair it may be possible to use external supports to hold the shutters in place, Figure C-4. However, for larger repairs the shutters need substantial fixings to support the weight of the repair concrete. These fixings were originally made outside the repair patch, but this results in additional holes in the parent concrete that require filling afterwards, Figure C-5. More recently shutters have been erected using steel rock anchors that are 'hammer fixed' into the back face of the repair areas and with threaded bars coming out for fixing the shutters to, Figure C-6. The threaded bars are removed after the repair has set and the fixing holes (which are now in the new repair patch) filled in.

The shutters should be cut to size and prepared with foam strips around the perimeter to prevent cement leakage and coated with a release agent.

PLACING THE CONCRETE

The actual mix of the concrete should be selected from the slab library to match that of the particular area. A typical composition may be 1:2:3 cement: sand: aggregate. This should be suitably mixed with a typical water:cement ratio of 0.4. Additives, such as Styrene Butadiene Rubber (SBR) may be beneficial in minimising the water:cement ratio whilst maintaining the workability of the concrete repair. SBR also increases the bond strength and provides water resistance to the concrete repair. The conservator should be consulted if additives are being considered.

The repair area should be thoroughly wetted before the repair is made. The concrete should be placed through a letterbox at the top of the shutters and a poker used to vibrate the mix to remove air pockets and to completely fill the mould. The repair should be left to set and the shutters removed typically after 12 to 24 hours. The exact time depends upon the environmental conditions (mainly temperature) and the thickness and bulk of the repair and may be shortened (early breakout) if the concrete surface requires brushing to reveal the aggregate.

If the repair is to be hand placed, a cement slurry primer should first be used on the back of the breakout and the repair gradually built up using a number of layers.

SURFACE FINISH TO THE REPAIRS

If surface finishing is required to the repair concrete, this is best carried out soon after setting and before the curing or hardening takes place. Simply rubbing with Hessian sacking or wire brushing is suitable if the repairs are broken out early enough or if retardants have been used. Alternatives are the use of a surface grinder or a high-pressure water jet to remove the cementitious layer and to expose the aggregate.

Concrete repairs frequently take up a lighter colour than the parent concrete as their surfaces have not yet been weathered. They will not therefore support algal or moss growth, which darkens aged concrete. Early natural weathering involves the neutralisation of the high alkalinity of the surface layer and an increase in its porosity. This assists in the establishment of growth. Mechanical brushing of the new concrete repair will assist in achieving increased porosity of the outer surface, but it normally takes between 5 to 10 years before growth becomes established. This may be accelerated somewhat by the use of plant growth accelerators, such as live yoghurt. This procedure is only required if the parent concrete has weathered or if the concrete surface had originally exposed the aggregate. If the concrete has not weathered or has been coated then surface finishing is not required.

REPAIRING CRACKS

Cracks of any width should never be filled until their causes have been fully diagnosed and the benefits of the proposed crack injection procedure have been demonstrated. If the crack is the result of corrosion of underlying reinforcements, then simply filling the crack will not stop the deterioration. The corrosion process needs to be stopped either by re-passivating the steel by repairing the surrounding concrete or preventing water ingressing to the steel.

Cracks due to shrinkage or thermal movement and wider than 0.5mm wide should be opened up and filled using a flexible resin to minimise water ingress into the bulk concrete.



Figure C-1 Flag library using different constituents for the test concrete. Some of the flags used retardants together with post-brushing of the surfaces.



Figure C-2 Core drilling of the corners of the breakouts and dovetail cuts between to achieve additional mechanical fixing of the repairs.



Figure C-3 Stainless steel cramps being inserted in the breakouts to bond the two concrete layers together and assist the mechanical bond of the repair.



Figure C-4 Shutters fixed externally into the parent concrete to achieve board-marked finish to concrete repairs. This resulted in additional holes to be filled afterwards.



Figure C-5 Shutters fixed using external supports.



Figure C-6 Rock anchors used to fix shutters internally within the breakout.