Restoring Mrigadayavan Palace:
Understanding Causes of Concrete Deterioration and Determining Viable Concrete Rehabilitation Methods

Supplementary Materials

Sponsored by
Mrigadayavan Palace Foundation

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A. Professional Condition Assessment

The evaluation of concrete structures prior to rehabilitation is used for several purposes. It is important to determine the feasibility of changing a structure and the deterioration of a structure due to unusual loading or exposure conditions, inadequate design, or poor construction practices. The American Concrete Institute (ACI) Committee reports are used to guide the planning, design, and execution of a condition assessment of a concrete structure.

The steps for completing a condition assessment as determined by the ACI Committee is as follows:

1. Review of plans, specifications, and construction records
2. Site observations of conditions
3. Measurement of geometry, deflections, displacements, cracks, and other damage
4. Nondestructive testing
5. Exploratory removal
6. Sampling, testing, and analysis

The first task in a condition assessment is to review any plans, specifications, and construction records to determine critical design details and arrangement of particular areas of focus. In this initial step, building or structure codes must be reevaluated to ensure that proper safety measures will be taken. Once the plans have been properly analyzed, a walk-through of the structure can be completed to observe the conditions and properly document the frequency and severity of problems. Photography and videography may be introduced at this step. The physical conditions that should be noted are seen in *Figure S1*. During the field observation, measurements of any displacement, cracks, separations, or distortion will be noted. Once specific areas of damage are determined by the field observations nondestructive testing can begin. The most common methods of nondestructive testing are acoustic impact (sounding and chain dragging), magnetic detection instrument (cover meters), rebound hammer, and penetration resistance.

Some of these steps can be used to assess the extent of concrete deterioration at the Mrigadayavan Palace. The ACI Committee Report for condition assessments includes further information about performing an initial assessment of concrete structures.[14]

EVALUATION PROCEDURE / PHYSICAL CONDITION	ACOUSTIC EMISSIONS (Table 6.3)	ACOUSTIC IMPACT (Table 6.3)	CHEMICAL TESTS	CORE TESTING (ASTM C42)	FIBER OPTICS (Table 6.3)	GAMMA RADIOGRAPHY (Table 6.3)	INFRARED THERMOGRAPHY (Table 6.3)	LOAD TESTING (ACI 437R)	PETROGRAPHIC ANYLYSIS (ASTM C856)	PHYSICAL MEASUREMENT	RADAR (Table 6.3)	REBOUND HAMMER (ASTM C805)	ULTRASONIC PULSE (ASTM C597)	ULTRASONIC PULSE-ECHO (Table 6.3)	VISUAL EXAMINATION (ACI 201.1R, ASTM C823)	WINDSOR PROBE (ASTM C803)
BLEEDING CHANNELS									●						●	
CHEMICAL DETERIORATION			●						●						●	
CORROSION OF STEEL			●	●					●						●	
CRACKING	●	●		●	●		●		●	●	●		●	●	●	
CROSS SECT PROPERTIES AND THICKNESS				●		●				●			●			
DELAMINATION		●		●	●	●	●		●		●		●	●	●	
DISCOLORATION			●						●						●	
DISINTEGRATION				●		●	●		●				●		●	
DISTORTION															●	
EFFLORESCENCE			●						●						●	
EROSION									●						●	
FREEZE-THAW DAMAGE									●						●	
HONEYCOMB				●	●	●	●		●				●		●	
POPOUTS															●	
SCALING															●	
SPALLING				●		●	●								●	
STRATIFICATION		●			●									●	●	
STRUCTURAL PERFORMACE	●							●							●	
UNIFORMITY OF CONCRETE						●			●			●	●	●	●	

Figure S1. Evaluation of Physical Conditions of Concrete[1]

B. Questions for Interviews and Surveys

The following questions were asked to the Mrigadayavan Palace Foundation during the scheduled visits to the Palace.

First Palace Visit Interview Questions

Topic: General Information

1. What is your role at the Palace?
2. How many years has the current administration been here at the Palace?

Topic: Extent of the concrete corrosion

1. How are the buildings at the Palace grouped? Are there any official building diagrams of the Palace?
2. Which group of buildings experiences corrosion of concrete?
3. How many types of concrete structures experience corrosion of concrete?
4. Which type of concrete structure experiences the worst degree of corrosion?
5. How many types of corrosion patterns are there?
6. Are the corroded concrete structures renovated right away when detected?

Topic: Causes of concrete corrosion

1. Do buildings in different locations experience the same degree of corrosion?
2. Do concrete structures near the shore experience a higher degree of corrosion than buildings further from the shore?
3. Does corrosion in different types of concrete structures have the same cause?
4. What are some external factors that you think play a part in the corrosion of concrete structures?
5. Are there any major changes or renovations that enhanced the degree of corrosion of concrete structures?
6. What types of renovations have been done to different concrete structures?
7. What is the composition of the concrete that is used for construction at the Palace?
    a. What type or brand of cement?
8. Which concrete structures contain steel reinforcement support or rebar?
    a. Do concrete structures that contain steel reinforcement support or rebar experience a higher degree of corrosion than ones that do not contain steel?

Second Palace Visit Interview Questions

1. Does the Palace Foundation prefer we focus on restoring the concrete to its original form, maintaining the concrete's current material and only filling in the cracks, protecting the concrete against further corrosion, or some combination of the three?
2. How does the Palace Foundation know what's causing the corrosion? Are there any areas you are unsure about?

3. We are going to study the concrete deterioration of other seaside households as well to see if the problem is similar to the Palace, so our suggestion may be useful for both the Palace and the community.
   What types of buildings in Cha-Am should we be looking at for concrete deterioration?
   a. I.e. old beach houses, condominiums, businesses, houses
   b. Modern vs. old
4. Are issues with concrete corrosion on buildings often discussed in the community? Has anything been done to address it in the past?
5. What might be the best way to distribute our findings to the community? Is there a community website we could post to
6. What are the literacy and education levels of the local community? How can we make this accessible for everyone?
7. Are there any organizations or personnel that conduct related community work such as city officials that you recommend we reach out to and have the contact information for?

The following questions on the survey were completed by the directors and staff at the Mrigadayavan Palace Foundation. The google form survey can also be accessed here through the following link as well:
https://docs.google.com/forms/d/e/1FAIpQLSfFDvA9z7Uuk3t0GbRK5UK0pydkVje18syYmtvpr0NvF2WSXQ/viewform?usp=sf_link

Survey Questions on Languages Proficiency and Technical Knowledges (แบบสอบถามเกี่ยวกับทักษะภาษาและความรู้เฉพาะทาง)

Topics: Background Information (ข้อมูลพื้นฐาน)

1. Age (อายุ)
2. Gender (เพศ)
3. Roles at the Mrigadayavan Palace (บทบาทหน้าที่ของท่านในพระราชนิเวศน์มฤคทายวัน)
4. How many years have you been working at the Mrigadayavan Palace? (ท่านทำงานที่พระราชนิเวศน์มฤคทายวันมาแล้วกี่ปี)
5. How many hours per day on average do you spend working at the Mrigadayavan Palace? (จำนวนชั่วโมงต่อวันที่ท่านทำงานที่พระราชนิเวศน์มฤคทายวัน)
6. Highest educational level (วุฒิการศึกษาสูงสุด)

Topics: Language Proficiency (ทักษะทางด้านภาษา)

7. What is your native language? (ภาษาแรกของท่านคืออะไร)
8. English Proficiency (ทักษะทางภาษาอังกฤษ)
   a. Listening (การฟัง)
   b. Speaking (การพูด)
   c. Reading (การอ่าน)

    d. Writing (การเขียน)
9. Thai Proficiency (ทักษะทางภาษาไทย)
    a. Listening (การฟัง)
    b. Speaking (การพูด)
    c. Reading (การอ่าน)
    d. Writing (การเขียน)

Topic: Technical Knowledge (ความรู้เฉพาะทาง)

10. Do you understand the following topics? Select all the topics you understand.
    (ท่านมีความเข้าใจเกี่ยวกับหัวข้อต่อไปนี้หรือไม่ เลือกหัวข้อทั้งหมดที่ท่านเข้าใจ)
    a. Concrete's components (ส่วนผสมของคอนกรีต)
    b. Building construction using concrete (การก่อสร้างอาคารโดยใช้คอนกรีต)
    c. Factors that make concrete corrodes (ปัจจัยที่ทำให้คอนกรีตผุฝังหรือเสื่อมสภาพ)
11. Do you understand any of the following conventional methods of repairing concrete cracks? Select all the methods you understand.
    (ท่านมีความรู้ความเข้าใจเกี่ยวกับวิธีการซ่อมซ่อมแซมคอนกรีตแบบดั้งเดิมต่อไปนี้หรือไม่ เลือกหัวข้อทั้งหมดที่ท่านเข้าใจ)
12. How well do you think you understand cathodic protection techniques?
    (ท่านคิดว่าตนเองเข้าใจเกี่ยวกับวิธีแคโทดิกสำหรับป้องกันสนิมมากน้อยแค่ไหน)
13. How well do you think you understand re-alkalization techniques?
    (ท่านคิดว่าตนเองเข้าใจเกี่ยวกับวิธี re-alkalization สำหรับป้องกันสนิมมากน้อยแค่ไหน)
14. How well do you think you understand about chloride extraction techniques?
    (ท่านคิดว่าตนเองเข้าใจเกี่ยวกับการสกัดคลอไรด์ไอออนออกจากคอนกรีตมากน้อยแค่ไหน)
15. How well do you think you understand self-healing concrete?
    (ท่านคิดว่าตนเองเข้าใจเกี่ยวกับคอนกรีตซ่อมแซมตัวเองมากน้อยแค่ไหน)

C. Effect of External Factors on Concrete Columns Sampling Methodology: Usage of Metal Detector and Qualitative Analysis

Context and Goal:

- The Mrigadayavan Palace is divided into many different sections and different sections contain many columns. The columns in each section have different types of cracks and degrees of corrosion. The goal of the sampling methodology was to collect both quantitative and qualitative information that allows the team to analyze the cause of the corrosion and degree of corrosion in concrete columns. However, the records of renovation time for many of the sections are unknown making it difficult to analyze any information that is collected to come up with an accurate conclusion without the records of renovation time. Therefore, the team picked sections of the Palace that have records of the most recent renovations. The specifics of the section are mentioned below in the sampling methodology section.

Sampling Methodology:

- *Step 1:* Divide the area of the Palace sampled into 3 areas. The specifics of the map can be seen in *Figure 8* in the booklet which contains legends:
    - Area 1:
        - C: Stairs and walkway down to the northern seaside room
        - D: Corridor connecting the northern male bathing room
        - 5: Front bathing room
    - Area 2:
        - F: The corridor connecting the front of the throne - the inside
    - Area 3:
        - H: Stairs and walkway down to the southern seaside room
        - J: Corridor connecting the southern seaside room
        - 11: North seaside room
- *Step 2:* Use qualitative observation methods to locate the concrete columns that contain cracks in Area 1 and note both the degree of corrosion and the location of the cracks.
- *Step 3:* Use the TX-2002 metal detector with detection range of three to six centimeters depth to scan all the concrete columns in Area 1 to determine the existence of steel reinforcement.[2]
- *Step 4:* Repeat steps 2 and 3 for Area 2 and Area 3.
- *Step 5:* Analyze the collected data from all three of the Areas to see how much effect the external factors have on the concrete columns.

D. Crack Map

To collect data from these sample locations, every crack of the selected sample deteriorating concrete structure has to be noted. A measuring tape can be used to follow the length and shape of the crack. It is also important to measure the width of a crack at its largest point. This can be measured using a crack width ruler, as seen in *Figure S2*, if it is available, or by using a normal ruler. The measured cracks are then displayed on a crack map, as seen in *Figure S3*, of the concrete structure in a sample section. This fieldwork is not season-dependent, so it can be done anytime when there is enough light to see the space well. Temperature and humidity are not critical factors that will change day-to-day, so they can be omitted in this procedure. The data collection process should also record any signs of rust, change in the appearance of the concrete structure, or visible steel reinforcement.

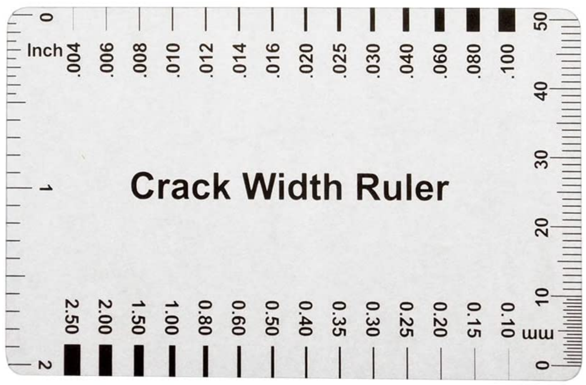


Figure S2. Crack Width Ruler[3]

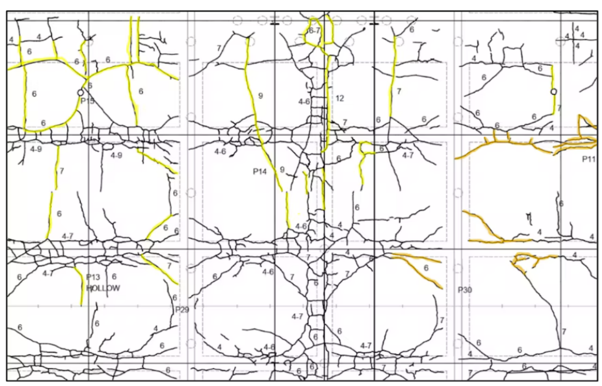
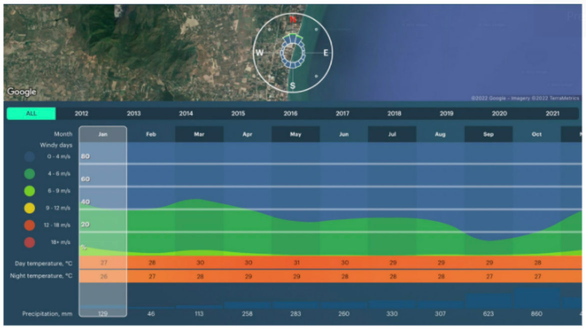


Figure S3. Color Coded Crack Map[4]

E. Graphical Data on Wind Direction and Speed

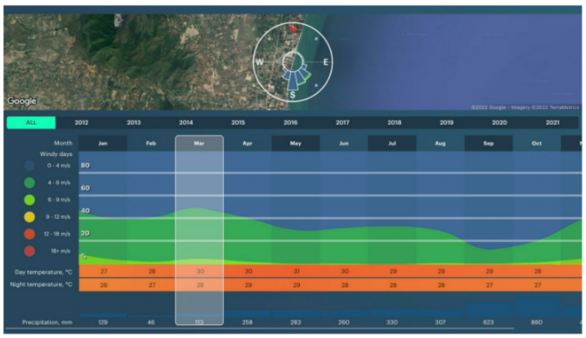
Graphical data on wind direction and speed around the Palace was collected. Specifically, the area where the data was collected is Cha-Am - Thailand. This is the area with the closest proximity to the Palace that has data available. The graphical data that is shown in *Figure S4-6*. were the average wind direction and speed from 2012-2021. By taking a closer look at the graph, there will be a few important aspects that must be pointed out. The first important aspect is the circular graph on top of each of the month's graphical data. In each of the circular graphs, there will be blue bars or green bars that pop out from the center of the graphs. The direction that the bars point to represents the direction of the flow of wind in the area. The height of the bars represents the amount of time that the wind flows into that specific direction. An interpretation could be made that the higher the bar, the more amount of time that the wind flows into that specific direction. The second important aspect is the color of the bars. The bottom part of the graph shows a few different layers of colors. The layers of color can be matched with the scale on the side to figure out the specific speed of the wind in a specific direction.

The interpretation for the wind direction and speed based on *Figure S4-6.* will now be discussed in detail. The summary of the graphical data that was mentioned in the findings and analysis earlier stated that eight out of the twelve months of the year, the wind's direction flows directly into the Palace from either the north or the south. These 8 months are May, June, July, August, September, October, November, and December. The other 4 months where the effect of wind is not as strong as these 8 months and does not flow directly into the Palace are January, February, March, and April. A general trend could also be stated that the bars in these 8 months are also higher than the other 4 months as well. Another general trend that could be stated is that the green bars are also mostly located in these 8 months, especially in November and December. The interpretation of these graphical data supports the assumption that wind is one of the causes of horizontal cracks because the number of months that wind flows directly into the Palace doubles the months that wind flows out of the Palace.



January

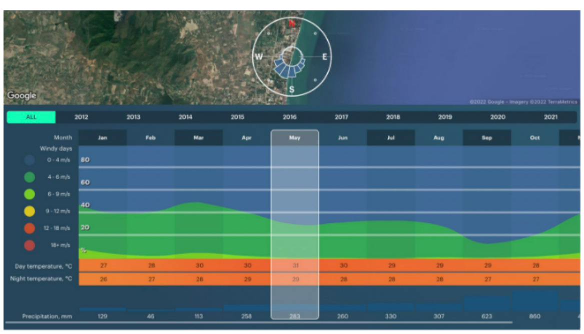
February



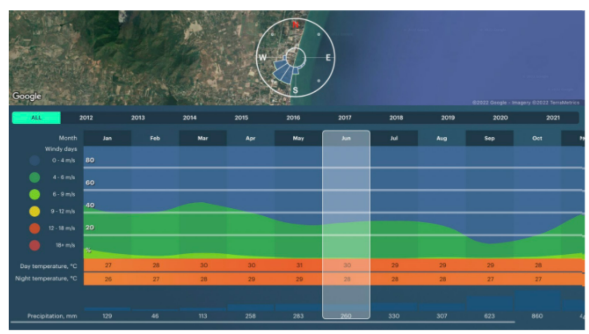
March

April

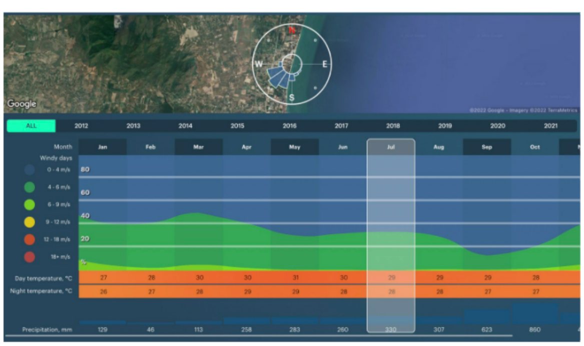
Figure S4. Detailed Graphs on Direction and Speed of Wind from January to April



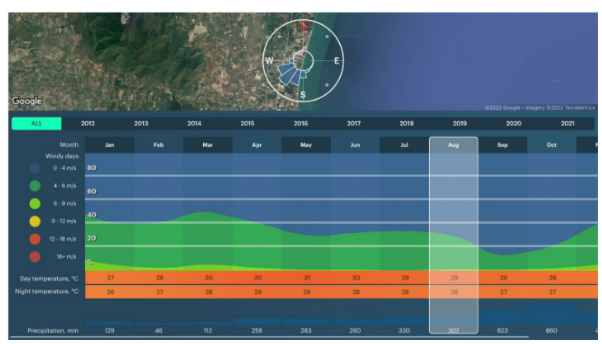
May



June

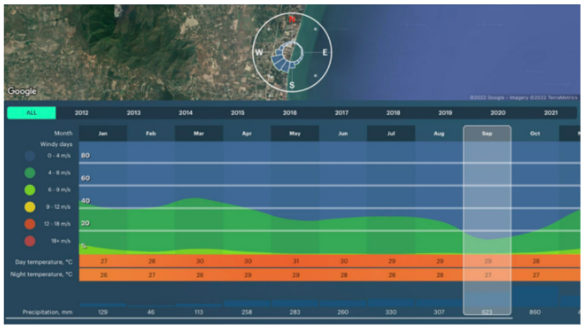


July



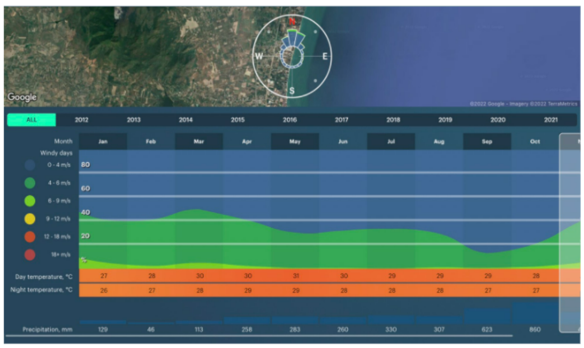
August

Figure S5. Detailed Graphs on Direction and Speed of Wind from May to June

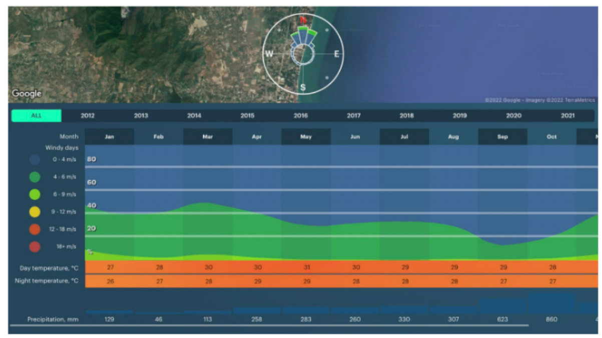


September

October



November



December

Figure S6. Detailed Graphs on Direction and Speed of Wind from September to December

F. Supplemental Criteria Table

Table S1. Supplemental Criteria Table

Method		Ease of Implementation		Implementation Time		Longevity	Aesthetics	Historical Accuracy	Deterioration Type	Advantages	Disadvantages	Repair or Protect
		Availability of Materials	Expertise Needed	Manpower	Time until Usability							
Jacketing	Reinforced Concrete Jacketing	Steel rebar is widely available and pre-cast concrete/ shotcrete is low- cost	Qualified and experienced engineers or specialists	Up to 17 days of work	28 Days	Typical service life - 50 years	New concrete will be lighter in color than the existing concrete, column width will be increased	Concrete can be matched in material and color	Spalling, cracking, major deterioration	Columns gain 100% of initial strength	High increase in space around column	Repair
	Reinforced Concrete Wire Mesh Jacketing	Wire mesh is widely available and pre-cast concrete/ shotcrete is low- cost	Qualified and experienced engineers or specialists	Up to 17 days of work	28 Days	Typical service life - 50 years	New concrete will be lighter in color than the existing concrete, column width will be increased	Concrete can be matched in material and color	Spalling, cracking, major deterioration	Columns gain 45% of initial strength	Weaker than jacketing with steel rebar, high increase in space around column	Repair
Injections	Epoxy	Cleaning equipment, surface-mounted injection ports, injection equipment - easily found, may be expensive	Experience preferred but not required	A day	Up to 12 hours	5 years	Epoxies are not concrete and will look different than the surrounding concrete, may need finish and paint	Epoxies can not be matched to concrete and are not historically accurate, they do not change the makeup or style of the column	Floor and column cracks without further deterioration - cracks 0.002 in. (0.05 mm) in width or greater	Epoxies have slightly greater compression strength than concrete	If the cause of cracking is corrosion of the reinforcing steel or if movement of the concrete is anticipated after repairs, epoxy injection may not be the best solution to the problem	Repair
Cathodic Protection	Impressed Current Cathodic Protection	Requires state-of-the-art power supplies and monitoring equipment capable of delivering milliamp precision protection currents	Qualified and experienced engineers or specialists	Time to apply permanent galvanic anodes and connected power source, on-going monitoring and maintenance	Immediate polarization with power source	20-30 years with maintenanc e	Wiring may be visible, anodes can be placed discreetly or be embedded	Not for historical accuracy, no need for physical alterations of material	Significant signs of leaks, cracks, delaminated concrete, and corrosion	No other method is capable of reversing the damage caused to the passivation layer of the steel reinforcement with such efficiency for an extended period of time	Impressed current cathodic protection systems are not recommended for general usage on prestressed concrete structures because hydrogen produced can make the high-strength steels brittle in nature	Protect

	Galvanic Corrosion Protection	Anodes are widely available	Somewhat qualified and experienced engineers or specialists	Time to apply permanent galvanic anodes, on-going monitoring	2 to 4 weeks until complete polarization	10-20 years	Anodes can be placed discreetly or be embedded	Not for historical accuracy, no need for physical alterations of material	Corroded steel rebar, can be combined with jacketing to prevent deterioration in a marine environment			Protect
	Fusion anodes	Requires power supply and anodes - available, power supply may be expensive	Qualified and experienced engineers or specialists	Time to apply permanent galvanic anodes and connected power source, on-going monitoring	Immediate polarization with power source	10-20 years	Anodes can be placed discreetly or be embedded	Not for historical accuracy, no need for physical alterations of material	Corroded steel rebar, maintains passive layer after initial polarization	Combines the power of impressed current cathodic protection with the maintenance free performance of galvanic anodes		Protect
	Chloride Extraction	DC power supply is connected to the reinforcing steel, positive terminal of an anode in electrolyte medium is applied to the surface of concrete	Minimal	hours - 1 day	3-8 weeks until full chloride extraction	5-20 years depending on further exposure	No change to physical appearance	Preserves the existing concrete from discoloration and corrosion	Mitigates active corrosion	Non-destructive	Dependent on treatment density, distribution of chloride ions, permeability, electrical resistivity	Protect
	Re-Alkalization	Electric field between the reinforcement and the concrete with an externally mounted anode mesh	Minimal	hours - 1 day	1 week	5 years post re-alkalization brings to initial corrosion rates	No change to physical appearance	Chemical change but no physical change	Mitigates active corrosion	Re-establishes a high pH environment and repassivating the reinforcing steel	Does not fix cracks or deterioration, purely preventative	Protect
Concrete Finishes		Can be very difficult and expensive to match and find the correct materials	Concrete Matching Expertise	1-3 days	2 weeks to match concrete 3-4 days to walk on 28 total days to be fully cured once laid	10 years	Vary depending on implementation of stain, texture, and concrete matching. Overall, finishes are for aesthetic purpose	If professionals are working on concrete matching, the historical accuracy will be as close as possible.	N/A, this is largely an aesthetic procedure			Protect

Partial-Depth Repair		Materials include compressible material, cement, light jack hammers and milling machines, cleaning equipment - actual repair materials can easily be bought from a concrete manufacturer	Workers with experience in concrete removal, mixing, placing, and curing	1-3 days	Curing time dependent on type of concrete	5-15 Years	May be rougher than surrounding pavement, concrete color can be matched, can be smoothed down	Concrete can be matched in material and color	Cracks, spalling, and joint deterioration in top half of walkways	Solves issue of thermal expansion by inserting compressible materials between new concrete and old slab	Not useful for spalling of transverse or longitudinal cracks caused by shrinkage, fatigue, or foundation movement	Repair
Self-Healing Concrete		Materials include dry portland cement powder, DI water, and Carbonic anhydrase that can be purchased through Sigma-Aldrich	Some chemical knowledge as well as lab materials would be required. Set up and development of concrete paste most likely not feasible without a science background	1-2 hours	28 days	Research is still being completed	Concrete color will be lighter compared to the surrounding concrete. Finish will be needed for aesthetic purposes	Concrete will not be matched accurately because portland cement and water are the only add mixtures used	small cracks 3-4 mm	Inexpensive compared to other methods	Can not be used for long or thick cracks. The development of the concrete material requires the ability to pipette enzymes and a lab. This is not feasible by the Palace	Repair
Concrete Overlay		Materials bought from a concrete manufacturer, geotextile material easily bought as well	Workers with experience in concrete mixing, placing, and curing	Hours, cracks may need patching beforehand, if using unbonded overlay a geotextile material will need to be laid down	24-48 hours until set and 28 hours until fully set	20+ years	Concrete material and color can be developed to match the former concrete, 51-254 mm (2-10 in)	Materials can potentially be found that are from the time period desired,	Cracks and spalling, bonded overlay needs good conditions and is for surface distress, unbonded overlay can work for more major deterioration	Accurately restores the look of concrete as well as the function in an aesthetically pleasing way	Potentially adds thick concrete to a walkway. Needs to repair all sidewalks to keep even structure	Both, mostly aesthetic
Sealants	Cold-applied thermosetting sealants	Somewhat expensive material but low labor and equipment costs and very little time required each day, requires cleaning and applying	Absolutely no expertise needed	Less than a day	Minutes to hours	4-7 years, silicone may last longer and has strong resistance to weathering	Relatively thin, different material than the concrete, overlay may be used as historically accurate cover	Not for historical accuracy, overlay may be used as historically accurate cover	Preventative - reduces moisture and chemical attacks, most effective when performed on concrete pavements that exhibit minimal structural deterioration and when the cracks are relatively narrow with minimal spalling and faulting, width <13 mm		Does not strengthen material, purely for waterproofing and filling surface cracks	Both

G. Definitions and Explanations to Support Decision Tree

Cracks:

A complete or incomplete separation of concrete into two or more parts produced by breaking or fracturing.[5] Cracks have been categorized into large and small sized cracks. Small cracks are less than three millimeters, as seen in *Figure S7* and a large crack is larger than three millimeters, as seen in *Figure S8*.

Figure S7. Small Crack

Figure S8. Large Crack

Spalling:

A phenomenon where concrete breaks, peels and chips away from the structure usually due to rusting of steel within the concrete which expands outwards causing cracks. The cracks begin below internally and lead to surface damage.[6] This is different from cracking as can be seen in *Figure S9*.

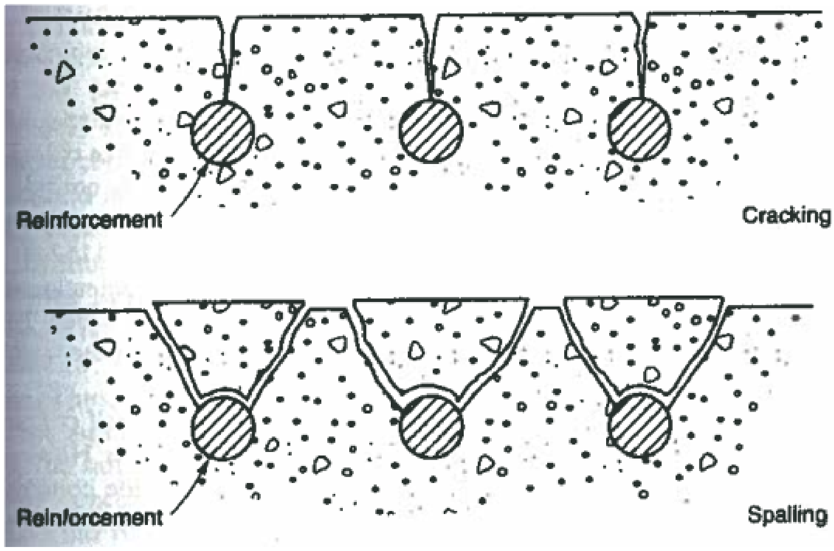


Figure S9. Cracking versus Spalling[7]

Major: characterized by breaking, peeling, and chipping that exposes the steel reinforcement of the concrete. Major spalling leads to exposed steel reinforcement as seen in *Figure S10.*

Figure S10. Major Concrete Spalling

Minor: characterized by superficial peeling and chipping that does not expose the steel reinforcement of the concrete. An example of minor spalling can be seen in *Figure S11*.

Figure S11. Minor Spalling

Chipping:

Defined for the purpose of this project as the breaking away of concrete in small sections from the structure, usually at an edge or corner, due to external factors as opposed to from spalling. This can be seen in *Figure S12*.

Figure S12. Concrete Chipping

Passivation Layer:
An alkaline iron oxide film surrounding the steel rebar which protects against corrosion.[8]

Electrochemical Chloride Extraction (ECE):
ECE is a temporary process that extracts or removes chloride ions from chloride-contaminated reinforced concrete structures to restore the passivation layer. The process of ECE requires applying an external anode in an electrolyte medium to the surface of the concrete. A DC power source must then be connected with the positive terminal attached to the external anode and the negative terminal attached to the steel rebar serving as a cathode. A current is then applied which draws the chloride ions to the anode and out of the concrete. Additionally the formation of hydroxide ions during the process helps rebuild the passive layer and create an alkaline environment around the steel. After the process is completed the anodes and power source are removed.[9] A clear illustration of the ECE mechanism as mentioned above can be seen in *Figure S13*. This is a temporary process to return the level of chloride ions in the concrete to below the point of causing deterioration. It does not prevent chloride ions from accumulating again in the future so it is best for extending the service life of steel rebar that is relatively undamaged.[10]

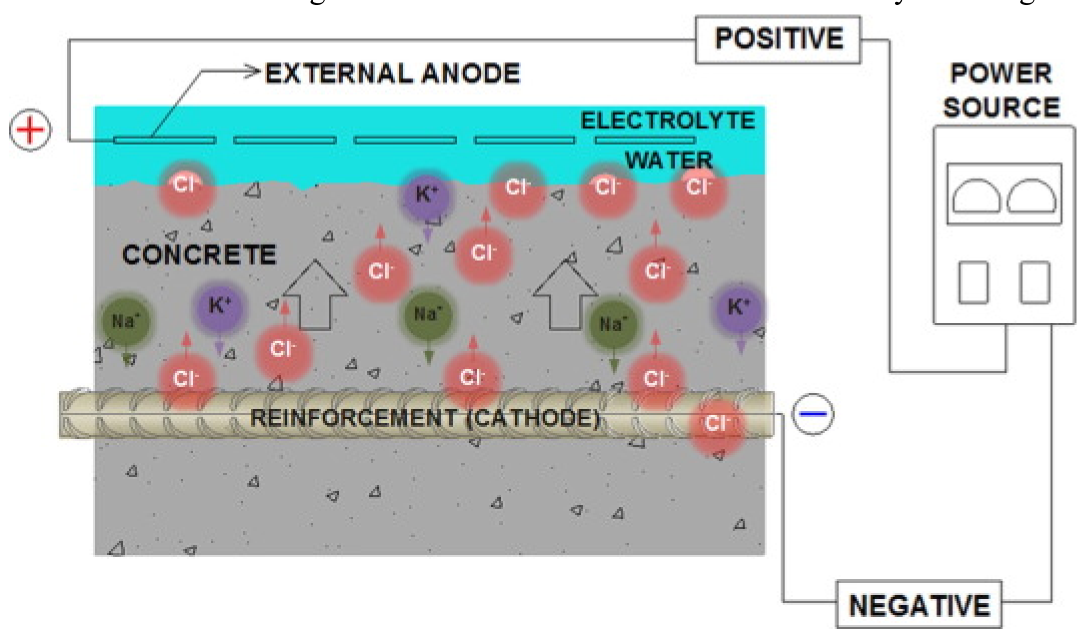


Figure S13. Chloride Extraction Mechanism[10]

Re-Alkalization:
Re-alkalization is used to restore the alkalinity and rebuild the passive layer in carbonated concrete. Like with ECE, re-alkalization involves passing an electrical current through concrete to the reinforcement using an external power source attached to an anode in an electrolyte medium such as sodium carbonate attached to the concrete's surface.[11] The connection of anode to a power supply can be seen clearly in *Figure S14*. In the case of re-alkalization, hydroxide ions are produced and move into the concrete from both the cathodic steel rebar and the alkaline external anode to rebuild the passive oxide layer. Additionally the alkaline electrolytes in

solution travel through the porous concrete increasing the alkalinity further. This requires no concrete removal and helps prevent further carbonation.[12]

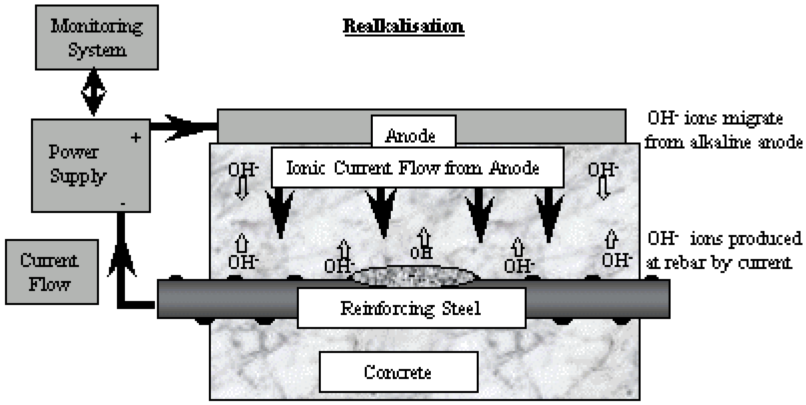


Figure S14. Re-alkalization Mechanism[13]

Cathodic Protection:

Cathodic protection is a method of reversing the damage caused to the passivation layer and preventing further corrosion of steel through the delivery of a positive current to the reinforcing steel. Some form of cathodic protection or chloride extraction is necessary when there are signs of steel reinforcement deterioration because the problem will persist if not properly addressed as seen in *Figure S15*. Severely corroded steel will need to be removed and replaced before any repairs can be done. Cathodic protection will not undo the effects of corrosion, but will prevent further damage.

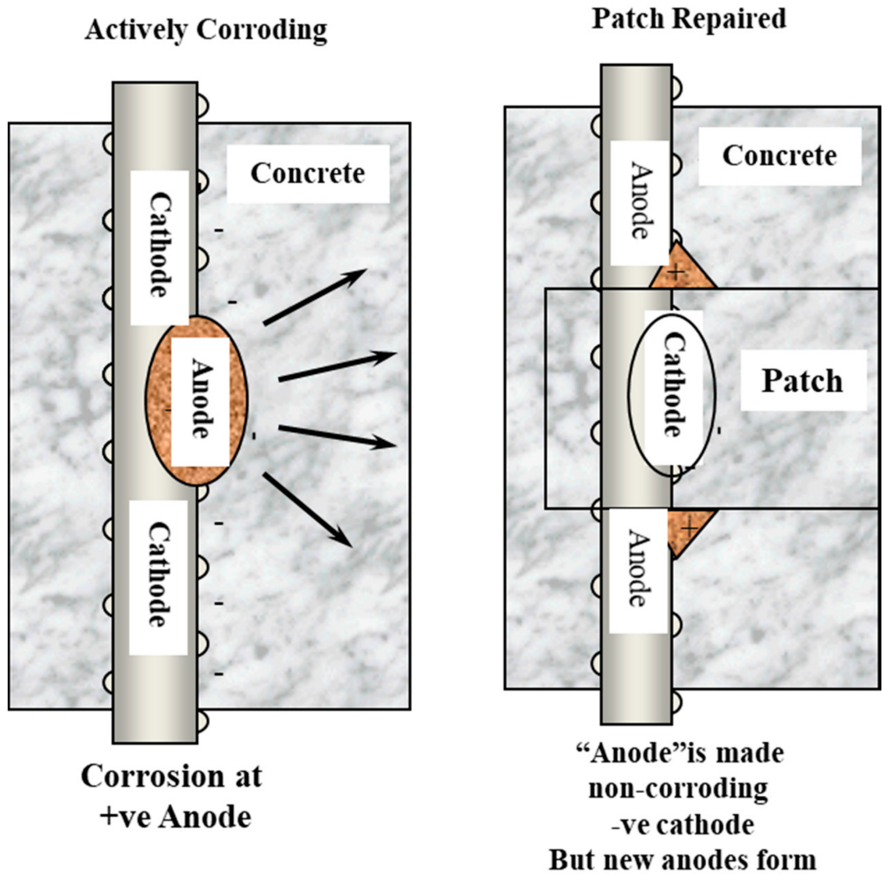


Figure S15. Active Corrosion versus Patch Repair in Reinforced Concrete[14]

Impressed Current Cathodic Protection (ICCP):

ICCP consists of permanent inert galvanic anodes and an external DC power source to supply the current. The inert anodes used may be titanium mesh, conductive ceramics, or conductive coatings applied to the outside of the concrete or discretely embedded. An impressed current turns the embedded steel into the cathode of an electrical cell with a constant current of electrons being supplied from outside the concrete to the steel which diminishes the reactivity of the steel rebar and prevents rusting.[15] A clear illustration of how the embedded steel is protected through impressed currents can be seen in *Figure S16.* The power supply must be monitored and extremely precise in its delivery of milliamp currents. Due to the nature of a constant externally sourced current, ICCP is better for extreme levels of chemical contamination and corrosion than galvanic corrosion protection.[16]

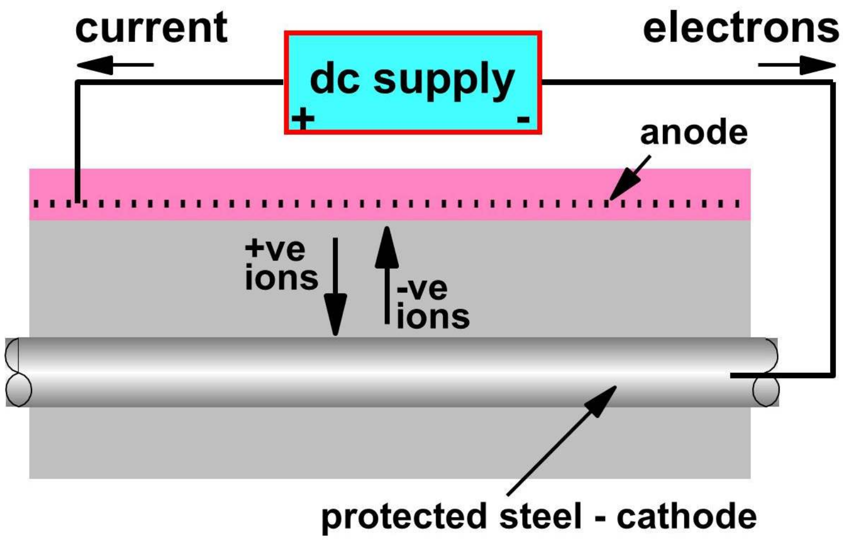


Figure S16. Impressed Current Cathodic Protection Mechanism[17]

Galvanic Corrosion Protection: This method utilizes galvanic anodes which are metals with sufficient voltage difference with respect to the corroding steel in order to deteriorate more easily making them "sacrificial" anodes. These anodes are able to generate a protective current without an external power supply. Usually the anode chosen is zinc which generates a sufficient current over a long period of time making it an effective "sacrificial" anode. The anodes can be placed using one of two systems: discrete anodes or distributed anodes. Discrete, or embedded, anodes are either tied to exposed reinforced steel before repairs or inserted by drilling holes into existing concrete surrounding repaired sections. Distributed anodes are placed over a wide area through some form of metallic coating or mesh.[18] Distributed anodes can be combined with concrete jacketing by embedding them in the concrete jacket to provide a method of both repair and protection.[19]

Figure S17. Discrete Anode Tied to Steel Rebar[18]

Fusion Anodes: Hybrid system that combines the efficiency and longevity of impressed current cathodic protection. This system works based on a two–phase protection. Phase 1 delivers an intense electrical current to the reinforcing steel and restores the passive layer. Phase 2 utilizes discreet galvanic anodes to protect the structure from future corrosion. This system provides both long–term and maintenance–free protection.[18]

Reinforced Concrete Jacketing:

This method reinforces columns with steel rebar by adding a layer of concrete reinforced by longitudinal steel reinforcements and traversing steel ties around the original column in the form of a jacket. Reinforced concrete jacketing is used when there is damage to a reinforced concrete due to environmental wear and tear as well as poor construction, poor maintenance or accidents. Jacketing is a process that restores deteriorated concrete to original dimensions or increased in size by encasement using suitable materials. To perform jacketing, a steel reinforcement cage is constructed around the damaged section and then, shotcrete or cast-in-place concrete is placed.[20]

For reinforced concrete jacketing, a professional structural engineer must carry out this procedure due to the necessary calculations. Typically reinforced concrete jacketing is done on columns with the longitudinal and lateral tie reinforcement, however for beams, as is shown in *Figure S18*. To perform the reinforced concrete jacketing on the beam, holes will need to be drilled through the concrete slab for the stirrups.[20]

Figure S18. Reinforced Concrete Jacketing on a Beam[20]

When creating this concrete jacket, the width of the jacket is typically more than 10 cm to allow for the concrete to be cast without voids or gaps. If using shotcrete, the jacket thickness can be as low as 5 cm but are usually closer to 7.5 cm or more. This thickness is to allow for the positioning of the longitudinal and transverse reinforcements, as well as some space between the new rebar and the existing concrete member.

Steps:

1. **Prepare the existing concrete member's surface** by cleaning it and roughening it to increase the strength of the concrete's bonds. The roughening of the existing surface as seen in *Figure S19*.[17]
2. **Install the new longitudinal steel bars and stirrups of the jacket** according to the designed dimensions and diameters. Particularly, it is important to ensure the closing of these hoops. If the width of the jacket does not allow for bending, welding the ends of the hoops together may be necessary.
3. **Consider any beam-column joint regions** where jacketing may be extended to. Drilling into a concrete slab may be required to extend the jacketing.
4. **Connect any existing rebars** in the concrete structure with the new rebar in the jacketing. Recently, steel dowels are considered to be a better method than U-shaped steel connectors or plates, since the welding of the often corroded, existing reinforcement is unreliable, or even impossible.
5. **Pour concrete** and let it set in a concrete mold around the reinforcement jacket.

Figure S19. The Roughening of an Existing Member's Surface[21]

Patching:

The application of concrete over minor cracks and holes in existing concrete structures. Concrete around the deterioration will need to be removed and the crack will need to be cleaned. A bonding material may be necessary.[22]

Patching steps:

1. **Remove any damaged or crumbling concrete**. Use a small sledgehammer and chisel to undercut the edges of the damaged area.
2. **Clean the concrete within and around the area of damage** with a wire brush and broom. Then wash the concrete with a concrete cleaner and water.
3. **Position the concrete patch form.** Use a board as a form by securing it against the side of the area intended for repair. Place bricks or heavy objects against the board to stabilize it. The top of the form should be flush with the desired height of the edge. Usage of form guides you to smooth the patch.
4. **Mix the concrete crack sealer.** Mix vinyl patching compound as directed by the manufacturer and trowel the compound into the area to be repaired. Tamp the mixture to remove air pockets. If mortar is being used instead of vinyl, either mix it with a bonding agent instead of water or coat the edges of the surface to be repaired with a bonding agent.
5. **Smooth the concrete patch** with the trowel using the top of the form as a guide.

Sealants:

Plastics or other polymers applied in joints or over surfaces to serve as protection against water and chemical attacks. Sealants work by filling in fine cracks or pores, creating a waterproof seal to prevent additional moisture from attacking the concrete. A grinder is typically used to widen the cracks in preparation for the sealant, as seen in *Figure S20, top*. Although sealant repairs can provide a durable, watertight repair for moving cracks, they tend to be very visible.[23]

Figure S20. Grinder Used in Preparation for Sealant (top). Sealant for Concrete (bottom)[22]

Epoxy Injection:

The injection through mounted ports of an epoxy to fill surface level cracks and provide minor reinforcements to deteriorated areas. Once the concrete has been cleaned, the process for injection can begin. Surface-mounted injection ports, seen in *Figure S21*, are installed along the cracks. The crack depth and width must be measured prior to injection to ensure the appropriate amount of epoxy is available. Epoxy is injected beginning at the lowest elevation and continuing to the next highest port once epoxy emerges at it. The epoxy injection must take into account aspects like pressure of the seal, type of resin used, and also if the crack is horizontal or vertical.[24]

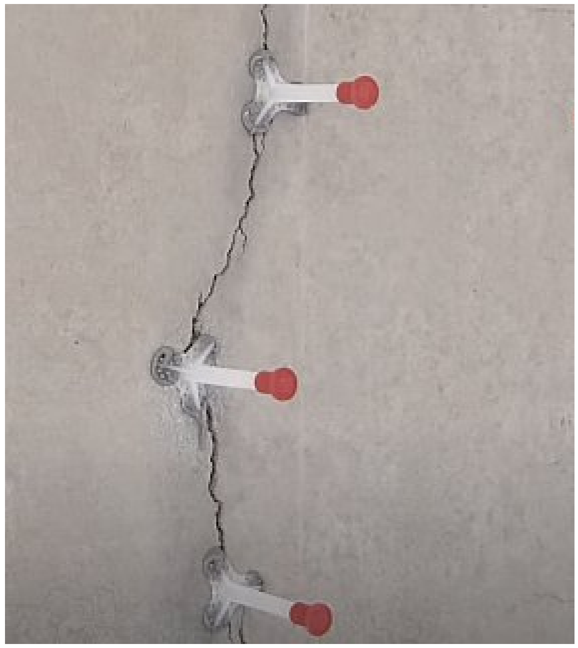


Figure S21. Surface-Mounted Injection Ports

Concrete Casting:

A method of fixing chipped concrete by either taking a mold of a missing section and filling it with concrete or by filling the holes that can easily be sectioned off with concrete directly. Concrete around the deterioration will need to be removed and the area will need to be cleaned. A bonding material may be necessary.[25]

Steps:

1. **Make a mold** of the missing section of chipped concrete **or section the hole off** with wood blocks.
2. **Mix the concrete** with water in a wheelbarrow or use a mixer.
3. **Pour the wet concrete** into the mold or into the missing section in the concrete columns. Make sure there are no voids or air pockets.
4. Use a large metal or wood board to **screed the top of the concrete layer**. Screeding helps compact and consolidate the concrete, and begins the smoothing and leveling process.
5. Next, **use a float to further compact the concrete**, even out any high or low areas, and create a smooth finish. Small hand-held floats are good for edges and detail work, large bull floats are best for working large areas.
6. If the concrete will receive a rough broom finish, no additional finishing may be needed. If the concrete will be smooth, toweled, or stamped, a steel trowel finish is needed. Let

the concrete rest until the surface begins to firm up. Once firm, **use a steel trowel to create a smooth, hard and uniform finish**.

7. Once all the troweling (float or steel) is complete, **the final finish can be applied to the concrete**. The most basic type of finish is known as a "broom finish". A special broom is pulled across the concrete surface creating a rough textured surface. Other types of finishes include stamped, textured, or smooth trowel.
8. Next is the curing step. **Let the concrete rest and begin to cure**. The curing process lasts 28 days, with the first 48 hours being the most critical. Apply a liquid chemical curing and sealing compound to help the concrete cure slowly and evenly, which helps reduce cracks, curling, and surface discoloration. You can start to use your concrete for light foot traffic 3 to 4 days after placement, and you can drive and park on your concrete 5 to 7 days after placement.

Partial-Depth Repair:

Removal of small areas of deteriorated concrete found in only the top half of a walkway slab followed by the insertion of a compressible material between the new concrete and the old and then the subsequent application of a patching material to the area. A bonding material may be necessary and the concrete will need to be cleaned after the initial removal process.[26]

Steps:

1. **Determine repair boundaries** for where the partial-depth repair will happen. Taking the already identified area of deterioration, mark the area extending about two to four in beyond the visible distressed area.
2. **Concrete removal** uses either sawing and chipping with a jackhammer or milling to remove the concrete from the boundaries.
3. **Repair area preparation** through sandblasting or other compressed airblasting to ensure an adequately clean surface.
4. **Prepare joints** because this is often the greatest way that this method of repair fails. To prevent this failure at the joints, a strip of polystyrene or polyethylene compressible material is typically placed in the joint to act as a bond breaker.
5. **Apply a bonding agent** to the surface of all vertical and horizontal surfaces. This bonding agent is often a cement grout that ensures complete bonding of the repair material to the surrounding concrete. This should be placed immediately before a repair is done.
6. **Apply a patching material** to the area.
7. **Cure the concrete** by applying a white-pigmented curing compound as soon as water has evaporated from the repair surface.
8. **Seal the joint** to prevent any further spalling[26]

Concrete Overlay:

The application of a thin concrete layer (at least 51 mm thick) to a walkway slab. Cracks may require patching before-hand and if using an unbonded overlay (for areas of greater deterioration) then a geotextile material will need to be laid down first. Concrete overlays require uniform support conditions and effective management of movement in the design process. There are both bonded and unbonded overlay options, both are shown below in *Figure S22*.[27]

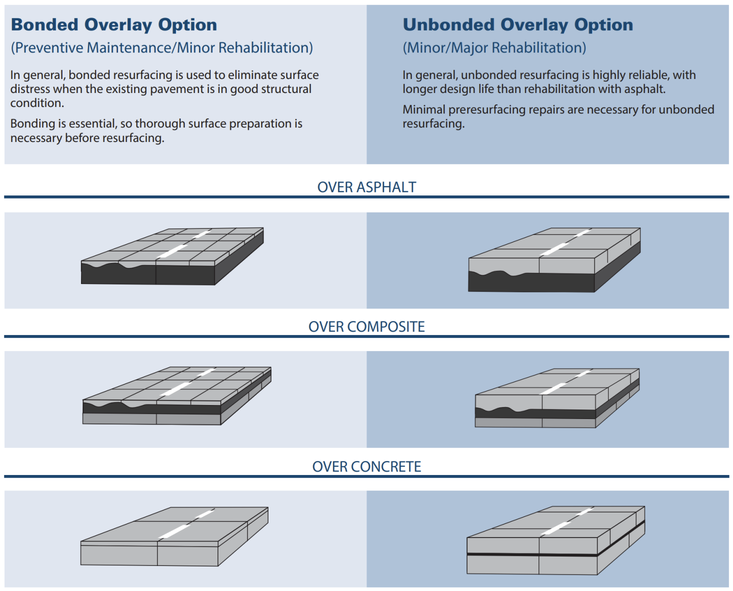


Figure S22. Bonded and Unbonded Overlay Options

H. Concrete Matching Process

The process of concrete matching requires the expertise of professionals as well as a long implementation period. There are three steps to the concrete matching process:

1. **Source assessment:** Try to find documentation on what materials were used for the project in its original construction
2. **Visual assessment:** Measure and document color of concrete and size and shape of aggregates and their breakage
3. **Geographical assessment:** Send a sample of the building's original concrete to geologists and have them analyze the kind of rock, its hardness and color to then locate the aggregate's original geographical location

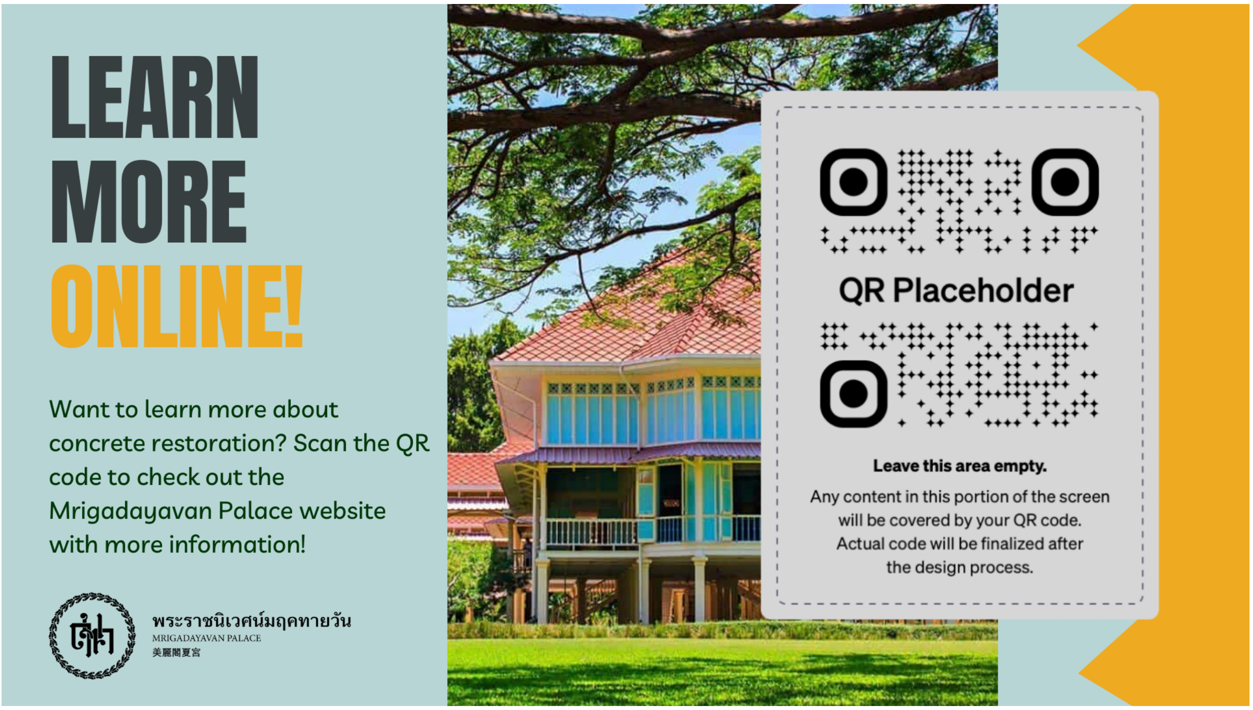
When the historically accurate materials of cement, aggregate and sand are gathered in correspondence to the assessments listed above, then trail slabs can be created. These trial slabs will be generally small in size and have a variety of variations in the mixes to find best fits for color, aggregate size, and texture. These slabs of different mixes then allow for variations in surface on different parts of the Palace to be considered. A surface out of the sun and farther from the coast will have a different look of concrete than one right on the coast in direct sun all day. The trial slabs are left out in the concrete's future site for several weeks. An example of trial slabs used in concrete matching are shown in *Figure S23*.[28]

Figure S23. Samples of Trial Mixes Placed Next to the Existing Concrete to Determine the Best Match

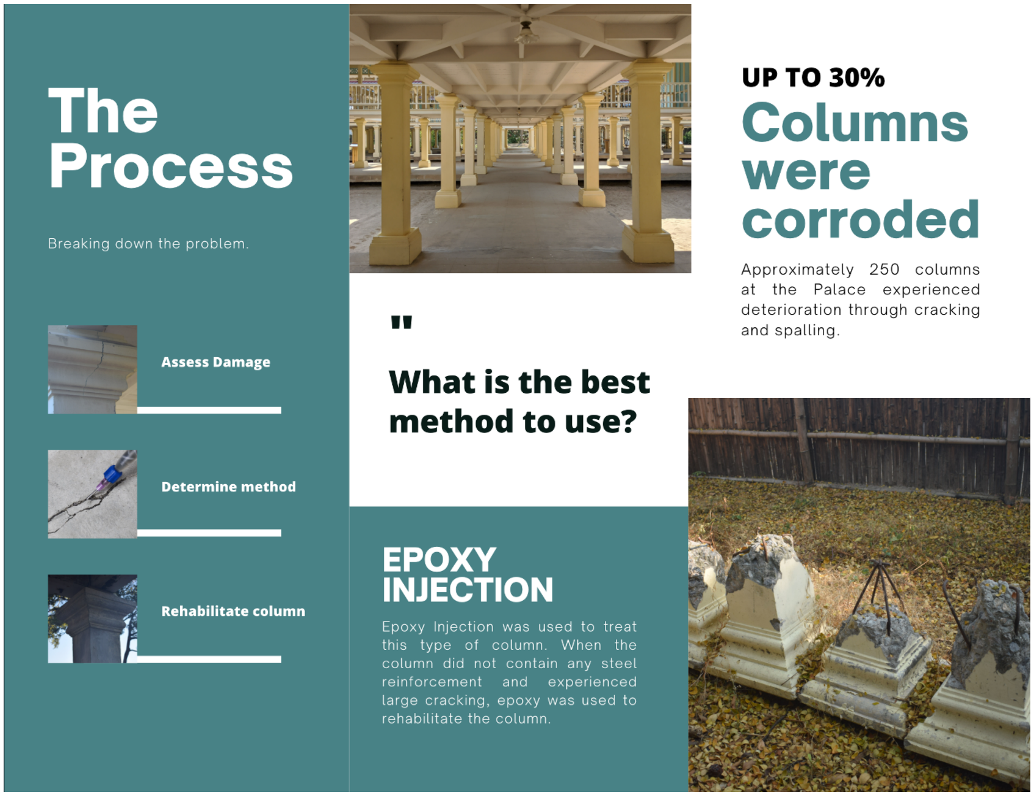
To create a repair mix, various slabs of concrete are mixed and the trial mix slabs are placed next to the existing concrete to determine the best color and texture match. An additional step is to 'finish' the surface of the concrete. This means that you must erode the concrete surface to expedite the aging process to help match the original older concrete, a similar process can be seen in *Figure S24*.[28]

Figure S24. Proper Aggregate Exposure Achieved by Spraying the Surface with Water, then Hand-Brushing off the Surface Mortar Layer Soon After Placement

I. Example of a QR Code Poster



J. Example of a Paper Pamphlet to be located at each QR Code



Bibliography (Supplementary Materials)

1. American Concrete Institute Committee 364. (1994). *Guide for evaluation of concrete structures prior to rehabilitation*. http://civilwares.free.fr/ACI/MCP04/3641r_94.pdf
2. Krêuuang dtrùuat jàp loh-hà TX-2002. SJ gadget. (n.d.). Retrieved February 21, 2022, from https://www.sjgadget.com/product/554/เครื่องตรวจจับโลหะ-tx-2002
3. FPrimeC. (2017, May 31). *3 methods for crack depth measurement in concrete*. FPrimeC Solutions Inc. Retrieved February 21, 2022, from https://www.fprimec.com/3-methods-crack-depth-measurement-in-concrete/#:~:text=Crack%20severity%20on%20the%20surface
4. Basham, K. (2021, March 1). *How to evaluate and troubleshoot concrete cracks*. For Construction Pros. Retrieved February 21, 2022, from https://www.forconstructionpros.com/concrete/equipment-products/repair-rehabilitation-products/article/21232603/how-to-evaluate-and-troubleshoot-concrete-cracks-recommendations
5. American Concrete Institute. (n.d.-a). *Cracking in concrete*. Www.concrete.org. https://www.concrete.org/topicsinconcrete/topicdetail/Cracking%20in%20Concrete?search=Cracking%20in%20Concrete
6. Daily Civil. (2020, September 2). *What is spalling of concrete - Its causes and repairs*. DAILYCIVIL. https://dailycivil.com/spalling-of-concrete-its-causes-and-repair/
7. TeamCivil. (2017, May 7). *Surface scaling and spalling of concrete*. Civil Engineering Forum. https://www.civilengineeringforum.me/surface-scaling-spalling-concrete/
8. Kryton Marketing. (2014, December 11). Simple science: Reinforced concrete corrosion. *Kryton Smart Concrete*. https://blog.kryton.com/2014/12/simple-science/
9. *Electrochemical chloride extraction [PDF]: Process, and applications*. (2020, April 21). The Constructor. https://theconstructor.org/practical-guide/electrochemical-chloride-extraction/5859/
10. de Almeida Souza, Luan. R., de Medeiros, M. H. F., Pereira, E., & Capraro, A. P. B. (2017). Electrochemical chloride extraction: Efficiency and impact on concrete containing 1% of NaCl. *Construction and Building Materials*, 145, 435–444. https://doi.org/10.1016/j.conbuildmat.2017.04.010
11. Banfill, P. F. G. (1977, June). Re-alkalisation of carbonated concrete — Effect on concrete properties. *Construction and Building Materials*, 11(4), 255–258. https://doi.org/10.1016/S0950-0618(97)00045-7
12. *Realkalization*. (2020, August 5). Corrosionpedia. http://www.corrosionpedia.com/definition/1259/realkalization

13. Hema, J., Guthrie, W., Assistant, F., Fonseca, P., & Associate. (2022). *Concrete bridge deck condition assessment and improvement strategies*. https://www.researchgate.net/publication/267786550_CONCRETE_BRIDGE_DECK_CONDITION_ASSESSMENT_AND_IMPROVEMENT_STRATEGIES
14. Broomfield, J. P. (2021). A historical review of impressed current cathodic protection of steel in concrete. *Construction Materials*, 1(1), 1–21. https://doi.org/10.3390/constrmater1010001
15. *How does impressed current cathodic protection work in concrete repair*. (2019, Nov. 6). https://www.vector-corrosion.com/blog/how-does-impressed-current-cathodic-protection-work-in-concrete-repair
16. Alhariri, E. (n.d.). *The case for cathodic protection of concrete in aggressive environments*. 5. https://structuraltechnologies.com/wp-content/uploads/2018/09/case-for-cathodic-protection-in-aggressive-environmnent.pdf
17. The Concrete Society. (n.d.). *Cathodic protection*. Retrieved February 26, 2022, from https://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=498
18. *Cathodic protection & concrete corrosion prevention*. 12 Feb. 2020, https://www.vector-corrosion.com/blog/cathodic-protection-concrete-corrosion-prevention
19. Whitmore, D. (2018). Galvanic cathodic protection of corroded reinforced concrete structures. *MATEC Web of Conferences*, *199*, 05006. www.matec-conferences.org, https://doi.org/10.1051/matecconf/201819905006
20. Constro Facilitator. (2020, September 4). Structural retrofitting and strengthening by jacketing. *Constro Facilitator.* https://www.constrofacilitator.com/structural-retrofitting-and-strengthening-by-jacketing/#:~:text=It%20consists%20of%20added%20concrete
21. Antoniou, S. (2021, December 17). Application of reinforced concrete jackets. *Seismosoft*. https://seismosoft.com/application-of-reinforced-concrete-jackets/
22. How to repair cracked concrete. (n.d.). Lowe's. Retrieved February 26, 2022, from https://www.lowes.com/n/how-to/simple-concrete-repairs
23. *Preservation brief 15: Preservation of historic concrete*. (n.d.). National Park Service. Retrieved February 26, 2022, from https://www.nps.gov/tps/how-to-preserve/briefs/15-concrete.htm
24. Mancs, L. (2018). *Concrete repair: Epoxy crack injection*. Concrete Preservation Alliance: We Save Structures. https://www.wesavestructures.info/epoxy-crack-repair

25. Sullivan, C. (2020, October 9). *Guide to pouring concrete*. The Concrete Network. https://www.concretenetwork.com/install-concrete.html
26. Frentress, D., & Harrington, D. (n.d.). Partial-depth repairs for concrete pavements. *CP Road Map*. https://intrans.iastate.edu/app/uploads/2018/08/MAPbrief7-2.pdf
27. *Concrete pavement preservation guide, second edition*. (2014, September). U.S. Department of Transportation Federal Highway Administration. https://www.fhwa.dot.gov/pavement/concrete/pubs/hif14004.pdf
28. Gaudette, P., Aspin, J., & Slaton, D. (1999). *Repairing historic concrete*. Concreteconstruction.net; The Aberdeen Group. https://www.concreteconstruction.net/_view-object?id=00000153-8bc0-dbf3-a177-9ff9bdea0000