

# SUSTAINABILITY FOR REPAIRING AND MAINTAINING CONCRETE AND MASONRY BUILDINGS

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**S**ustainability is meeting the needs of the present without compromising the ability of future generations to meet their own needs. The purpose of this white paper is to educate manufacturers, contractors, design professionals, and building owners on the benefits of sustainable maintenance, repairs, and adaptive use for concrete and masonry buildings.

## INTRODUCTION

Sustainability has encouraged a plethora of responses toward meeting the goals of living more gently with the Earth. The building industry has an undeniably important place in this dialog. As such, new technological solutions have emerged in all corners from cement production to high-rise building design, new and refined models have been developed to calculate efficiencies from cradle to grave, and clearer understandings have emerged that illuminate how we produce and interact with our built environment. These endeavors often highlight the inherent advantages of building with durable materials such as concrete and masonry. This paper will make the case that proactive protection, maintenance, and repairs offer the ultimate inherent sustainable advantages in terms of cost, longevity, energy, and even cultural responsibility.

Sustainable design and construction is a rapidly evolving area of importance to Architects, Engineers, Contractors, and Owners (A/E/C/O) and others involved in the design and construction industry. New building codes and certification programs attempt to define, and often place, different parameters around what is required for a building project to be considered “sustainable.” As sustainable design and construction practices continue to evolve, the repair project team will be faced with an increasingly diverse set of standards to apply to their projects.<sup>1</sup> Green building codes, such as the 2010 California Green Building Standards Code,<sup>2</sup> establish mandatory baselines for energy and environmental performance that all building projects are required to meet. The International Code Council (ICC) issued the 2012 International Green Construction Code (IgCC).<sup>3</sup> The IgCC is the first model code that includes sustainability measures for the entire construction project and its site, from design through construction, certificate of occupancy, and beyond. The new code is expected to make buildings more efficient, reduce waste, and have a positive impact on health, safety, and community welfare.

Sustainable design is moving into the mainstream of many jurisdictions and federal programs. Presidential Executive Order 13514,<sup>4</sup> “Federal Leadership in Environmental, Energy, and Economic Performance,” issued October 5, 2009, establishes an integrated strategy toward sustainability in the federal government. “The U.S. General Services Administration (GSA) is committed to achieving President Obama’s sustainability agenda. GSA will achieve a Zero Environmental Footprint (ZEF): it will eliminate its own impact on the natural environment, and use its government-wide influence to reduce the environmental impact of the Federal government.”<sup>5</sup> “GSA’s mission is to use expertise to provide innovative solutions for our customers in support of their missions and by so doing foster an effective, sustainable, and transparent Government for the American people.”<sup>5</sup> The impact that this mission presents is enormous to the built environment. As of September 30, 2010, the total space owned or leased by GSA was over 414 million ft<sup>2</sup> (39 million m<sup>2</sup>). The U.S. Army Corps of Engineers states, “As a prominent Federal entity, a key participant in the use and management of many of the Nation’s water resources, a critical team member in the design, construction, and management of military and civil infrastructure, and as responsive members of the Nation’s citizenry, the U.S. Army Corps of Engineers (USACE) strives to protect, sustain, and improve the natural and manmade environment of our Nation, and is committed to compliance with applicable environmental and energy statutes, regulations, and Executive Orders.”<sup>6</sup>

With broadening awareness and understanding, sustainable thinking demands that we consider repairing and preserving existing structures whenever possible, rather than building new, simply because of perceived need, technological “why not,” or misguided intentions. Some of the most useful, responsible, and durable building projects begin with existing structures. Blair Kamin, the Pulitzer Prize-winning architecture critic of the *Chicago Tribune*, puts the idea of a new, broader reality squarely in perspective in his discussion about preservation versus conservation (building green) when he suggests that these endeavors are really about the same ends. The argument is “not technical but cultural. It’s about how we live and how we ought to navigate between perilous extremes: not with overzealous ideology but with an enlightened pragmatism that reshapes and reinvigorates old ideals in response

to new realities.<sup>77</sup> The thoughtful extension of the life of existing structures through careful repair and a commitment to long-term maintenance is a responsible answer to the reality of reducing our impact on the environment.

Concrete and masonry are durable, ultimately energy-efficient, and versatile construction materials. Much of our historical built environment still standing today was built using concrete or masonry construction (or both). Most of the environmental impact of concrete and masonry components occurs during material manufacturing. For concrete structures, much of its impact is from the production of the cementitious binder and associated reinforcing steel, the mining and transport of aggregates, and the transportation of the mixed concrete to the job site. As a result, concrete possesses one of the highest embodied energy coefficients and carbon footprints of construction materials. After construction, the benefits of concrete and masonry materials' durability, low maintenance, thermal mass, flood/fire/decay resistance, and the environmental impact of concrete and masonry disposal can have less impact than other construction materials. The disposal of cementitious materials should account for their alkalinity and their potential for leaching some of their constituents. The recycling of cementitious materials can have a benefit of absorption of CO<sub>2</sub> and eventual neutralization of the high pH. Therefore, the longer these buildings can stay in service, the more the environmental impact is diminished over their full life cycle. Protective measures during construction and proactive maintenance can prevent the need for repairs and are ultimately the most sustainable approach. Repairs themselves contribute to a structure's overall environmental impact but are much less impactful than a "demolish and rebuild" approach that is often required for structures that have been allowed to deteriorate.

Because concrete and masonry are typically highly durable, they are frequently ignored until signs of deterioration are evident. When durability is compromised, it can be classified into root causes of design and construction errors or improper maintenance, damage, and deterioration—shortening the potential life cycle of structures. In terms of design and construction errors alone, visible defects in new construction often require repair while those that go unnoticed and remain out of view—such as inadequate concrete cover for reinforcing steel, improper consolidation, lack of attention to jointing details, and improper curing—can eventually lead to deterioration. A 1979 survey by the American Concrete Institute (ACI) estimated that 52% of concrete failure is discovered during construction.<sup>8</sup> Another study reported in the same publication states that many corrosion issues are preventable during construction by following good trade practices.<sup>9</sup> The lowest-cost technique to improve concrete durability in new construction is to merely follow good industry practices, such as use of proper mixture design, providing sufficient cover over reinforcement, and thoroughly curing the concrete. Similarly, proper design and construction of masonry buildings will greatly enhance durability in a cost-effective manner. With adherence to these best practices, concrete and masonry stand above many other construction materials in their ability to resist insect damage, fire, impact,

abrasion, moisture exposure, and other factors, provided these structures are systematically maintained.

The most effective sustainability strategy for concrete and masonry structures is to avoid the need for repairs altogether. The Building Research Establishment, a well-known entity in the United Kingdom, concurs that prevention through monitoring, inspection, and maintenance can result in a huge savings over the life cycle of a structure.<sup>10</sup> Investment in preventative maintenance results in shorter, less-disruptive interventions that are highly cost-effective over the life cycle of the structure compared to waiting until deterioration, such as that from reinforcement corrosion, has initiated. Addressing repairs after the deterioration has caused damage, which can be evident as rust weeping, spalling, cracks, and other processes, greatly increases the cost of mitigation. For example, keeping concrete dry minimizes freezing-and-thawing damage, alkali-aggregate reaction, most types of sulfate attack, deicer salt scaling, and carbonation. For new concrete construction of good quality, addressing cracks; providing treatment with penetrating sealers, coatings, or membranes; and other proactive maintenance over the life of a structure can postpone repair needs almost indefinitely. Similarly for masonry, proper water-shedding details and moisture protection measures will postpone the need for repairs.

The need for repair is never more evident than when considering the large scale of existing infrastructure. With each report card, the American Society of Civil Engineers (ASCE) estimates the investment needed in each infrastructure category to maintain a state of good repair. In 1988, when *Fragile Foundations* was released, the nation's infrastructure earned a "C," representing an average grade based on the performance and capacity of existing public works.<sup>11</sup> The 2013 report card gives the U.S.'s infrastructure a grade of D+ averaged over 16 categories. This rating estimates that the cumulative investment requirement, extended to the year 2020, is \$3.635 trillion in 2010 dollars (or greater than \$3100 per family in the U.S. per year) to return to a "B" grade. It further estimates that, despite an estimated spending of \$2.024 trillion, a shortfall of \$1.611 trillion will still occur compared to what is needed to restore our infrastructure to a "B" grade. Some of the statistics especially relevant to concrete construction include:

- Poor road conditions cost U.S. motorists an estimated \$101 billion a year in wasted time and fuel;
- Americans undertake over 200 million trips a day across deficient bridges. It is estimated that \$20.5 billion a year until 2028 is required to eliminate the nation's deficient bridge backlog;
- State dam safety programs have identified more than 4000 deficient dams, with 2000 classified as high-hazard; and
- In many cases, the inland waterways system has not been updated since the 1950s, and more than a half of the locks are over 50 years old.<sup>11</sup> Projects to repair and replace aging locks and dredge channels takes decades to approve and complete, so continued deterioration will likely continue, resulting in increased freight costs and environmental impacts.

The only categories showing a grade of “C” or better are bridges, public parks and recreation, rail, ports, and solid waste, yet even these relatively bright spots contain alarming details. The ASCE report card site states: “Usually built to last 50 years, the average bridge in our country is now 42 years old. According to the U.S. Department of Transportation, of the 607,380 bridges across the country as of December, 2012, 66,749 (11%) were categorized as structurally deficient and approximately 84,500 (13.9%) were categorized as functionally obsolete.”<sup>11</sup>

ASCE has developed three key solutions to begin raising the grades<sup>11</sup>:

1. **Increase leadership in infrastructure renewal:** “America’s infrastructure needs bold leadership and a compelling vision at the national level. During the 20th century, the federal government led the way in building our nation’s greatest infrastructure systems, from the New Deal programs to the Interstate Highway System and the Clean Water Act. Since that time, federal leadership has decreased, and the condition of the nation’s infrastructure has suffered. Currently, most infrastructure investment decisions are made without the benefit of a national vision. That strong national vision must originate with strong leadership at all levels of government and the private sector. Without embracing a strong national vision, the infrastructure will continue to deteriorate.”
2. **Promote sustainability and resilience:** “America’s infrastructure must meet the ongoing needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management, and at the same time protect and improve environmental quality. Sustainability, resiliency, and ongoing maintenance must be an integral part of improving the nation’s infrastructure. Today’s transportation systems, water treatment systems, and flood control systems must be able to withstand both current and future challenges. As infrastructure is built or rehabilitated, life-cycle cost analysis should be performed for all infrastructure systems to account for initial construction, operation, maintenance, environmental, safety, and other costs reasonably anticipated during the life of the project, such as recovery after disruption by natural or manmade hazards. Both structural and non-structural methods must be applied to meet challenges. Infrastructure systems must be designed to protect the natural environment and withstand both natural and manmade hazards, using sustainable practices, to ensure that future generations can use and enjoy what we build today, as we have benefited from past generations. Additionally, research and development should be funded at the federal level to develop new, more efficient methods and materials for building and maintaining the nation’s infrastructure.”
3. **Develop and fund plans to maintain and enhance America’s infrastructure:** “While infrastructure investment must be increased at all levels, it must also be prioritized and executed according to well-conceived plans that both complement the national vision and focus on system wide outputs...”

In terms of buildings, the National Trust for Historic Preservation provides the following illuminating evidence in favor of reusing existing structures rather than building new<sup>12</sup>:

- In terms of waste, construction of an average 2000 ft<sup>2</sup> (190 m<sup>2</sup>) home generates 3000 lb (1400 kg) of wood waste, 2000 lb (900 kg) of drywall waste, and 600 lb (270 kg) of waste cardboard. Moreover, the construction of an average single-family home generates 4 lb/ft<sup>2</sup> (6 kg/m<sup>2</sup>) of waste. On average, only about 20 to 30% of that waste is recycled or reused.
- It takes a lot of energy to construct a building. For example, building a 50,000 ft<sup>2</sup> (4600 m<sup>2</sup>) commercial building requires the same amount of energy needed to drive a car 20,000 miles (32,000 km) a year for 730 years.
- We are much too inclined to think of our buildings as disposable rather than a renewable resource. A 2004 report from the Brookings Institution<sup>13</sup> projects that by 2030, we will have demolished and replaced 82 billion ft<sup>2</sup> (7.6 billion m<sup>2</sup>) of our current building stock. Because it is estimated that there are about 300 billion ft<sup>2</sup> (28 billion m<sup>2</sup>) of space in the United States today, we anticipate demolishing nearly one-third of our building stock in the next 20 to 25 years.
- It will take as much energy to demolish and reconstruct this 82 billion ft<sup>2</sup> (7.6 billion m<sup>2</sup>) of space (as predicted by the Brookings study) as it would to power the entire state of California—the 10th largest economy in the world with a population of about 36 million people—for 10 years.
- If we were to rehabilitate even 10% of this 82 billion ft<sup>2</sup> (7.6 billion m<sup>2</sup>), we would save enough energy to power the state of New York for well over a year.
- Construction debris accounts for 25% of the waste in the municipal waste stream each year. Demolishing 82 billion ft<sup>2</sup> (7.6 billion m<sup>2</sup>) of space will create enough debris to fill 2500 National Football League (NFL) stadiums.

Although repair of existing structures is typically a responsible solution to the need for useable buildings and infrastructure, repair and associated demolition do generate the need for new replacement materials and create waste destined for landfills. Nonmunicipal solid waste is the discarded solid material from industry, agriculture, mining, and oil and gas production. It makes up almost 99% of all the waste in the United States. Some common items that are classified as nonmunicipal waste are: construction materials (roofing shingles, electrical fixtures, bricks); water-waste (sludge); incinerator residues; ash; scrubber sludge; oil/gas/mining waste; railroad ties; and pesticide containers.<sup>14</sup> Much of the effort in recycling programs focuses on municipal solid waste (MSW), ignoring the significant volumes of the other waste streams. One such classification scheme is shown in Fig. 1.<sup>15</sup>

A survey of 11 states estimates that 4.2 lb (1.9 kg) of MSW is generated per person per day. Construction and demolition (C&D) waste was estimated at 20.9% of total solid waste, with some states indicating C&D nearly 30% of their solid waste.<sup>16</sup>

In 2003, renovation was estimated at 42% of C&D waste (Fig. 2).<sup>17</sup> Assuming that these figures can be combined yields an estimate of roughly 9% of all solid waste coming from renovation. Making concrete last longer as well as having more durable repairs can help reduce this waste stream.

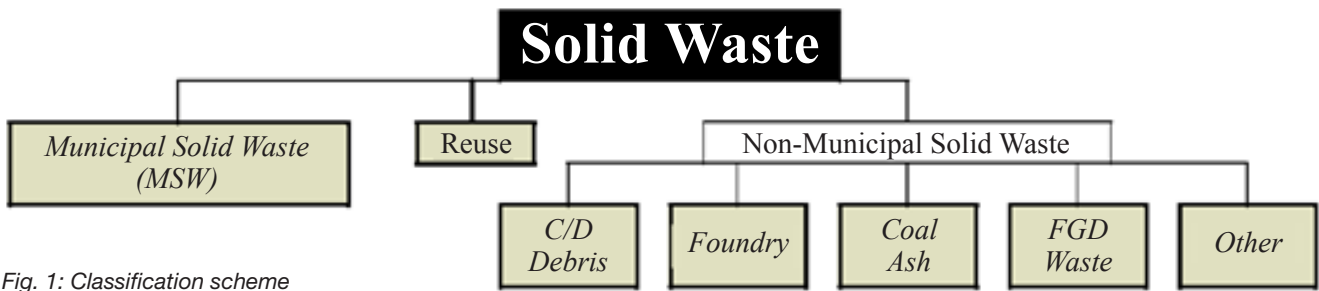


Fig. 1: Classification scheme

Source	Residential		Nonresidential		Totals	
	Million tons	Percent	Million tons	Percent	Million tons	Percent
Construction	10	15%	5	5%	15	9%
Renovation	38	57%	33	32%	71	42%
Demolition	19	28%	65	63%	84	49%
Totals	67	100%	103	100%	170	100%
Percent	39%	—	61%	—	100%	—

Fig. 2: Estimated amount of building-related C&D materials generated in the United States in 2003

## PROTECTION AND PREVENTATIVE MAINTENANCE

The most sustainable management approach for buildings is to diligently perform preventative maintenance to avoid, or at least minimize, the need for repairs. In some cases, the original design and construction included measures to proactively protect the building (such as protection against the intrusion of moisture or contaminants and corrosion prevention measures). However, these measures are often not included to reduce the initial construction cost, despite the significantly lower life-cycle impact that would ensue over the longer term.

Preventative maintenance is required whether or not the original design included adequate protection measures. For instance, periodic maintenance such as traffic deck coating resurfacing or penetrating sealer reapplication may be required to maintain adequate protection. Building sealants and mortar joints also have a limited life and may require replacement. Repointing or tuckpointing (the replacement of masonry mortar) may help control moisture in masonry structures.

Design professionals can be retained to periodically review the conditions of protective systems and develop long-term preventative maintenance plans with recommended timing and associated budgets. This condition monitoring typically involves visual inspections and nondestructive testing. Such inspections should be carried out every 2 to 5 years to update the maintenance plan.

## REPAIR PROCESS TO MINIMIZE THE ENVIRONMENTAL IMPACT

Even with preventative maintenance, isolated structural repairs may be required. Whether they are isolated or required on a wider scale, structural repairs are inherently more sustainable than complete removal and replacement. However, there are key steps to the repair process that should be considered to minimize its environmental impact.

## CONDITION EVALUATION

The first step is having a qualified design professional conduct a comprehensive condition evaluation to identify the cause(s) and degree of deterioration or damage. To design a durable repair, it is important to understand specific deterioration mechanisms that affect a structure. For example, it is important to know whether the concrete that is being salvaged is contaminated with chlorides and/or has carbonated. Without considering such key factors, and countering them with appropriate corrosion control measures, repairs could actually accelerate deterioration in the parent concrete. ACI 364.1R<sup>18</sup> provides additional information on evaluation of concrete structures before rehabilitation. In the case of masonry, the condition evaluation should identify whether deterioration is related to conditions such as excessive loading, thermal movements, and excessive wetting so that an appropriate repair can be designed. Refer to ICRI Technical Guideline No. 410.1 for evaluation of masonry façade structures.<sup>19</sup>

## LIFE-CYCLE COST ANALYSIS

By considering anticipated repair and maintenance requirements over an extended period of time, an optimal repair and maintenance plan can be devised following the condition evaluation. For example, reducing initial costs by deleting corrosion-control measures could greatly increase repair costs over the long term. Repairs should not be planned or carried out with a narrow focus. Life-cycle cost implications of various options should be considered to highlight their strengths and weaknesses over the long term.

## REPAIR DESIGN

To minimize the environmental impact, a repair approach should salvage as much existing material as possible while achieving durability. For this to happen in concrete structures,

the repairs must include appropriate measures to control reinforcing steel corrosion in both the parent concrete and in the repairs themselves. The repairs should also include measures that will address the potential for future concrete contamination such as from chlorides and carbonation. This can normally be achieved by protecting the concrete on the surface to prevent contamination or through intrinsic corrosion control measures. For masonry structures, the repair design must account for the actual cause of the deterioration. Otherwise, the deterioration may reappear shortly after repairing or replacing affected masonry components.

## WASTE MANAGEMENT

A plan must be devised and implemented to deal with waste from the portions of the structure that must be removed, and for packaging of new materials. Where possible, removed materials should be recycled, or preferably reused, to avoid being sent to landfills. Similarly, new materials should be shipped with minimal, reusable, and recyclable packaging.

## USE GREEN REPAIR MATERIALS

Once a repair approach has been selected, it is important to implement it using repair materials that will minimize the environmental impact. Factors that should be considered include:

- Recycled content;
- Locally sourced content;
- Volatile organic compound (VOC) content;
- Durability;
- Service life;
- Packaging;
- Recyclability;
- Ease of use (lowering probability of premature failure);
- Embodied energy;
- Mixing and application method;
- Greenhouse gas emissions from manufacturing and transport;
- Hazardous components such as heavy metals; and
- Impact on heat island effect (solar reflectance and emissivity).

With Leadership in Energy and Environmental Design (LEED) certification of buildings becoming more mainstream, many manufacturers have started to document readily available information supporting the green aspects of their product line. This readily available information provided usually only scratches the surface of the sustainability of their products and the manufacturer usually needs to be asked to provide additional sustainability properties for their products.

## USE SUSTAINABLE REPAIR TECHNIQUES

The most common repair technique involves removing deteriorated concrete and repairing with a new material. In the case of masonry, it involves removing deteriorated or cracked mortar joints or bricks and replacing them with new material.

As stated previously, it is important to perform a condition evaluation before designing a repair to identify applicable deterioration mechanisms. The repair design should include measures to address the factors that caused the deterioration. Otherwise, repairs may not be durable and could even accelerate deterioration in adjacent areas, or the deterioration could soon return to the same area.

## Concrete Repairs

*Concrete Removal*—For repairs to be durable, concrete removal should extend to sound, uncontaminated concrete. Often this will require removing sound concrete that is chloride-contaminated or carbonated and concrete from around corroding reinforcing steel. Concrete removal methods must also be selected to account for factors that include:

- Environmental impact of removal process (carbon emissions, water use, other pollution);
- Dust generation;
- Noise level and vibrations to the structure;
- Potential fracturing of parent concrete;
- Cost; and
- Schedule.

Common concrete removal techniques include:

- Concrete breakers: Electric and pneumatic hammers are available in different sizes and have different bit shapes; most frequently used for targeted repairs;
- Rotomilling: Used for large flat areas that do not contain reinforcing steel;
- Hydrodemolition: Different devices are available to remove concrete by propelling water at a very high pressure; most frequently used where large areas require repairs or areas where concrete must be removed from around embedded metal items such as reinforcing steel; and
- Concrete sawing: most frequently used where large areas require complete replacement.

Table 1 compares different concrete removal techniques.

*Corrosion Control*—Because corrosion of steel components is a contributing factor to the majority of concrete repairs, corrosion control is one of the most important considerations impacting the sustainability of concrete repairs. When applied as part of a sustainable concrete repair protocol, corrosion-control techniques and preventive maintenance can extend the service life of the repair, increasing the time until additional repairs are required.

When applied during construction or early in the deterioration process—that is, prior to the appearance of cracks, spalls, or other forms of visible deterioration—corrosion-control techniques can be used to extend the service life of the structure and reduce or eliminate the need to perform concrete repairs.

To determine the appropriate corrosion-control approach, it is recommended to perform a thorough evaluation of the structure to determine the cause, extent, and severity of the corrosion. With this information, an appropriate corrosion mitigation strategy can be developed and implemented.

There is a wide range of corrosion-mitigation techniques available that function in different ways. To achieve the desired corrosion-control result, the technique must be understood in order to select what is appropriate for existing and anticipated site conditions. Refer to ICRI Technical Guideline No. 510.1<sup>20</sup> for electrochemical techniques to mitigate the corrosion of steel for reinforced concrete structures.

Some of the corrosion-mitigation techniques available include:

- Applying coatings and sealers on the concrete or reinforcing steel surface;
- Crack treatment;

**TABLE 1: CONCRETE REMOVAL TECHNIQUES**

Factor	Concrete breakers	Rotomilling	Hydrodemolition	Sawing
Environmental impact	Exhaust from diesel-powered equipment, or impact from power generation for electrically powered equipment.	Exhaust from diesel-powered equipment.	Diesel-powered pumps, water use, hazardous waste, significant water consumption. Risk of wastewater contaminating sewage or water sources.	Exhaust from diesel- and gas-powered equipment.
Dust	Large quantity of dust unless water or vacuum attachment used. Surface may need to be sandblasted.	Large quantity of dust. Surface may need to be sandblasted.	No dust—wet process.	Minimal dust using water-cooled blades.
Noise and vibrations	Loud noise and significant vibration to structure.	Loud noise and substantial vibration to structure.	Loud noise in immediate work area only—minimal vibration to structure.	Loud noise. No vibration to structure.
Fracturing of parent concrete	Significant microcracking. May be minimized using small hammers (<15 lb [6.8 kg]) with sharp points.	Very significant microcracking.	No microcracking.	N/A—method used to remove entire section or member.
Cost	Small capital investment—labor-intensive.	Large capital investment. Least expensive for large areas.	Large capital investment. Cost-effective in exposing reinforcing bar.	Cost-effective when cutting and removing complete sections.
Schedule	Labor-intensive. Effective in small areas or small repairs.	Very fast method for removing large areas of unreinforced concrete.	Most effective when removing concrete from around reinforcing steel.	Very fast when removing complete sections.

- Increasing cover over embedded steel reinforcing;
- Incorporating low-permeability concrete;
- Incorporating corrosion inhibitors in the concrete mixture;
- Galvanic cathodic protection;
- Impressed current cathodic protection;
- Electrochemical chloride extraction;
- Electrochemical realkalization for carbonated concrete; and
- Providing proper drainage.

**Masonry Repairs**

Like concrete, masonry is susceptible to deterioration from moisture intrusion and overloading as a result of improper design and inadequate construction practices. Such deterioration can be minimized with a thorough design and construction by a skilled mason. However, periodic condition evaluations and preventative maintenance are also required over the life of the building to maximize the service life.

For masonry repairs to be sustainable, the repairs, such as repointing/tuckpointing and replacing cracked or spalled bricks, must not only address the symptoms but must also address the root cause of the problem. Examples of addressing the root cause include:

- Introducing vertical control joints to address cracking from thermal movements;
- Introducing horizontal soft joints at floor slabs to relieve overloading from stacking (vertical load transfer over several floors); and

- Installing drip flashings to shed water away from the building to address spalling bricks or deteriorated mortar joints.

**Building Envelope Repairs**

Behind the concrete and masonry façade, the building envelope itself must be energy-efficient and sustainable in design. Energy codes have begun to require airtightness of the building envelope. Air leakage has proven to be a significant potential source of condensation and moisture accumulation in building envelope assemblies. Thus, in addition to preventing water intrusion with design and construction details that protect against wind-driven rainwater entry, minimizing airflow through the building envelope with an air barrier system is also important. A waterproof air barrier system that reduces unintended air movement and water infiltration is an efficient way of preventing moisture deterioration of building materials.

According to the National Institute of Standards and Technology (NIST), continuous air barrier systems can reduce air leakage by up to 83% and energy consumption for heating and cooling by up to 40%.<sup>21</sup> The report states that: “Despite common assumptions that envelope air leakage is not significant in office and other commercial buildings, measurements have shown that these buildings are subject to larger infiltration rates than commonly believed. Infiltration in commercial buildings can have many negative consequences, including reduced thermal comfort, interference with proper operation of mechanical ventilation systems, degraded indoor

air quality, moisture damage of building envelope components and increased energy consumption.”

## SUCCESSFUL REPAIR IMPLEMENTATION

Even with an optimal design and green material selection, a repair project must be implemented properly to minimize its environmental impact. To maximize the likelihood of success, the repairs should be carried out by a competent contractor in combination with a comprehensive quality control plan. The quality control should include the designer’s site review to check for compliance with the design specifications, site visits by manufacturers’ representatives to check compliance with their requirements, and field and laboratory testing to verify that measurable requirements (such as strength, adhesion, temperature, and environmental conditions) are met.

## MONITORING

Effective monitoring and preventative maintenance can be very cost-effective compared to allowing deterioration to progress until repair is required. Through monitoring, small, low-cost, and relatively innocuous actions taken early in the life cycle yield more sustainable and more durable results than waiting until repair is required.

Once repairs are completed, it is important to monitor the condition of the structure to determine when preventative maintenance or subsequent repairs will be required. This is typically achieved by periodic condition evaluations. Embedded sensors and data acquisition systems can also be used to continuously monitor certain performance parameters (including corrosion activity, chloride contamination, water leakage, temperature, structural deformations, and cracking).

## REPAIR BENEFITS

To merely claim a place for repair in the relatively recent environmental dialog is to diminish the fact that it is truly part of the foundation of a repair/preservation philosophy that has a long and distinguished history—a history that began long before the green building movement.

It is enlightening to consider concrete repair, as we know it today, from the perspective of the early development of the historic preservation movement in the United States that was codified in the National Historic Preservation Act (NHPA) of 1966. At the time NHPA was enacted, there was a growing acceptance that reusing existing structures was desirable on many levels. NHPA is based on the belief that “the spirit and direction of the Nation are founded upon and reflected in its historic heritage.”<sup>22</sup> In its infancy, the application of NHPA tended to focus on nationally important historic landmarks, but it quickly grew to encompass a wide range of structure types and sites as well as professionals and tradespeople from many design- and construction-related fields. Involved individuals and organizations recognized long ago that preservation of the existing built environment is beneficial for preserving cultural heritage for social reasons, but also for limiting urban sprawl, assisting with economic growth and development, and many other reasons now at the focus of sustainable practices.

Many of the arguments commonly heard in current mainstream dialogs about the need to create sustainable communi-

ties have been, for decades, the very tenants by which the repair and preservation communities have purposefully extended the life of those communities as they already exist.

In 1966, the U.S. Congress stated in the text of the NHPA that “the preservation of this irreplaceable heritage is in the public interest so that its vital legacy of cultural, educational, aesthetic, inspirational, economic, and energy benefits will be maintained and enriched for future generations of Americans.”<sup>21</sup> This statement, issued 48 years ago, is clearly echoed in the widely accepted definition of sustainability offered by the U.N. Brundtland Commission’s 1987 report, “Our Common Future,” which defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs,”<sup>23</sup> and the context of the three separate but interrelated principles of sustainability that are currently recognized, including environmental, economic, and social sustainability.<sup>24</sup> In other words, the principles of preservation formed long ago, which have underscored the motivation for repair projects for ages, are an intrinsic component of current efforts toward environmental sustainability.

The U.S. Green Building Council’s building program, LEED, has been responsible for many successes in encouraging environmentally responsible building practices. LEED’s early focus on new construction has expanded to include existing building operations, rewards for projects in urban settings, and projects near mass transit, all of which encourage density in existing settings. This in turn creates the need for renovation and repair.<sup>7</sup> However, LEED still does not adequately address the reuse of entire structures, as it lacks baseline recognition for overall building rehabilitation versus demolition and new construction. The Heritage Canada Foundation offers a compelling look at a possible scenario for the future of the repair-versus-replacement argument: “Currently, the challenge is to prove that an old building is so valuable that it ought to be saved; rather the owner/developer should be required to prove that an old building cannot be adapted to new use.”<sup>24</sup> In other words, begin with building retention as the first rewarded option with the burden of proof falling to alternative new options.

Giving economic teeth to programs that encourage sustainable building practices, the Federal Historic Preservation Tax Incentives program, an outgrowth of NHPA, allows for 10 to 20% tax credits for the substantial rehabilitation of qualified existing structures. This program has become one of the nation’s most successful and cost-effective community revitalization programs ever enacted. In Fiscal Year 2006, 1253 projects that represented a record-breaking \$4.08 billion in private investment were approved. “Taking into account new construction, which often occurs in conjunction with approved rehabilitations but is not eligible for the credit, the program leverages far greater than 5 to 1 in private to public investment in the preservation and renewal of our communities. With nearly 34,000 approved projects, the Tax Incentives program attracts private investment to historic cores of cities and Main Street towns across America, generates jobs, enhances property values, creates affordable housing, and augments revenues for Federal,

State, and local governments.”<sup>25</sup> Additionally, more than half of the states in the country have also enacted tax credit laws for building preservation that offer tax relief for owners of existing buildings.

## BEYOND GREEN

A unique public/private partnership grew from the successes of NHPA, namely the supportive working relationship between the federal government and the National Trust for Historic Preservation (NTHP). NTHP is the only public/private partnership of its kind at the federal level. The Trust’s focus goes beyond historic buildings to include all existing buildings and has a strong position on sustainability, “Historic preservation can—and should—be an important component of any effort to promote sustainable development. The conservation and improvement of our existing built resources, including reuse of historic and older buildings, greening the existing building stock, and reinvestment in older and historic communities, is crucial to combating climate change.”<sup>12</sup>

Extending the life of existing structures is the ultimate act of sustainability. It reduces the depletion of additional natural resources and reduces energy consumption. Through the conservation of materials and overall structures, we benefit from the energy that was consumed during the original material manufacturing and construction of existing structures. Models have been developed that can calculate the energy consumption for many types of structures. A useful model is embodied energy (embodied energy is defined as the amount of energy associated with the extracting, processing, manufacturing, transporting, and assembling of raw materials into a useable product). The NTHP offers a telling comparison: “The average embodied energy in existing buildings is 5 to 15 gal./ft<sup>2</sup> (20 to 60 L/m<sup>2</sup>) of gasoline.”<sup>12</sup> To make this image more vivid, “The average embodied energy in a 250,000 ft<sup>2</sup> (23,000 m<sup>2</sup>) office building is 3.75 million gal. (14 million L) of gasoline.”<sup>12</sup> Further, “over a building’s life time, embodied energy amounts for approximately 16% of a building’s total life cycle energy consumption; in contrast, 74% of energy use is attributed to building operations. . . thus, there is a common misconception that the energy wasted in the demolition and reconstruction is quickly recovered in [new] building operations.”<sup>24</sup> However, recent research shows that “a new building’s life span must reach 26 years to save more energy than the continued use of an existing building. . . if a building were demolished and partially salvaged and replaced with a new energy-efficient building, it would take 65 years to recover the energy lost in demolishing a building and reconstructing a new structure in its place.”<sup>24</sup>

Another model for assessing energy cost is life-cycle analysis (LCA). It “examines impacts during a building’s entire life, rather than focusing on environmental impacts at a particular stage”<sup>24</sup> and reveals that repairing and reusing structures is more environmentally friendly than new construction. Interpretative issues exist with both energy calculation models, but the evidence is compelling in favor of reuse for many reasons including energy conservation.

To this end, consider the concrete repair industry in terms of the NTHP’s Sustainability Initiative, designed “to develop

a national policy for the integration of sustainability and preservation. . . The organizations currently involved are the American Institute of Architects (AIA), the Association for Preservation Technology International (APT), the National Park Service (NPS), the National Trust for Historic Preservation (NTHP), the General Services Administration (GSA), and the National Conference of State Historic Preservation Officers (NCSHPO).”<sup>24</sup> This effort toward integrating the practices and principles of preservation into the green building movement are directly supportive of the evidence that shows how repair is environmentally and economically desirable.

In “Making the Case: Historic Preservation as Sustainable Development,” a white paper written in advance of a research retreat for the Trust’s Sustainability Initiative, conservation of energy and natural resources through building reuse are addressed in support of the idea that preservation promotes environmentally, economically, and socially sustainable development. The Trust’s Initiative addresses several perceived environmental weaknesses of historic buildings, including that old buildings are often considered to be energy hogs. In reality, many historic buildings are more energy-efficient than more recent buildings, particularly concrete and masonry buildings that inherently possess significant thermal mass, which reduces mechanical heating and cooling needs. “2003 data from the U.S. Energy Information Agency suggests that buildings constructed before 1920 are actually more energy efficient than buildings built any time afterwards—except for those built after 2000. Even then, the improved energy performance of new construction is marginal.”<sup>24</sup> “In 1999, the General Services Administration examined its building inventory and found that utility costs for historic buildings were 27% less than for more modern buildings.”<sup>12</sup> These older structures have survived because of the absence of construction defects, while those not well-built have been replaced—only the best survive, like in natural selection. However, many inefficient older buildings certainly do exist and misguided alterations to others have actually reduced their energy efficiency.

## VISION FOR THE FUTURE

Because sustainability is here to stay, some of the questions that may remain regarding interventions in the built environment may exist more in the philosophical realm than the technological one. After many years of having clients ask if he could do “such-and-such a thing,” engineer Robert Silman wrote: “I realized that I can do practically anything these days in constructing and preserving the built environment. It suddenly occurred to me that the proper question to ask now was, ‘Ought we do such-and-such a thing?’ The inquiry had shifted from the technical to the philosophical and moral.”<sup>26</sup>

As the design and construction industries become increasingly more complex, we must be personally and collectively equipped to sit at the table and present the environmental, economic, and social arguments supporting the idea that just because we can build new, tall, and large, it does not follow that we should if viable repair and modification alternatives



exist. And conversely, that just because the technology exists for almost any level of repair, that we should not do it at all costs, or in every situation.

## CONCRETE REPAIR CODE

For those buildings where repair is a viable method of sustainability, ACI 562-13, “Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary,” and the Guide to ACI 562, scheduled for publication in 2015, give design professionals very clear procedures for designing durable concrete repairs. Not only will the design professional have clear procedures, owners and building managers will also have directives for maintaining and sustaining concrete repairs and concrete buildings.

## OTHER BUILDING CODES

Merely meeting today’s building code requirements does not achieve a sustainable outcome. These requirements must be exceeded, often significantly, to make buildings durable and energy-efficient.

Improvements are being made to incorporate sustainable design into some building codes as they get updated. For example, ACI 318, “Building Code Requirements for Structural Concrete and Commentary,” continues to improve the concrete design requirements to enhance durability.

New codes and standards are also being written to supplement the requirements of the current building codes. For example, the 2012 IgCC was developed to reduce the negative environmental impact from buildings. The IgCC is intended to be used in conjunction with the International Building Code (IBC), augmenting the requirements for buildings other than low-rise residential buildings. The National Green Building Standard (NGBS) has been developed for low-rise construction and includes a performance rating system.

There have also been initiatives by state and municipal governments to promote durable building designs. For example, California has developed its own green building code called “CalGreen.” New York City has also created a task force to review and update its codes to make them greener.

As the implementation of these green codes and standards becomes more widespread, buildings will become more durable. Adherence to comprehensive condition evaluation programs and proactive maintenance will further reduce their environmental impact.

## BRIEF HISTORY OF CONCRETE

Lime mortars were likely one of the first synthesized construction materials.<sup>27</sup> To prevent a fire from spreading, rocks would often be used to create a fire pit. When limestone became sufficiently hot, changes in the appearance likely prompted some curious ancient individual to experiment, especially because the calcined limestone probably did not make the best fire pit, having become soft and crumbly. Mixing the lime with water created a material that eventually hardened due to carbonation. The oldest concrete found so far dates to about 7000 BC and was found in south Galilee, Yiftah El, in Israel, and consisted of a mixture of lime with stones. Lime combined with water and sand forms

a “slime” mortar which reacts with atmospheric carbon dioxide to harden. If this mortar is mixed with stones, it bonds the stones together and forms a type of concrete.<sup>28</sup> Some limestone, when heated to a very high temperature, actually became hydraulic lime, which produced an even better binder. Meanwhile, Mother Nature had long been at work on making something even better. Likely near the town of Pozzuoli, Italy, someone discovered magical rocks that, when ground and mixed with water, would turn into another kind of rock. Natural cement was discovered. It did not take long for the person doing the grinding to realize it was a lot of work. “What can I add to stretch the amount of magic rock that I have to grind?” was likely a thought. “Let’s try sand.” Mortar was born. Then the sand became depleted nearby, so someone thought of also adding rocks; thus, concrete was invented. Not only did these additions reduce the amount of energy required to make the costly ground natural cement go further in the mixture but the performance also actually improved, the transportation cost decreased (as local sand and rock could be used), and the whole system became more popular.

Lime was then added to these natural cements and properties improved even more. Pretty soon, this natural cement became popular in holding together much of the construction of the Roman Empire. People continued to experiment by adding different waste and by-products to their plasters, mortars, and concretes. Broken terra cotta (likely a recycled material) was used as a reactive aggregate in combination with lime mortars by the Romans<sup>29</sup> to create a waterproof mortar that eliminated the need for the ground pozzolana magic rocks. Blood and hair, both by-products of butchering, were also added to some of these ancient mortars to improve durability and create fiber reinforcement. The use of natural admixtures in concrete was a logical progression. Materials used as admixtures included milk and lard by the Romans; eggs during the middle ages in Europe; polished glutinous rice paste, lacquer, tung oil, blackstrap molasses, and extracts from elm soaked in water and boiled bananas by the Chinese; and in Mesoamerica and Peru, cactus juice and latex from rubber plants. The Mayans also used bark extracts and other substances as set retarders to keep stucco workable for a long period of time.<sup>30</sup> There is supposition that air entrainment of concrete as a means of improving resistance to freezing and thawing was either discovered using tallow, or by mixing concrete with used soapy washing water, and later neutralized vinsol resin (a wood resin salt by-product). The original water reducers used for concrete were Lignosulfanotes recovered from the spent pulping liquids used in the paper manufacturing process.

This evolution of different additives by trial and error, as well as the growth of hydraulic cements as construction materials, has led to the current popularity of concrete, where approximately 1.3 yd<sup>3</sup> (1 m<sup>3</sup>) is placed per year for each person currently living.<sup>31</sup> Most concrete made today uses portland cement, which is manufactured in a very energy-intensive process that produces an estimated 5% of global CO<sub>2</sub> emissions. To reduce the energy cost of cement manufacturing, the high temperatures used for cement clinkeriza-

tion can be used to dispose of many wastes, including spent solvent<sup>32</sup> and tires.<sup>33</sup> With the large volume of concrete produced and the long history of empirical development of additives, if a large quantity of something is being disposed of, someone will add it to concrete to see what happens. Fly ash (a waste product from coal combustion) was added to concrete as early as 1929,<sup>34</sup> and today 30% of the fly ash produced is added to concrete, making it one of the largest (by weight) recycled materials. Silica fume, another industrial by-product, was first added to concrete in 1952<sup>35</sup> and is now widely used for high-strength, decreased-permeability, and other high-performance concretes to such an extent that its cost is only several times that of portland cement. Ground-granulated blast-furnace slag, another former waste product from iron smelting, can also replace cement in a mixture or provide enhanced properties compared to pure portland cement concrete. Ternary portland-pozzolan mixtures have been shown to have several synergistic benefits in performance compared to conventional concretes.<sup>36</sup> Performance-enhanced concrete mixtures are also becoming popular, using high volumes of fly ash and other pozzolans that are clearly demonstrating the possibilities of the use of recycled materials regarding reduced environmental impact, lower cost, and superior characteristics.<sup>37</sup>

## REDUCED WASTE GENERATION

Concrete itself is growing in recycling. Estimates are as high as 140 million tons (127 billion kg) per year or roughly 18% of the weight of concrete placed each year is recycled in the United States, mostly by crushing and using as a base course for new concrete.<sup>38,39</sup> An additional benefit is that the crushing of concrete increases the absorption of carbon dioxide that is estimated to be as high as 80% of the CO<sub>2</sub> emissions occurring during manufacture.<sup>40</sup> A recent paper indicates that a potentially successful binder can be produced by calcining recycled hydrated cement paste, resulting in a significant reduction in the CO<sub>2</sub> emissions compared to direct manufacture of portland cement, which requires limestone decarbonation and activation of fly ash with the reburned cement paste.<sup>41</sup>

Repair of concrete is really the ultimate act of sustainability. Much of the life-cycle cost and comparatively low environmental impact of concrete are due to its longevity, and extension of that longevity further enhances these benefits. De Sitter and Tuuti<sup>10</sup> point out in “Residual Life Models for Concrete Repair - Assessment of the Concrete Repair Process,” prevention through monitoring, inspection, and maintenance can result in a huge savings over the life cycle of a concrete structure. Investment in preventative maintenance results in shorter, less-disruptive interventions that are significantly cost-effective over the life cycle of the structure, compared to waiting until deterioration (such as from reinforcement corrosion) has been initiated or attempting repairs after the deterioration has caused damage (such as rust staining, concrete spalling, and cracking). Preventive maintenance includes minimizing moisture ingress and providing for natural drying once the concrete has cured; preventing freezing-and-thawing

damage; and minimizing alkali-aggregate reaction, most types of sulfate attack, deicer salt scaling, and carbonation. For new concrete construction of good quality, addressing cracks; treating with penetrating sealers, coatings, or membranes; and other proactive maintenance can postpone repair almost indefinitely.

## TRIPLE-BOTTOM-LINE CONSIDERATIONS

The importance to society of sustainability for concrete repair cannot be overestimated. Nations rely upon continuously deteriorating concrete and masonry infrastructures to satisfy ever-increasing demands. It is necessary to consider the effects of concrete repair upon society because of its potential impact upon expected economics, safety, and quality of life. To meet the needs of today without sacrificing the capabilities of tomorrow, sustainability must involve a synergy of environmental, economic, and social requirements. These three parameters (economic, environmental, and social) have been labeled the “Triple Bottom Line” in an attempt to discourage sacrificing ethical considerations to protect shareholder value.

The concrete repair industry is uniquely situated to have a profound effect upon the society in which it operates. The industry’s ability to maintain the constructed world represents an integral necessity for civilization. The process of concrete repair must continually evolve to further mitigate burdens upon society through the use of best practices and increasing technological sophistication. For example, the use of repair materials engineered with reduced VOCs prevents adverse short- and long-term health issues. Also, the use of local materials and labor promotes the strong social connection of concrete repair and sustainability. The process of concrete repair empowers organizations and individuals to make positive changes in their environment and become active participants in maintaining the future of society.

## PERFORMANCE MONITORING

Rehabilitation of buildings accounts for an increasing proportion of architecture, engineering, and construction activities. Buildings are routinely transformed from one use to another, such as offices to condominiums, factories to restaurants, and old houses to museums. The act of adaptively reusing an existing structure is, by itself, an act of sustainability. The savings of the embodied energy in restoring an existing structure as opposed to manufacturing new building materials is enormous. However, one of the challenges is the control of heat, air, and moisture flow through the building envelope. Buildings will experience a change in indoor climate because higher standards of comfort are required. Changes should not adversely affect the long-term durability of the building envelope. Installing sensors in buildings is an effective method of obtaining information on building performance.

The purpose of the monitoring program is generally to provide data which will be used to assess the effectiveness of a restoration or enhancement. The measurements can also be analyzed to determine whether wetting has occurred in susceptible materials and, if so, under what circumstances of

weather and wall characteristics. The monitoring program should be designed and implemented on buildings being rehabilitated. While the focus of a program could be on obtaining the raw data for analysis, the opportunity for the use and analysis of the data is enormous. Examples of the use of the monitoring data are as follows:

- To correlate moisture intrusion/wetting events with exposure, weather conditions, and building interior conditions;
- To determine if wetted walls dry quickly enough to resist damage, and under what conditions drying takes place;
- To evaluate the effectiveness of additional insulation and roofing repairs to a structure;
- To provide baseline data that can be used comparatively when assessing the performance of other repaired buildings when they are investigated in the future as part of warranty and maintenance requirements; and
- To schedule preventative maintenance before deterioration can progress.

Instrumentation can be used to monitor temperature, relative humidity, air pressure, and air quality. The cost of monitoring is relatively inexpensive compared to the cost of the repairs or the actual value obtained from the knowledge of the performance of the repairs implemented.

## ICRI COMMITTEE 160 GOALS

To promote sustainable practices in the concrete and masonry repair industries, ICRI's Committee 160, Sustainability, will develop sustainability criteria for ICRI's technical committees to consider when developing new or updating existing documents. Committee 160 will also be reviewing existing ICRI documents and will provide feedback to the authoring committee to incorporate sustainability themes. Finally, Committee 160 will develop guidelines on sustainable concrete and masonry maintenance and repair.

## VISION 2020

The Strategic Development Council (SDC) of the ACI Foundation facilitated a meeting of concrete repair industry stakeholders to develop Vision 2020, "A Vision for the Concrete Repair, Protection and Strengthening Industry," to establish goals to improve the efficiency, safety, and quality of concrete repair, protection, and strengthening activities. Each goal was broken down into strategies and actions that were assigned to industry leadership. Although many of Vision 2020's original 13 goals were inherently sustainable, there was not a goal that specifically mentioned and addressed sustainability. For this reason, SDC held a breakout session on September 20, 2011, with a follow-up webinar on April 18, 2012, to develop a sustainability goal. The result of this brainstorming was "Recommendations for Sustainability Goal #15 for Update to SDC Vision 2020," prepared by Charles Hanskat.<sup>42</sup> The Vision Statement is: "Increasing the longevity, resiliency, durability, utility, and sustainability of concrete structures by providing tools to repurpose, protect, upgrade, extend the life, and maintain concrete structures."

The "Strategies" to support the Vision Statement are:

1. **Models and Analytical Tools**—Develop analytical tools and models with rating systems and decision trees as asset evaluation tools.
2. **Promotion/Perception/Celebration**—Celebrate success of repair by promoting media coverage of the benefits.
3. **Training and Education**—Certification/training/case histories/LEED interaction/adoption of new technology/owner appreciation of sustainable solutions.
4. **Funding**—Capital funding doesn't address sustainability of maintenance and repair.
5. **Interact with the U.S. Green Building Council and other recognized groups** to have Rating System improved and repair sustainability recognized.

## SUMMARY

Concrete that is properly designed, constructed, and maintained requires fewer repairs over its service life. Preventive maintenance and periodic repair tends to be more effective in extending the service cycle of concrete structures than allowing deterioration to propagate with occasional poor-quality repairs.

Due to the continued deterioration of our existing building inventory and infrastructure, a large volume of concrete repair will be needed for the foreseeable future. Each cycle of repair contributes to the waste stream, consumes resources, and may be less durable than desired. The debris from the repair as well as the replacement material composition and packaging should have a management plan developed for recycling, reuse, or disposal to minimize the environmental impact.

When repairs are required, a proper condition evaluation is needed to understand the causes and extent of deterioration. A life-cycle cost analysis can demonstrate the financial implications of deferred repairs, proactive maintenance, and cost effectiveness of remedial measures.

To minimize environmental impact, repairs that are implemented should be at least as durable as the remaining structure, address the root cause of the deterioration, and prevent future deterioration, such as deterioration which results from reinforcement corrosion. The quality of the installed repairs should be verified during installation and the structure should be monitored and inspected as appropriate based on the importance of the structure.

Current sustainability initiatives tend to focus on new construction. It is more difficult to develop analytical tools and models with rating systems and decision trees as asset evaluation tools. The decision regarding the fate of a structure is biased to favor replacement instead of realizing that the time to offset the energy consumption of new construction is often many years compared to modernizing the operating efficiency of existing structures.

The issues addressed in this report argue for the intrinsic value of our existing built environment. Acknowledging their validity, these facts further point to the need for extending the life of existing structures, which entails understanding the essential repair tools and approaches used in that pursuit. Full participation in the commitment to living and building sustainably must include prioritizing preventive maintenance and quality repairs for our existing structures.

## CASE STUDY NO. 1: RESTORATION AND CORROSION PROTECTION OF A REINFORCED CONCRETE AIRPORT TERMINAL BUILDING

In 2005, the Washington Airports Authority decided to rehabilitate and maintain the exterior façade of the architecturally unique and historic Terminal A at Washington Reagan National Airport.

Instead of demolishing the 60-plus-year-old structure, repairs were made to the damaged concrete areas (Fig.3) and electrochemical realkalization was used (Fig. 4) to increase the pH of the severely carbonated concrete façade, mitigate further corrosion, and extend the service life of the structure.

Completing this work allowed the building to remain in service (Fig. 5). As a result, 6755 yd<sup>3</sup> (5165 m<sup>3</sup>) of concrete were maintained in service and a comparable quantity of new concrete was not needed to rebuild a similar structure. This prevented the release of 1688 tons (1,531,000 kg) of CO<sub>2</sub> (equivalent to the annual emissions of 335 people) and 67 tons (61,000 kg) of acid rain constituents (SO<sub>2</sub> and NO<sub>x</sub>). In terms of thermal pollution, maintaining the existing structure prevented the release of 17,000 MMBtu (18,000 GJ) of heat into the environment. These quantities do not include the impact or contribution of demolition and disposal activities.



Fig. 3: Deteriorated concrete façade prior to repair



Fig. 4: Installation of realkalization system



Fig. 5: Restored structure

## CASE STUDY NO. 2: RESTORATION AND SERVICE LIFE EXTENSION OF THE RAINBOW BRIDGE

Through the use of ICRI-recommended concrete repair procedures, chloride extraction, and galvanic protection, a 50-year service life extension to this 75-year-old structure was designed and implemented (Fig. 6).

Designed and built in the 1930s as a Depression-era work project, the Rainbow Bridge is a critical transportation link located in the Cascade Mountains north of Boise, ID.

Completion of this project kept 1809 yd<sup>3</sup> (1400 m<sup>3</sup>) of concrete in service. This quantity of concrete is equivalent to 450 tons (410,000 kg), or 90 person-years of CO<sub>2</sub> emissions.

The embedded energy in this quantity of concrete is approximately 4550 MMBtu (4800 GJ), or enough heat to boil the water in three Olympic-size swimming pools.



Fig. 6: Rainbow Bridge during rehabilitation

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