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康特MCI滲透移動鋼筋阻鏽劑
應用於美國五角大廈

刊登標題：美國五角大廈採光牆—延長使用50年的修復、翻新與保護計劃

刊登摘要：美國五角大廈係全世界最大的辦公大廈，目前正進行全面性翻新、修復與現代化的整修計劃，此計劃的目標爲延長其使用年限至少達 50 年。

五角大廈中的所有結構皆爲鋼筋混凝土，但因混凝土碳化與鋼筋鏽蝕問題而嚴重剝落損壞。在嚴格評估下，慎選由美國 Cortec Corporation 所製造含胺基羧酸鹽的 MCI-2020 V/O 滲透移動鋼筋阻鏽劑，其滲透入混凝土中，並在埋置的鋼筋表面形成 MCI 保護阻隔層，其有效保護碳化混凝土中的鋼筋，且降低其腐蝕速率，而達到阻鏽的功效。

The Pentagon Lightwell Walls

Repair, Rehabilitation and Protection for the Next 50 Years

By Rick Edelson

Constructed in just 16 months during WWII, the Pentagon, the world's largest office building, today is undergoing a complete renovation, rehabilitation, and modernization program. A program with the goal of a minimum 50 year design life has been mandated by Penren (**www.pentagon.renovation.mil**), the governing agency for the Pentagon renovation. That's right, it is anticipated that repairs will last at least 50 years! Taking over 10 years to complete, every component, the walls, the floors, the roofs, the windows, the mechanical and electrical systems, everything, is being renovated or replaced. This article is about one component – the single largest component in the Pentagon. The concrete. All structural elements of the Pentagon, except one, are constructed of reinforced concrete. And that concrete is sadly deteriorating. This is the story of how to breathe at least 50 years of new life into deteriorating concrete is told in this article.

The one element of the Pentagon not constructed of reinforced concrete is the outermost perimeter wall. It is the limestone wall that everyone sees on the outside of the building. This article is primarily about the remainder of the 1,000,000 square feet of the lightwell walls which are now undergoing a complete Repair, Rehabilitation, and Protection program.

Figure 2: Scaffolding constructed to allow direct access to walls.

The Pentagon consists of five separate rings, each approximately 90 feet wide with approximately 30 feet between the rings. The space between the rings is known as the lightwells. Thus, we call the perimeter walls of each ring the lightwell walls. The lightwell walls, constructed of poured in place, reinforced concrete, are both bearing and shear walls.

Figure 1: Typical lightwell wall damage showing spalling and exposed rusting reinforcing bars.

The problem is corrosion, i.e., rusting, of the reinforcing bars in the lightwell walls and related spalling damage caused by the expansive forces created by the rusting bars. As steel rusts, it expands 4 to 10 times its original size creating extreme tensile forces in the surrounding concrete. From these tensile forces, the concrete cracks the spalls. The Pentagon program is about the repair and rehabilitation of the more than 250,000 square feet of spalling, typically represented in *Figure 1*, plus an innovative protection system designed to resist the damage for the next 50+ years.

Concrete testing prior to the implementation of the program revealed that the lightwell walls were constructed of approximately 3,500 psi concrete. However, the reinforcing bars were often placed less than ½-inch from the outer surface, and the testing revealed carbonation extending into the walls a distance of 3½ inches or more. Reinforcing bars, normally protected against corrosion by highly alkaline concrete, loose their protection as a result of the carbonation process which lowers the alkalinity concrete from a pH of over 13 to less than 11. Without corrosion protection, approximately 20% to 30% of the walls have suffered spalling damage; corrosion rate testing reveals active corrosion over in virtually every other section of walls.

Figure 3: Jackhammer demolition in progress exposing corrosion damaged reinforcing bars.

So, here's the problem: Structurally repair and rehabilitate the corrosion damaged concrete and protect the remainder of the walls to resist future damage for the next 50 years.

The Structural Engineer of Record for the concrete repair program designed the concrete repair work closely following the International Concrete Repair Institute guidelines for concrete repair. All damaged and spalling concrete, some 3 to 4 inches deep, is removed with 15-pound jack hammers, fully exposing rusting reinforcing bars. Where corrosion has extended around a bar, the bar is undercut; this allows the full surface of the bar to be sandblasted clean, removing all rust. Working closely with U.S. Concrete Products, Timonium, MD, the manufacturer of the repair concrete, a color matching, low shrinkage, pumpable repair concrete was developed to comply with the Specifications which require a color and texture match when viewed from a distance of 30 feet (the view from any window across a lightwell). This is easier said than done. Although some of the repairs are as much as 4 inches deep, some repairs are less than 1 inch deep, and some are too small to economically build formwork. For the minor amount of hand patching that is being performed on small repairs, a trowelable mix was developed. For the remaining repairs, U.S Concrete developed a polymer modified, plasticized, bagged material that is mixed onsite. This material easily flows into the formed repairs with extremely little shrinkage cracking. The mix allows repairs up to 4 inches deep without large aggregate extension, and almost no cracking. Simple external vibration is all that is needed for good consolidation. And, it obtains at least 2000 psi in under 3 days, to allow for early stripping.

Concrete Protection and Restoration, Inc., the concrete repair subcontractor, developed a formwork system (*Figure 5*) which allows easy placement of the repair concrete, as well as a match to the original form board finish. After trial and error, they quickly learned that the best method of forming was to use the same 2x12 board construction, just like the original contractor did in 1944, thus creating a perfect match to the original finish.

To accommodate the Pentagon workers, noisy concrete demolition must be performed at night. Concrete placement and other "non-noisy work" is performed during the day, allowing an almost continuous scheduled of activity. But the real challenge is yet to come – how to protect 1,000,000 square feet of wall surface from the devastating damage resulting from rusting reinforcing bars for the next 50 years.

Figure 4: Close view of corrosion damaged reinforcing bars taken after completion of jackhammer demolition. Note the severe loss of cross section at the bottom of the vertical bars in the photo.

Protection must overcome two difficult deficiencies: bars too close to the surface and very deep carbonation. A porous material, rain water is easily absorbed into concrete. With many of the bars ½-inch or less from the surface of the concrete, the bars are constantly wetted whenever it rains. Under the normally alkaline condition of good concrete with a pH of over 13, a passive oxide layer builds around each bar effectively protecting the bar from corrosion even if the bars are wetted. The carbonation process forces the pH to drop below 11. When the pH drops below 11, the passive layer is destroyed and leaves the bar precariously exposed to corrosion. Therefore, the protection system must both resist water penetration and compensate for the loss of alkalinity.

Compensation for the loss of alkalinity is provided by the newer technology of migrating corrosion inhibitors. Several methods of corrosion inhibition technology are available today, including corrosion rate reduction, corrosion threshold reduction, and chloride or CO_2 absorption rate reduction. An amino based corrosion inhibitor was selected for the Pentagon because of the ability of amino based inhibitors to protect reinforcing in carbonated concrete, effectively reducing the rate of corrosion. Amino based migrating inhibitors work in three ways: capillary action, vapor phase diffusion, and ionic attraction. During the capillary action, the concrete acts like a sponge, drawing the water based inhibitor inside. Once inside the concrete, amino molecules have a vapor phase that allows them to diffuse throughout the concrete matrix. This diffusion is based on Fick's 2nd Law, which states that molecules will diffuse from areas of high concentration to areas of low concentration until they reach an equilibrium. Finally, when the amino molecules get near embedded metals, they have a physical attraction to them which results in a tenacious bond to the metal.

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Figure 5: Formwork in place constructed to match original formboard finish on the existing walls.

Figure 7: Complete wall ready for presentation.

With four separate products applied to an existing building, and on top of each other, compatibility was a major concern. During the design of the system, compatibility testing was performed by the manufacturers of the corrosion inhibitor, the silane, and the potassium silicate. Each issued not only a joint compatibility statement, but a 20 year warranty for the performance of the system components. Quality Control by the Prime Contractor, Hensel Phelps, Quality Assurance by a third party inspection agency, and Quality Assurance by Penren all assure a complete installation.

Thus we have it. The Penren design goal of repairs to last 50 years is achieved. Concrete repair has restored both the integrity and appearance of the lightwell walls, and future corrosion damage is resisted with a system designed to protect the Pentagon concrete for the next 50+ years.▪

MCI 2020 V/O by Cortec Corporation, of St. Paul, MN was selected with its ability to migrate into a vertical surface at least to the depth of the reinforcing bars and for the additional enhancement of amine carboxylates. The carboxylate group on the MCI molecule is hydrophobic, meaning water hating. When attached to the reinforcement, it repels water away and allows the amine group to have an even stronger affinity for the metal. Corrosion rate monitoring has verified a reduction in the rate of corrosion from well above active corrosion to almost complete inactivity. Chemical testing of core extractions have shown the depth of migration beyond the outer layers of reinforcing bars.

But, corrosion rate reduction is only half the battle. Without water, corrosion can be halted. How to stop water from absorbing into the walls for 50 years? Further protection is provided by a system reducing the absorption of water into the walls. A 100% solids silane is applied to the wall surface, after the application of the corrosion inhibitor, to reduce absorption and to repel water. Silane is a water repellant only and breaks down when exposed to ultraviolet light. To further protect the walls, a much more durable surface is needed, one which will last 50+ years and will prevent the breakdown of the silane. To accomplish this, potassium silicate was selected to enhance the surface and to protect both the water repellant and the corrosion inhibitor. Potassium silicate, originally developed and manufactured in Germany by Keim over 100 years ago, is reported in their literature to remain in service today 100 years later. The potassium silicate itself also resists water absorption by creating a tough, water resistant mineral surface on the concrete. With both the potassium silicate and the silane, water now sheds off the surface of the concrete. In addition, a uniform color is achieved with the addition of pigments to the potassium silicate, further improving the repair to meet the required Specification of a color match as seen across the lightwells.

Figure 8: Corrosion rate monitoring of corrosion activity in unrepaired portion of wall adjacent to exposed corrosion damage.

Figure 6: Portion of wall completed prior to application of silane and potassium silicate coating.

The program discussed here, with Eric, "Rick", Edelson of Tadjer Cohen Edelson Associates, Silver Spring, MD, as the Engineer of Record for the design of concrete repair is being implemented by Concrete Protection and Restoration of Baltimore, MD. Both are proud members of the Hensel Phelps of Arlington, VA, design/build team for the Wedge 2-5 renovation.

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美國五角大廈採光牆

延長使用50年的修復、翻新、保護計劃

圖 1：搭鷹架以利直接在牆面上施工

美國五角大廈係世界上最大的辦公大廈，其在第二次世界大戰期間只花16個月即建造完成，如今正進行全面翻新、修復與現代化的整修計劃。五角大廈翻新管理局所設定的計劃目標爲延長其使用年限至少達50年，即期待此次修復可維持至少50年，且需耗費10年完成每一結構，包括牆面、地面、屋頂、窗戶、機電系統等，皆進行全面的翻修與更新。此文章提及五角大廈中佔最大的單一部份－混凝土。除一項結構外，五角大廈中的所有結構皆爲鋼筋混凝土；不幸地，其卻已遭嚴重損壞，此文章即說明如何在損壞的混凝土中重新注入長達50年的新生命。

美國五角大廈中非由鋼筋混凝土所建造的結構僅爲最外面的圍牆，每個人所能見到建築物的外觀即是石灰牆。此文章主要談論其餘1,000,000平方英呎，目前正進行完整修復、翻新與保護計劃的採光牆。

美國五角大廈係由五個獨立的楔形建物所組成，每個楔形建物約90英呎，而每個楔形建物間的距離約30英呎，此空間即是所謂的採光井，每個楔形物的圍牆則稱爲採光牆，而現場澆置的鋼筋混凝土採光牆，皆爲承重牆與剪力牆。

圖 2：一般採光牆損壞後所顯現的剝落現象與暴露的鏽蝕強化鋼筋

採光牆中強化鋼筋的鏽蝕以及鏽蝕鋼筋產生膨脹所造成混凝土的剝落損壞係最大的問題。當鋼筋鏽蝕時，其體積將膨脹4~10倍，而對周圍混凝土產生極大的張力，造成混凝土龜裂損壞。五角大廈的計劃係進行250,000平方英呎以上如圖2所示剝落混凝土的修復與翻新，同時設計採用最新的保護工法，以抵抗後續50年內遭受損壞。

圖 3：以千斤鎚敲除腐蝕的強化鋼筋

進行計劃前所完成的混凝土測試顯示，採光牆的混凝土強度約3,500psi。然而，強化鋼筋的混凝土保護層常少於1/2英吋，而混凝土碳化的深度已達3½英吋以上。一般保護強化鋼筋的高鹼性混凝土因其pH值由13以上降至11以下，造成碳化現象，而喪失鋼筋的防蝕保護功效，因此造成約20~30%的牆面剝落損壞。由腐蝕速率測試顯示，每處牆面皆處於活性腐蝕狀態。

因此，最大的問題就是如何修復因腐蝕而損壞的混凝土結構，以及如何保護其餘牆面抵抗後續50年遭受損壞。

記錄混凝土修復計劃的結構工程師，遵照國際混凝土修復協會所訂定的混凝土修復指南，嚴格地執行此工程的修復計劃。所有已損壞與剝落的混凝土，甚至深達3~4英吋，皆以15磅的千斤鎚將其敲除，使鏽蝕的強化鋼筋完全外露。如鋼筋四周皆鏽蝕，則需將鋼筋底部切除，使能在鋼筋表面進行噴砂，而將鏽蝕完全清除乾淨。馬里蘭州 Timonium 的 U.S. Concrete Products公司爲修復用混凝土的製造商，爲符合由距離30英呎處(從窗戶越過採光井所見的距離)觀看牆面色彩與紋理需相稱的規範要求，而共同研發出一種顏色相稱、收縮低且可泵送的修復性混凝土。此要求說易行難，有些修復區域深度達4英吋，有些小於1英吋，更有些小到不符組裝模板的經濟效益。對於用手小量修補的修復區，即研發出適合以鏝刀施工的配方；對於其餘區域的修復，U.S. Concrete Products研發出一種可於現場拌製且具塑性的改良型聚合物袋裝材料。此材料易於泵送入模版中進行修復，且收縮龜裂極小。此配方未添加粗骨材，但其修復深度仍可達4英吋，且幾乎無龜裂，只需簡單地以外力振動即可達到良好的固結效能，且在3天內即可達到至少2,000psi的強度，而利於提早拆模。

圖 4：千斤鎚完成敲除腐蝕強化鋼筋的近照，箭頭所指爲底部十字交叉處，垂直鋼筋已嚴重損壞。

圖 5：在適當位置建造與原模板飾面相稱之新模板工程

圖 6：完成防蝕的牆面，但未完成矽烷與矽酸鉀塗料的塗佈。

修復混凝土的分包商 Concrete Protection and Restoration, Inc.,公司開發出一種模板工程工法(圖5)，其易於澆置修復用的混凝土，且能與原建模板飾紋相稱。歷經數次的試驗失敗，他們迅速地瞭解最佳的修復方法即是使用與1944年原承包商所使用相同的2x12模板建造工法，因而成功地作出完全相稱的飾面。

考量到五角大廈員工的作息，吵雜的混凝土敲除工程則於晚間進行，而混凝土的澆置與其他非吵雜性的工程則在白天進行，使工作能依計劃持續進行，但真正的挑戰卻是如何保護1,000,000平方英呎的外牆面長達50年之久，使其不因強化鋼筋的鏽蝕而遭受損壞。

鋼筋保護必須克服兩項困難點：鋼筋的保護層太薄且混凝土碳化深度過深；雨水易吸收入多孔隙的混凝土中。由於鋼筋的混凝土保護層只有或少於1/2英吋，一旦下雨，鋼筋即經常潮濕。一般pH值大於13的鹼性優質混凝土，即使鋼筋受潮，鋼筋四周所形成的惰性氧化層具有防蝕保護的作用；但混凝土碳化後將使混凝土的pH值降至11以下，而破壞此保護性氧化層，致使鋼筋暴露在腐蝕的威脅下，因此，保護方法需同時兼具抗水份的滲透與彌補鹼度的耗損。

圖 7：完成的展示牆面。

鹼度的耗損可藉由最新科技的滲透移動腐蝕阻鏽劑彌補達成。目前有許多的防蝕技術，包括降低腐蝕速率、降低腐蝕臨界值以及降低氯化物與二氧化碳的吸收率。五角大廈防蝕工程所選定的胺基阻鏽劑係因其可保護碳化混凝土中的鋼筋，而可有效降低腐蝕速率。胺基滲透移動阻鏽劑以三種方式產生作用：毛細管作用、氣化擴散作用與離子吸附作用。在毛細管作用中，混凝土如海綿般吸收水性阻鏽劑。一旦吸收入混凝土中，氣化的胺基分子即擴散遍佈整個混凝土基質。此擴散係根據菲克第二定律(Fick’s 2nd Law)，即分子會由高濃度區域擴散至低濃度區域直到兩者達到平衡為止。最後，當胺基分子接近埋置的鋼筋時，即產生物理吸附，而緊密地吸附於鋼筋的表面上。

美國明尼蘇達州聖保羅市Cortec Corporation所製造含胺基羧酸鹽的MCI 2020 V/O，因具有滲透入垂直面達鋼筋混凝土深度的特性以及其他強化功能，而被選爲此工程的阻鏽劑。MCI分子中所含的羧酸鹽具疏水性，當其吸附於鋼筋上，其可將水排開，而增強胺基對金屬的吸附力。腐蝕速率測試儀已證實其可有效減緩鋼筋的腐蝕速度，使腐蝕性由活性狀態降低至幾乎完全停頓狀態。鑽心樣本的化學萃取物測試也顯示其滲透的深度已遠超過鋼筋的表層。

然而，降低腐蝕速率僅達到一半的阻鏽功效，阻止水份的吸收才可使腐蝕完全停止。如何阻止水份吸收入牆面長達50年之久呢? 下一步的保護是提供減少水份吸收入牆面的工法。在MCI阻鏽劑噴塗後，於外牆面再噴塗100%固體的矽烷，將可降低水份的吸收並撥除水份。但矽烷只具撥水功效，當暴露於紫外線下即易遭破壞。爲進一步保護牆面，需使用一種更具耐久性的表層塗料，不但可維持50年壽命且可防止矽烷損壞。爲達到此要求，則選定矽酸鉀以強化表面，並同時保護撥水層與防蝕層。矽酸鉀係100多年前由德國Keim公司所研發與製造，當年其說明書中曾提及此產品而100年後的今天仍舊使用。矽酸鉀本身在混凝土表面上可形成一層堅韌與防水的無機表面，而具抵抗水份吸收的特性。經矽酸鉀與矽烷的雙重保護，水份可完全由混凝土的表面排除。此外，矽酸鉀易於均勻拌合色料，進一步改善符合規範中越過採光井觀看顏色的要求規定。

圖 8：以腐蝕速率偵測器偵測遭腐蝕損壞處的鄰牆，其未修繕下的腐蝕活動情況。

以四種不同產品一層接一層的施作於舊有建物上，其彼此的相容性是最重要的課題。在此工法設計期間，阻鏽劑、矽烷與矽酸鉀的製造商皆完成其相容性的測試，並提供聯合相容說明書，以對工法的材料功效提出20年的保證。

維持長達50年修繕工程目標的設計已完成。經修繕的混凝土已恢復其完整的結構與原採光牆的外觀，且此設計工法可在未來50年中保護五角大廈的混凝土不遭受腐蝕損壞。

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