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# HOW SILICONE-BASED INORGANIC COATINGS HELP PROTECT CULTURAL HERITAGE AND HISTORICAL MONUMENTS

Case studies on historical structures exposed to the natural environment show how a novel coating helps create a protective film with ceramic-like stability while preserving the original appearance.

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Many cultural heritage sites and historical monuments around the world have been suffering from environmental deterioration for a long time. To address this trend, the development of appropriate protective coatings has become one of the most important issues in modern conservation. This article focuses on one novel solution—silicone-based inorganic coatings, especially those derived from alkoxy silanes. Two case studies, conducted by the authors, are introduced to demonstrate the effectiveness of the coatings on historical structures.

## INTRODUCTION

Modern protective coatings are generally classified into two categories: organic coatings and inorganic coatings. Conventional organic coatings, such as acrylics, epoxies, and urethanes, are widely used because of their flexibility, strong adhesion, and ease of processing. However, when they are exposed to ultraviolet light, moisture, oxygen, and temperature fluctuations for a long time, their organic molecular structures gradually degrade through

photo-oxidation, chain scission, and hydrolysis. As a result, discoloration, cracking, and the loss of protective performance may occur over time.

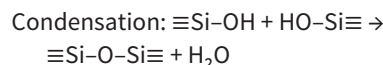
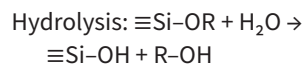
In contrast, inorganic coatings have been attracting increasing attention for applications requiring long-term durability and environmental resistance. Among various inorganic materials, those that are silicone-based have become particularly important. This is because they combine the flexibility of organic materials with the stability of inorganic networks.

## THE CHEMISTRY OF ALKOXY SILANE HYBRID COATINGS

The fundamental structure of silicone materials is based on siloxane bonds, represented by the Si–O–Si linkage. The Si–O bond (approximately 452 kJ/mol) is significantly stronger than the C–C bond (approximately 347 kJ/mol) found in conventional organic polymers. Therefore, silicone-based materials show excellent resistance to heat, ultraviolet radiation, oxidation, and weathering.

One important class of silicone-related materials is alkoxy silane-based resins. These materials contain alkoxy groups attached to silicone atoms. Although the term “silicone” usually refers to fully polymerized polysiloxanes, alkoxy silanes are their reactive precursors. Once cured, the resulting network is chemically continuous with silicone chemistry. Consequently, these coatings are often classified into the broader “silicone-based” family.

When alkoxy silanes are exposed to moisture in air or on substrate surfaces, the alkoxy groups undergo a two-step reaction, classically known as the sol-gel process:



Through this sequence, a dense inorganic or inorganic-organic hybrid network is gradually formed on the surface of the material and within the porous structure of the substrate. This moisture-curing mechanism is one of the key reasons why alkoxy silane-based systems are often described

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as “inorganic coatings,” even though they contain some organic functional groups. Unlike conventional organic paints, which mainly form carbon-based polymer films, these materials generate siloxane-based networks. The resulting films show ceramic-like stability while retaining moderate flexibility.

## WHY HERITAGE STONE NEEDS A SPECIAL COATING

Another important feature of alkoxy-silane-based materials is their strong affinity for mineral substrates, such as stone, concrete, ceramics, and glass. Silanol groups generated during hydrolysis first form hydrogen bonds with surface hydroxyls on the mineral substrate. Upon drying, they can undergo condensation to produce covalent Si–O–M (M = Si, Al, etc.) linkages. Therefore, the coating is anchored chemically rather than mechanically. This property, combined with the low pre-cure viscosity of the material, allows penetration into porous structures. As a result, alkoxy-silane-based coatings are particularly suitable for the conservation of historical monuments and cultural heritage objects.

In recent years, silicone and alkoxy-silane-based protective materials have been applied to the preservation of stone architectures and historical

structures exposed to severe environmental conditions. Their water repellency, weather resistance, and the ability to suppress deterioration while maintaining the original appearance of the substrate make them attractive candidates for cultural heritage conservation (Fig. 1).

One commercially available alkoxy-silane-based coating material has been used both experimentally and practically for the protection of historical stone structures. This includes applications related to cultural heritage sites in Cappadocia, Turkey, as well as traditional Japanese historical materials. These examples show the potential of silicone-derived inorganic coatings as an effective tool for the long-term preservation of irreplaceable cultural assets.

### CASE STUDY 1: CAPPADOCIA, TURKEY

Cappadocia, located in central Turkey, is one of the world’s most remarkable cultural heritage sites. It consists of unique rock formations, cave dwellings, underground cities, and historical monuments. Many of these structures were created by carving soft volcanic rocks and tuff. Although these materials have survived for centuries, they remain vulnerable to environmental deterioration caused by rainwater, moisture, wind erosion, temperature changes, and salt crystallization. As a result, cracks may form, surfaces may flake off, and parts of the rock structures may eventually collapse.

To address these issues, conservation projects have been carried out with the cooperation of the Turkish government, the Tokyo National Research Institute for Cultural Properties (Tobunken), and several universities and research institutions in Japan. In such projects, alkoxy-silane-based inorganic coating materials have played an important role.

Natural sandstone and volcanic tuff are porous materials. When water penetrates into their pore

structures, discoloration, weakening, and progressive deterioration may occur. By applying an alkoxy-silane-based resin to such stone surfaces, the liquid material can penetrate into the fine pores of the rock. After hydrolysis and condensation reactions, it forms a siloxane-based network inside the porous structure and on the surface. This network adheres strongly to the mineral substrate. Therefore, it helps protect the stone from water and other environmental factors.

Ideally, historical monuments should be preserved without any artificial treatment. However, in such cases where deterioration has already progressed and the risk of collapse becomes serious, carefully selected protective treatments are necessary. From a practical viewpoint, alkoxy-silane-based inorganic coatings are useful in this situation. They can reinforce fragile stone materials while maintaining, as much as possible, their original appearance and natural texture. In this sense, such materials offer a scientific and practical approach to passing valuable cultural heritage on to future generations.

### CASE STUDY 2: THE KITAZAWA SEKIBŌ, NAGANO, JAPAN

Another example is the Kitazawa Sekibō. A full-scale reproduction of the Kitazawa Sekibō, a large Jōmon-period ritual stone (sekibō) believed to represent fertility and regenerative power, was created in Sakuho Town, Nagano Prefecture, Japan. It was made of welded tuff. The Jōmon period, which lasted from approximately 14,000 BCE to 300 BCE, represents one of the earliest prehistoric cultures in Japan. It is well known for its pottery, stone artifacts, and spiritually symbolic objects. While the original artifact is carefully preserved and displayed in a museum environment, the reproduction serves as a protective surrogate for outdoor exhibition at the archaeological site (Fig. 2).

Because the exhibited object is a reproduction, an alkoxy-silane-based



**Fig. 1** — Dr. Katsuhiko Sano applying an alkoxy-silane-based coating on a rock surface in Cappadocia, Turkey. Courtesy of D&D K.K.



**Fig. 2** — The Kitazawa Sekibō and the application of silicone coating to the monument: (a) overall appearance; and (b) the coating shop. Courtesy of D&D K.K.

silicone coating could be applied to its surface. This treatment made it possible to display the object outdoors under severe environmental conditions, such as snowfall, rainwater exposure, freeze-thaw cycles, and significant temperature fluctuations, while preserving the original texture and color tone of the stone surface.

The effectiveness of silicone-based inorganic coatings in such applications is closely related to their unique molecular structure and to their interaction with porous mineral materials. Welded tuff contains numerous microscopic pores and pathways that allow water to penetrate into the interior of the stone. Once moisture enters these porous structures, repeated freezing and thawing may generate internal stress. As a result, cracking, surface exfoliation, and gradual deterioration may occur.

Alkoxysilane-based materials can penetrate deeply into these fine pore structures because of their low viscosity before curing. After penetration, hydrolysis and condensation reactions take place within the stone. They form a siloxane (Si–O–Si) network both inside the porous structure and on the surface. As a result, the treated stone

shows enhanced water repellency while still allowing trapped moisture to escape gradually. This combination of properties is collectively known as breathability. It is a fundamental difference from conventional acrylic and urethane coatings, which tend to form dense, near-impermeable organic films. From the practical viewpoint, this balance is particularly important in cultural heritage conservation. This is because the excessive sealing of stone surfaces may accelerate internal deterioration through freeze-thaw cycles or salt crystallization.

Another advantage of silicone-derived inorganic coatings is that they generally preserve the natural appearance of stone materials. Unlike thick organic paint films, these treatments form extremely thin protective layers. Therefore, they do not significantly alter surface texture, gloss, or color. As a result, the visual and tactile characteristics of historical stone objects can be maintained while improving environmental durability.

## OUTLOOK

Looking to the future, there are further studies to be carried out. The authors plan to continue investigating

the long-term behavior of alkoxysilane-derived coatings on heritage stone. For example, accelerated weathering tests, spectroscopic monitoring of the siloxane network, and depth-resolved analysis of resin penetration into porous lithologies are important issues in the next stage. Through these projects, the authors hope that conservators can choose the most suitable formulation for each heritage site, considering its specific mineralogy and microclimate. In this way, the application of materials science to cultural heritage will continue to develop further.

These examples show how silicone-based inorganic coatings can contribute not only to modern industrial materials protection but also to the long-term preservation of cultural heritage and archaeological monuments exposed to harsh natural environments. ~AM&P

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