Silane/Siloxane Surface Treatment for Cohesion Ability and Strengthening Agent of Historical Stone

Amir Ershad-Langroudi*, Hamid Fadaii, Kamran Ahmadi

1. Color & Surface Coating Group, Polymer processing Department, Iran Polymer and Petrochemical Institute (IPPI), Tehran, Iran
2. Research Center for Conservation of Cultural Relics, Tehran, Iran

ABSTRACT

Silane/siloxane surface treatment are proposed as potential polymeric materials for protective and consolidation coatings of limestone substrates. The silane and siloxane coatings are widely used to strengthen and waterproof of historical monuments. Historical stones are very fragile because of bearing many years in severe weathering conditions. Strengthening historical stones requires paying attention to surface treatment by the aim of decreasing humidity and improvement of mechanical properties. Toward this end, the consolidation coatings using silane and siloxane resins can improve the mechanical properties of historical stones against weathering condition. In this study, two types of coatings based on mixed of silane/siloxane as potential coatings to consolidate historical stones were proposed and the mechanical results were compared with uncoated stones. The mechanical tests approved the silane and siloxane resins can be considered as a proper choice to protect and strengthen historical stones. The results indicated that the contact angle of the coated samples rises up with treating by silane/siloxane resins. This could be due to the presence of organic groups of poly siloxanes act as hydrophobic agents which increase the hydrophobic nature of the surface contact angle. In addition, Si-OH bond of silane as well as consolidation effect can be created the covalent bonding by mineral surface and filling of the small fissures in the stone surfaces.

Keywords: Stone, Consolidation, Mechanical Properties, Coating, Silane, Siloxane

1. Introduction

Historical monuments have an immense aesthetic and cultural value as well as vital economic resource to absorb tourists from other countries (Beheshtifar, 2015; Xu, 2014). In general, the historical monuments are threatened by three types of weathering decays, i.e. chemical, physical and biological aging (Salazar-Hernández, Maria, Salgado, & Cervantes, 2010). However, these decays are often can have over all influence so that measuring their separate impact is almost impossible (Sadat-Shojai, Ershad-Langroudi, & Sadat-Shojai, 2009). For building materials such as lime stone, the acidic dissolution of the carbonate material is principal mechanism of chemical weathering (Ngoic Lan, Nishimura, Tsujino, & Phuong, 2005; Xu, Li, Chen, & Gao, 2010). Many classes of polymeric materials were developed in order to reduce or delay weathering effects on historical stone materials such as acrylics and methacrylate, alkoxysilanes, silicones and epoxies (Cardiano, Ponterio, Schiavo, & Piraino, 2005; Khallaf, El-Midayn, & El-Mofty, 2011; Morote-Martinez, Pascual-Sánchez, & Martinez, 2008; Zielecka & Bujnowska, 2005). Although, the using of these polymeric compounds have proved to be efficient in some case studies, such as granular disintegration, whereas the conservation of historical limestone is still challenging. This can be attributed to the pore and cracks as well as chemical composition of the limestone. Recently, calcium hydroxide nanoparticles and nanoparticles derived from calcium alkoxides are considered as an inorganic
consolidation materials to increase the durability and compatibility of historical limestone (Daniele & Taglieri, 2012; Favaro, Tomasini, Osso, & Vigato, 2008; Sadat-Shojai et al., 2009), however, the results shows poor resistance in acidic condition. Alkoxysilanes are usually selected for the protection and conservation of stone in research studies. The silica particles formed by hydrolysis and condensation of alkoxysilanes, such as tetraethoxysilane (TEOS) are used to coat (Ershad-Langroudi & Rahimi, 2009). However, the silica and calcite indicated weak compatibility and chemical affinity to each other (Doehne & Price, 2010; Snethlage, 2011; Wheeler, 2005). Several research studies have been conducted aiming at modifying and improving alkoxysilane performance (Li et al., 2013; Ngoic Lan et al., 2005; Xu, Li, Zhang, Zhang, & Xu, 2012). TEOS modified by non-octylamine in order to obtain crack-free products and reduce the shrinkage during drying of silica particles (Illescas & Mosquera, 2012). Another effort is done by adding PDMS-OH to the silica sol to prepare hydrophobic products (Facio & Mosquera, 2013; Fermo et al., 2014; Xu, Li, Zhang, Zhang, & Xu, 2013). The adding organic to inorganic component improves the toughness and flexibility of the conservation product, while decreasing the shrinkage of silica networking and preventing cracking of the inorganic gel. Furthermore, organic groups were integrated in the upper side of organic inorganic silica based composite enhancing hydrophobic properties (Ershad-Langroudi, Mai, Vigier, & Vasoille, 1997). The historical stone had been severely harmed by environmental weathering conditions. The study indicates that the environmental conditions such as humidity, improper installation place T transference, and porous structure of the stones had led to many mechanical defects such as, cracks, fractures, pores, peeling, and swelling. In order to find a proper method to consolidate these historical stones, two silane/siloxane coatings were performed on the prepared samples and the mechanical results were compared as a possible suggestion materials to protect and strengthening of the historical stones against weathering conditions.

2. Material and Methods

The Two commercial products (i.e., SILRES® BS-290 from Wacker Co. and IMPERMEABILIZANTE 10AG with commercial name Long Life) were used for comparison as hydrophobic protective coating and mechanical consolidation of stone. SILRES® BS-290, a solvent-less silicone concentrate that is based on a mixture of silane and siloxane products were purchased from Wacker Chemie AG. Typical general characteristics of these products are presented in the wacker site (Wacker Chemie AG).

Long life is formulated based on solvents and low molecular weight siloxanes, which makes easier the penetration in the treated substrates. This product is purchased from Pars Excir tiyam distributor of Satecma & Timon international company’s products in Iran (No 374983).

The stone samples were cut in cubic form and washed with alkaline detergent rinsed with methanol and deionized water, respectively and dried in hot oven before applying the coating. The stone samples were coated with four brush strokes and were left to cure/polymerize, for more than 24 h at room temperature, resulting a uniform and crack free coating of siloxane, enriched with SiO2 nanoparticles composite coatings.

The stone samples were characterized by laboratory X-ray powder diffraction technique, using a BRUCKER, D8 ADVANCE instrument equipped with Cu X-ray source. The tested samples was prepared in the powder form. First, about 5 grams of stone, picked, dried and ground into particles of 70 to 75 microns and then was spread on a metal plate. The diffraction pattern were obtained on the powdered sample using a Cu Kα incident beam (λ= 1.542 Å) at 2θ= 4°-70° and a scanning speed of 0.02°/s.

Scanning electron microscopy (SEM) was performed on the coated samples to characterize the surface morphology with scanning electron microscopy, SEM (VEGA\TESCAN, Czech Republic), at an accelerating voltage of 1500 kV. The semi-quantitative elemental composition was measured using energy-dispersive X-ray spectroscopy, EDX mapping (INCA Penta FET×3, Oxford, U.K.). The water contact angles on the coating samples were measured by G10 KRUS at ambient condition, with five replicates of water droplets placed at three different positions on one specimen.

Impact specimens of 63.5 mm in length, 12.7 mm in width, and 10.1 mm in thickness were performed by using the Charpy impact testing Zwick model 5102 equipment. All the test specimens were unnotched with a pendulum of 1J, in which the specimens were horizontally positioned between the 2 fixed supports at room temperature.

Flexural strength test was performed by the 3-point bending test using a universal testing machine with a crosshead speed of 5mm/min. The flexural testing device consisted of a central loading plunger and 2 polished cylindrical supports, 3.2 mm in diameter and 10.5 mm long. The distance between the centers of the supports was 50mm. The compressive force was applied perpendicular to the center of the specimens until a deviation of the load-deflection curve and the fracture of specimen occurred.
The dimensions of stone specimens were 10×10×108mm. All mechanical test was performed on the samples prepared from the core of stone at room temperature.

**Fig 1.** XRD spectrum of stone specimen (Beheshtifar, 2015)

### 3. Results and Discussion

X-ray test is a standard way to identify its composition. The XRD-spectrum of stone samples is presented in Fig 1. As seen in this figure, the major component is calcite (i.e. calcium carbonate) with hexagonal crystal lattice.

Table 1 presents the components of stone sample with chemical formula, crystalline structure and weight presentage of each phases. As a result, the major crystalline phase in the stone sample is calcite with 82.4 wt%, and aluminous silicate minerals as feldspars (i.e. Anorthite, Tremolite, Sepiolite and Albite) are the minor part about of 18wt%. From these data, it can be concluded that the main mineral is calcite with ~82 wt%, therefore the historical analyzed stone is limestone.

A typical outdoor historical stone samples are shown in Fig 2. This figure presents an incompact structure with many pores and fissures and cracking in the weathering stone surfaces. The pores and fissures indicated that the surface of historical stone is significantly affected and eroded by a variety of environmental factors.

Some of these pores can be developed to form a network of pore spaces by water, gas or ions penetration under natural environmental exposure conditions (Christodoulou, Goodier, Austin, Webb, & Glass, 2013). Ions such as chlorides and sulfates dissolved into water are transported into the pores and fissures by capillary suction, which subsequently cause corrosion of the limestone and ultimately spalling of the surrounding stone face. Therefore, hydrophobic coating can be used in the building materials such as stone to prevent water and ions entrance (Medeiros & Helene, 2008, 2009; Yang, Wang, & Weng, 2004).

**Table 1.** Crystalline structure and weight present of the analyzed sample (Beheshtifar, 2015)

| Component       | Chemical Formula     | Wt% | Crystalline Structure  |
|-----------------|----------------------|-----|-----------------------|
| Calcite, syn    | CaCO₃                | 82.4| Hexagonal (Rh)        |
| Anorthite, sodian, ordered | (Ca,Na)(Al,Si)₂Si₂O₈ | 5.5 | Triclinic             |
| Tremolite       | Ca₂Mg₅Si₈O₂₂(OH)₂    | 4.8 | Monoclinic            |
| Sepiolite-(Mn)  | Mn₂Fe₃Si₁₂O₃₀(OH)₁₆·8H₂O | 4.3 | Monoclinic            |
| Albite, ordered | NaAlSi₃O₈             | 3   | Triclinic             |
The relevant consolidation mechanisms for the water proof coatings can be divided into three categories: skin coatings, blocked pores and pore liners (Fig 3).

The consolidation with categories of $a$ and $b$ (i.e. $(a)$ skin coatings and $(b)$ blocked pores in Fig 3) is very risky. In practical terms, the results demonstrated that Paraloid B72 (and alike the other acrylic copolymers) acts like an adhesive or gluing agent and not as a real impregnating strengthening agent of historical limestone.

![Fig 3. Categories of surface impregnations: (a) skin coatings, (b) pore blocking and (c) pore liners adopted from (Christodoulou et al., 2013).](image)

The alkoxy groups (e.g. methoxy, ethoxy) of siloxane hydrolyzed and condensed with eliminating water or alcohol and reacted with creating Si-O-Si bonding with silicate or other polar groups presented in the stone surface. The organic groups (e.g. methyl (CH$_3$) or longer organic chain such as butyl or octyl) remaining in the upper side of hydrophobic structure are responsible for the hydrophobic characteristics (Christodoulou et al., 2013; Vries & Polder, 1997).

![Fig 4. Detachment of a thin hard skin coating during an ageing test of a porous limestone specimen treated with Paraloid B72 (adopted from Ferreira Pinto & Delgado Rodrigues, 2008)).](image)

Numerous studies approve that the application of silanes and siloxanes significantly reduces water uptake, which as a result reduces the entrance of destructive ions such as chlorides and sulfates, hence also improves the stone conservation (Christodoulou et al., 2013; Medeiros & Helene, 2008; Sadat-Shojai et al., 2009; Vries & Polder, 1997). However, their performance is also depended on the numerous parameters such as surface defects, weathering conditions, surface preparation method, skill of the operator and local environmental conditions at the time of application.

Surface morphology of the samples was examined by scanning electron microscopy. The surface of samples was cleaned with alcohol, dried in an oven and coated with thin layer of Au before the surface analysis. Fig 6 (a) to 6(c) present the surface of stone samples before and after coating by two silane/siloxane components, respectively.

As seen in Fig 4, the use of Paraloid B72 (and other polymers like it) for consolidation propose of the dense, fissured or fractured limestone, can be very risky or even disastrous when used inadequately particularly in the very porous limestone (Ferreira Pinto & Delgado Rodrigues, 2008).

![Fig 6. Surface of stone samples before and after coating by two silane/siloxane compositions.](image)

Alkoxy and alkyl silanes usually used for surface impregnations in the third category (i.e. see in Fig 3 (c) the pore liner) (Christodoulou et al., 2013). The adhesion of alkyl alkoxy silanes on a polar mineral surface is shown by Fig 5 (Snethlage, 2011).

![Fig 5. Alkoxy groups (e.g. methoxy, ethoxy) of siloxane hydrolyzed and condensed with eliminating water or alcohol and reacted with creating Si-O-Si bonding with silicate or other polar groups presented in the stone surface.](image)

Alkoxy and alkyl silanes usually used for surface impregnations in the third category (i.e. see in Fig 3 (c) the pore liner) (Christodoulou et al., 2013). The adhesion of alkyl alkoxy silanes on a polar mineral surface is shown by Fig 5 (Snethlage, 2011).

![Fig 5. Alkoxy groups (e.g. methoxy, ethoxy) of siloxane hydrolyzed and condensed with eliminating water or alcohol and reacted with creating Si-O-Si bonding with silicate or other polar groups presented in the stone surface.](image)

The SEM observation of the treated samples provided evidence that the silane/siloxane resins cover the crystalline structure of the lime stone samples and form a uniform and crack free smooth surface film (Fig. 6(b) and 6(c)), thus maintain their protective properties and avoid the penetration of water during the absorption test.

![Fig 6. Surface of stone samples before and after coating by two silane/siloxane compositions.](image)

In the both cases (i.e. Wacker BS 290 and Long life), the coating layers adhere well to the limestone while with Long Life in compared to BS 290, the coating layer is more uniform and smooth which can be attributed to more thickness which favor the good mechanical performances. In the case of Wacker BS 290, the coating layer is thin as seen by the rough grain morphology of stone under the film, thus it is expected better water vapor permeability in compared to thicker film layer in the long life coating.

![Fig 6. Surface of stone samples before and after coating by two silane/siloxane compositions.](image)
Fig 5. Adhesion of alkyl alkoxy silane molecular structure on a hydrophilic mineral surface (Snethlage, 2011)

Fig 6. SEM images of limestone specimens: (a) uncoated, (b) coated by BS 290 and (c) coated by Long Life.
Table 2 shows the concentrations of various elements in the surface of limestone specimens under two consolidation coatings as well as in the raw condition. According to Table 2, the calcium content is higher in the BS 290 coated sample than the specimen coated by long life, which is another reason for higher thickness of the Long life coating samples. While carbon content is higher in the Long Life from BS 290 coated samples. It can be an indication of the organic groups (e.g. methyl (CH₃) or longer organic chain such as butyl or octyl) responsible for the hydrophobic characteristics. Therefore, it is expected that the coated samples by BS 290 have the higher contact angles than it’s of Long Life. However, the higher amount of silicon and oxygen elements of Life Long coatings probably conducts a combination of strength and mechanical properties by creating more covalent bond, Si-O-Si or Si-O-M (where M is metallic elements like Al) between coating and substrate.

According to the results in Table 3, impact resistance of both coated samples in compared to uncoated samples is increased. As a result indicated in Table 3, the application of the Long life coated sample, is more effective than the BS 290 coated sample, in increasing the impact resistance of stone sample. It may be attributed to different silane to siloxane ratio in these products.

**Table 2.** EDX analysis of the surface of limestone specimens

| Elements | Raw | BS 290 coating | Long life coating |
|----------|-----|----------------|------------------|
| C        | -   | 76.34          | 34.39            |
| O        | 50.1| -              | 24.16            |
| Mg       | 1.47| -              | 0.23             |
| Al       | 3.83| 0.67           | -                |
| Si       | 10.4| 5.92           | 40.1             |
| Cl       | 1.75| -              | 0.24             |
| Ca       | 23.73| 16.9          | 0.7              |
| Fe       | 8.71| 0.51           | 0.17             |

Contact angle measurements on the stone samples are shown in Fig 2. As seen in this figure, the coated samples with BS290 has the higher contact angle. Increasing the contact angle can induce the higher hydrophobicity and lower water penetration in the coating.

According to the results in Table 3, impact resistance of both coated samples in compared to uncoated samples is increased. As a result indicated in Table 3, the application of the Long life coated sample, is more effective than the BS 290 coated sample, in increasing the impact resistance of stone sample. It may be attributed to different silane to siloxane ratio in these products.

**Table 3.** Sharpy measurements

| Treated Samples | Impact Strength (J/m) |
|-----------------|-----------------------|
| Raw             | 11.54±1               |
| BS 290          | 52.5±1.2              |
| Long Life       | 62.9±2.2              |

**Table 4.** Flexural measurement

| Samples      | $E_{\text{Flexural}}$ (MPa) | Flexural strength (MPa) | Energy of Break (J) |
|--------------|-----------------------------|-------------------------|---------------------|
| Raw          | 2620±250                    | 11.7885±2               | 12.9±1              |
| BS 290       | 3150±200                    | 17.1874±0.9             | 33.5±5              |
| Long Life    | 3876±400                    | 18.9735±1.1             | 21.7±3              |
4. Conclusion

In the present work, two silane/siloxane resins and their performances were evaluated for conservation of historical limestone. The hydrophobicity and surface morphology as well as elemental distribution were investigated. The performed experiments showed two commercial products can be performed uniform and crack free coatings. However, the higher hydrophobic and protection properties for silane/siloxane dilutable with organic solvents indicate it can be selected as a more suitable candidate for conservation and protection of the limestone artwork for cultural heritages.

Within the limits of this investigation, it seems that there are advantages to using silane siloxane coatings in compared to uncoated stone for consolidation of historical limestone. The performed experiments showed two silane/siloxane products are stable, with higher impact strength and flexural properties. Therefore, these coatings can be considered as the potential candidate for consolidation of the fragile and weathered limestone artwork heritages.

5. Acknowledgments

The authors would like to acknowledge with gratitude Iranian Research Institute for Cultural Heritage & tourism who kindly supported this work financially and Iran Polymer and Petrochemical Institute (IPPI) who kindly provided the facility for doing Laboratory research. The authors would like to gratitude of Mrs Beheshti far for comparing some data of her MSc Thesis in this study.

6. Conflict of Interest

Authors declared no conflict of interest.

7. References

Ershad-Langroudi, M., Sadat-Shojai, Siloxane-Based Coatings as Potential Materials for Protection of Brick-Made Monuments, Journal of color science and Technology (in Persian) 3 (2009) 177-188. available online @ www.jcst.icrc.ac.ir

Beheshtifar, M. (2015). Technical studies providing a protective mechanism stone plinth period Ghajar of hazrat masomeh (S) Transferred to the Green Dom. Tehran: Islamic Azad University.

C. Rodriguez-Navarro, A. Suzuki, E. Ruiz-Agudo, Alcohol dispersions of calcium hydroxide nanoparticles for stone conservation, Langmuir 29 (2013) (1470) 11457–11461.

Cardiano, P., Ponterio, R. C., Schiavo, S. L., & Piraino, P. (2005). Epoxy-silica polymers as stone conservation materials. Polymer, 46(6), 1857–1864.

Christodoulou, C., Goodier, C. I., Austin, S. A., Webb, J., & Glass, G. K. (2013). Long-term performance of surface impregnation of reinforced concrete structures with silane. Construction & Building Materials, 48, 708–716.

Daniele, V., & Taglieri, G. (2012). Synthesis of Ca(OH)2 nanoparticles with the addition of Triton X-100: Protective treatments on natural stones: Preliminary results. Journal of Cultural Heritage, 13(1), 40–46.

Delgado Rodrigues, J., & José Delgado Rodrigues. (2015). Defining, mapping and assessing deterioration patterns in stone conservation projects. Journal of Cultural Heritage,16(3), 267–275.

Dochne, E., & Price, C. A. (2010). Stone conservation. In Stone Conservation: An Overview of Current Research. Los Angeles: Getty Conservation Institute.

Ershad-Langroudi, A., & Rahimi, A. (2009). Synthesis and characterisation of nano silica-based coatings for protection of antique articles. International Journal of Nanotechnology,6(10/11), 915–925.

Ershad–Langroudi, A., Mai, C., Vigier, G., & Vasoille, R. (1997). Hydrophobic Hybrid Inorganic–Organic Thin Film Prepared by Sol–Gel Process for Glass Protection and Strengthening Applications. Journal of Applied Polymer Science, 65(12), 2387–2393.
30 Silane/Siloxane Surface Treatment

Facio, D. S., & Mosquera, M. J. (2013). Simple strategy for producing superhydrophobic nanocomposite coatings in situ on a building substrate. *Applied Material Interfaces, 5*(15), 7517–7526. https://doi.org/10.1021/am401826g

Favaro, M., Tomasin, P., Ossola, F., & Vigato, P. A. (2008). A novel approach to consolidation of historical limestone: The calcium alkoxides. *Applied Organometallic Chemistry, 22*, 698–704.

Fermo, P., Cappelletti, G., Cozzi, N., Padeletti, G., Kaciulis, S., Brucale, M., & Merlini, M. (2014). Hydrophobizing coatings for cultural heritage. A detailed study of resin/stone surface interaction. *Applied Physic A, 116*(1), 341–348.

Ferreira Pinto, A. P., & Delgado Rodrigues, J. (2008). Stone consolidation: The role of treatment procedures. *Journal of Cultural Heritage, 9*(1), 38–53. Retrieved from http://www.sciencedirect.com/science/article/pii/S1382969107000139.

Illescas, J. F., & Mosquera, M. J. (2012). Producing surfactant-synthesized nanomaterials in situ on a building substrate, without volatile organic compounds. *Applied Material Interfaces, 4*(8), 4259–4269.

J. Delgado Rodrigues, Consolidation of decayed stones. A delicate problem with few practical solutions, Historical Constructions, P.B. Lourenço, P. Roca (Eds.), International Seminar on Historical Constructions. Guimarães, Portugal Guimarães, (2001) 3-14.

Khallaf, M. K., El-Midany, A. A., & El-Mofty, S. E. (2011). Influence of acrylic coatings on the interfacial, physical, and mechanical properties of stone-based monuments. *Progress in Organic Coatings, 72*(3), 592–598.

Li, D., Xu, F., Liu, Z., Zhu, J., Zhang, Q., & Shao, L. (2013). The effect of adding PDMS-OH and silica nanoparticles on sol–gel properties and effectiveness in stone protection. *Applied Surface Science, 266*, 368–374.

Medeiros, M. H. F., & Helene, P. (2008). Efficacy of surface hydrophobic agents in reducing water and chloride ion penetration in concrete. *Materials and Structures, 41*(1), 59–71.

Medeiros, M. H. F., & Helene, P. (2009). Surface treatment of reinforced concrete in marine environment: Influence on chloride diffusion coefficient and capillary water absorption. *Construction & Building Materials, 23*(3), 1476–1484. https://doi.org/10.1016/j.conbuildmat.2008.06.013

Morote-Martínez, V., Pascual-Sánchez, V., & Martín-Martínez, J. M. (2008). Improvement in mechanical and structural integrity of natural stone by applying unsaturated polyester resin-nanosilica hybrid thin coating. *European Polymer Journal, 44*(10), 3146–3155.

Ngoic Lan, T. T., Nishimura, R., Tsujino, Y., & Phuong, T. (2005). The effects of air pollution and climatic factors on atmospheric corrosion of marble under field exposure. *Corrosion Science, 47*(4), 1023–1038.

Sada-Shojai, M., & Ershad-Langrudi, A., & the Mehdi Sada-Shojai. (2009). Amir Ershad-Langrudi, Polymeric Coatings for Protection of Historic Monuments: Opportunities and Challenges. *Journal of Applied Polymer Science, 112*(4), 2535–2551.

Salazar-Hernández, C., María, J. P. A., Salgado, P., & Cervantes, J. (2010). TEOS–colloidal silica–PDMS–OH hybrid formulation used for stone consolidation. *Applied Organometallic Chemistry, 24*, 481–488.

Snethlage, R. (2011). Stone Conservation. In S. Siegsmund & R. Snethlage (Eds.), *Stone in Architecture* (pp. 411–544). Springer Berlin Heidelberg; https://doi.org/10.1007/978-3-642-14475-2_7

Troiano, F., Vicini, S., Gioventù, E., Lorenzi, P. F., Impora, C. M., & Cappitelli, F. (2014). A methodology to select bacteria able to remove synthetic polymers. *Polymer Degradation & Stability, 107*, 321–327.

Vries, J., & Polder, R. B. (1997). Hydrophobic treatment of concrete. *Construction & Building Materials, 11*(4), 259–265.

Wheeler, G. (2005). *Alkoxysilanes and the Consolidation of Stone*. Los Angeles, CA: The Getty Conservation Institute.

Xu, F., Li, D., Chen, W., & Gao, S. (2010). Formation of hydrophobic silica coating on stones for conservation of historic sculptures. *Chinese Journal of Chemistry, 28*(8), 1487–1490.

Xu, F., Li, D., Zhang, Q., Zhang, H., & Xu, J. (2012). Effects of addition of colloidal silica particles on TEOS-based stone protection using n-octylamine as a catalyst. *Progress in Organic Coatings, 75*(4), 429–434.

Xu, F., Li, D., Zhang, Q., Zhang, H., & Xu, J. (2013). Effect of the addition of hydroxyl-terminated polydimethylsiloxane to TEOS-based stone protective materials. *Journal of Sol-Gel Science and Technology, 65*(2), 212–219.

Xu, F., Xiang, N., Li, D., Yu, J., Wu, D., & Zhang, Q. (2014). Use of coupling agents for increasing passivants and cohesion ability of consolidant on limestone. *Progress in Organic Coatings, 77*(11), 1613–1618.

Yang, C. C., Wang, L. C., & Weng, T. L. (2004). Using charge passed and total chloride content to assess the effect of penetrating silane sealer on the transport properties of concrete. *Materials Chemistry and Physics, 85*(1), 238–244.
Zhang, Z., MacMullen, J., Dhakal, H. N., Radulovic, J., Herodotou, C., Totomis, M., & Bennett, N. (2013). James MacMullen, Hom Nath Dhakal, Jovana Radulovic, Constandinos Herodotou, Miltiadis Totomis, Nick Bennett, Biofouling resistance of titanium dioxide and zinc oxide nanoparticulate silane/siloxane exterior facade treatments. Building and Environment, 59, 47–55.

Zielecka, M., & Bujnowska, E. (2005). Silicone-containing polymer matrices as protective coatings properties and applications. Progress in Organic Coatings, 55(2), 160–167.

How to Cite This Article:

Ershad-Langroudi A, Fadaii H, Ahmadi K. Silane/Siloxane Surface Treatment for Cohesion Ability and Strengthening Agent of Historical Stone. Ir Cons Sci J. 2017; 1 (1) :23-31

URL: http://journal.richt.ir/ics/article-1-24-en.html