https://doi.org/10.36910/6775-2410-6208-2023-10(20)-19

UDC 691.335:069.44

FEASIBILITY OF USING GEOPOLYMER SOLUTION IN THE CONSERVATION OF ARCHITECTURAL MONUMENTS

ДОЦІЛЬНІСТЬ ВИКОРИСТАННЯ ГЕОПОЛІМЕРНОГО РОЗЧИНУ ПРИ ВІДНОВЛЕННІ ПАМ'ЯТОК АРХІТЕКТУРИ

Chernieva O, Ph.D. in Engineering, Associate Professor (Odesa State Academy of Civil Engineering and Architecture, Ukraine); Morgenstern H., Dr.-Ing., Head of the Conservation and Repair Working Group (AG4) (Institute for Building Materials Research RWTH Aachen University, Germany); Raupach M., Dr.-Ing., Univ.-Prof. (Institute for Building Materials Research RWTH Aachen University, Germany)

Чернєва О., к.т.н., доц. (Одеська державна академія будівництва та архітектури, Україна); Моргенштерн Х., д.т.н., керівник робочої групи консервації та ремонту (AG4) (Інститут дослідження будівельних матеріалів RWTH Аахенського університету, Німеччина); Раупах М., д.т.н., проф. (Інститут дослідження будівельних матеріалів RWTH Аахенського університету, Німеччина)

Preservation and maintenance of architectural monuments have always been the number one task for civil engineers. In this context, the engineer encounters a "wagon load" of problems. On the one hand, there are strict requirements for the composition of materials used for restoration. On the other hand, it is the almost insurmountable challenge of selecting the right materials with the essential properties for the proper restoration of an architectural monument. Fixing of cracks and cavities is crucial for the durability of reinforced concrete and stone structures. These need to be treated scientifically to ensure usability.

In this setting, the use of Epoxy resins has become common. While Epoxy resins perform well under certain circumstances, they have many disadvantages such as heat instability, high costs, high resource demand, and serious health and environmental hazards. Furthermore, Epoxy resins are proscribed in monument preservation. To overcome the potential disadvantages of Epoxy resins, Geopolymers offer a promising alternative. Geopolymers are an environmentally friendly and durable substitute with low viscosity, supported by high-temperature stability. Using inorganic additives, geopolymer can expand and create a preload during solidification; this is a salient favorable feature since any decrease in volume will lead to the creation of a new cavity or crack of a smaller size. According to previous studies [1], the implementation of this low-CO2 geopolymer cement in construction and civil engineering would reduce CO_2 emissions caused by the cement and concrete industry by 80%

This article presents the main advantages and disadvantages of the proposed *geopolymer solution, in comparison to the ordinary cement mortar. The authors present the argument for the expediency of using a geopolymer solution in the reconstruction of architectural monuments.*

Збереження та утримання пам'яток архітектури завжди було завданням номер один для інженерів-будівельників. У зв'язку з цим інженер стикається з величезною кількістю проблем. З одного боку, це жорсткі вимоги до складу матеріалів, які використовуються для реставрації. З іншого боку, це неможливість підібрати відповідні властивості матеріалів для належної реставрації пам'ятки архітектури. Усунення тріщин та порожнин має вирішальне значення для довговічності залізобетонних та кам'яних конструкцій. Щоб забезпечити їх експлуатаційну придатність, потрібен науковий підхід. Для вирішення цього питання зазвичай використовують епоксидні смоли. Хоча епоксидні смоли добре працюють за певних обставин, але вони мають багато недоліків, таких як чутливість до нагрівання, висока вартість, високі вимоги до ресурсів і небезпека для навколишнього середовища та здоров'я. Крім того, епоксидні смоли заборонені при охороні пам'яток. Щоб подолати потенційні недоліки епоксидних смол, геополімери пропонують багатообіцяючу альтернативу. Геополімери є екологічно чистим і довговічним замінником з низькою в'язкістю, що підтримується високотемпературною стабільністю. Завдяки неорганічним добавкам геополімер при затвердінні розширюється і створює попереднє навантаження, це помітна перевага, оскільки будь-яке зменшення об'єму призведе до утворення нової порожнини або тріщини меншого розміру. Згідно з попередніми дослідженнями [1], застосування цих геополімерних цементів з низьким вмістом CO_2 у будівництві та цивільній інженерії зменшить викиди CO_2, спричинені цементною та бетонною промисловістю, на 80%.

У статті наведено основні переваги та недоліки геополімерного розчину, приводиться його порівняння зі звичайним цементним розчином. Автори обґрунтовують доцільність використання геополімерного розчину при реконструкції пам'яток архітектури.

Keywords: geopolymer, epoxy resins, restoration, cracks
Ключові слова: геополімер, епоксидні смоли, відновлення, тріщини

Introduction

On the question of ensuring the preservation of architectural monuments, the main legislative document is the Venice Charter. Article 10 of the Venice Charter says: "Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience" [2]. According to Article 12 of the Venice Charter "Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence" [2].

The use of new materials is always decided on a case-by-case basis together with the responsible monument protection office; there is no general, material-specific regulation [3].

According to the above arguments, the use of geopolymer-based solutions for filling cracks and chips in architectural masonry is possible and does not contradict current rules and regulations.

Goals and objectives of the study.

Under the circumstances, this technical paper attempts to discuss the nature of geopolymer binders and presents the line of reasoning to support their utilization in the new era for the restoration of buildings.

What is Geopolymer?

Geopolymer mortars - what are they - a long-forgotten past or a potential bright prospect for the ecological construction of the future?

Looking into history and drawing an analogy between the properties of modern geopolymer mortars and Roman cement or the stones of the Egyptian pyramids, it becomes clear that our ancestors already knew the recipe for this durable and corrosion-resistant material. However, with the development of Portland cement and its mass production and use, people stopped thinking about the environmental friendliness of materials and began to inconsiderately erect buildings from concrete. Now, due to a realistically foreseeable environmental disaster, long-forgotten geopolymers are becoming the object of modern construction science.

Geopolymers are inorganic, typically ceramic, alumino-silicate forming long-range, covalently bonded, non-crystalline (amorphous) networks. Obsidian (volcanic glass) fragments are a component of some geopolymer blends [4].

In 1979 Joseph Davidovits created and applied the term “Geopolymer” as the raw materials used in the synthesis of silicon-based polymers are mainly rock-forming minerals of geological origin [5]. Geopolymers are divided into two main groups: pure inorganic geopolymers and geopolymers containing organic substances, synthetic analogs of naturally occurring macromolecules.

Main properties of Geopolymer vs Portland Cement

Based on the precursor material geopolymer cement could be divided into slag-based geopolymer cement, rock-based geopolymer cement, fly ash-based geopolymer cement, and ferro-sialate-based geopolymer cement.

a. Influence of location (source of feedstock)

Research by Australian scientists McLellan, Williams, Lay, Arie van Riessen, and Corder (2011) proves the environmental friendliness and cost-effectiveness of using geopolymers compared to ordinary Portland cement (OPC). For the proposed “typical” Australian geopolymer product, there is an estimated 44-64% improvement in greenhouse gas emissions over OPC, while on the flip side, the cost of these geopolymers can go up to twice as high as OPC [6]. However, the paper also indicates that those benefits are only realizable given the most appropriate source of feedstock, supported by reduced transportation costs. The broad range of potential feedstock sources offers a very wide range of potential impacts: compared with emissions from OPC concrete, emissions from geopolymer concrete can be 97% lower and up to 14% higher. Each application for geopolymers therefore needs to be assessed based on its specific location, given that the impact of the location on the overall sustainability is one of the determining factors [6].

b. Resistance to destructive/acidic impact

The results of the study [7] show that geopolymer fine-grained concrete based on lignite ash has a higher resistance to the effects of a 3% sulfuric acid solution and a 5% sodium sulfate solution compared to cement mortars. The loss of strength when exposed to sulfuric acid for 120 days in these concretes did not exceed 3,6%. The acid and sulfate resistance of geopolymer materials is explained [7] by the high resistance to destruction under the influence of aggressive environments due to the three-dimensional polymer structure of the geopolymer binder compared to the multiphase structure of hydrated cement.

Work [8] shows that the acid resistance of geopolymer fine-grained concrete when using sodium hydroxide as an activator is higher than that of concrete with sodium silicate.

It has been established [9] that geopolymer concrete, despite its higher alkali content than cement concrete, is not characterized by an alkali-silica reaction.

When geopolymer fine-grained concrete is exposed to acids and sulfates in 28 days, according to [10], they lose no more than 2,5% of the original mass, while the mass of cement concrete samples decreases: in H_2SO_4 solution - by more than 22%, and in HCl solution – 8%. The authors of [11] believe that the reason for the increased acid and sulfate resistance of geopolymer concretes is the absence of $Ca(OH)_2$ in their composition.

c. Reduced carbon emissions/environmental impact

According to Komnitsas's (2011) study, geopolymer concrete made from fly ash (FA) and GBFS results in lower CO_2 emissions than OPC concrete [12]. The environmental impact of geopolymer concrete is associated with the use of a sodium silicate solution, the production of which uses a pure glass cullet. However, discarded cullet can easily be used as an alternative source of silicate. Slag-based geopolymer concrete requires only a small amount of sodium silicate and therefore has a low environmental impact. In addition, the use of these wastes reduces the environmental impact associated with their disposal and the subsequent formation of hazardous leachates.

Problems of Geopolymers

a. Lack of supporting regulations

The use of any building material must be based on:

- the relevant regulatory documents and standards governing and regulating the composition.

- the necessary physical, chemical, and mechanical properties of the output material,
- susceptibility to corrosion and the possibility of application.

Necessary supportive regulatory documents and standards must be created for Geopolymers. This would serve as an impetus to their increased use and expose the product to a wide consumer market.

b. Drawback with "fast setting"

Another problem of geopolymer binder was discussed by M. Criado (2009) and it is its poor workability: "Alkali-activated fly ash has a much greater plastic viscosity than ordinary Portland cement and is prone to fast setting" [13]. The viscosity can be adjusted with the right mixture, but the fast setting is a limiting factor for certain applications.

c. Work environment safety

It is essential, in an industrial work environment to give adequate importance to the issue of operational safety. Lack of proper care in handling sodium hydroxide used in the manufacture of geopolymers can cause chemical burns of varying degrees.

d. Inadequate study on Geopolymer shrinkage

Despite the great importance of the shrinkage of geopolymer and other alkali-activated binders, this phenomenon has not been sufficiently studied and results documented. This occasionally results in a high degree of unpredictability – this in turn adversely affects the use of these binders on an industrial scale.

Geopolymer mortar as a repair material

The possibility of using Geopolymer mortars as a gap compensation material for wind power plants has been proven. Good results were obtained, during the experimentation conducted by Hendrik Morgenstern and Michael Raupach [14]. The research successfully established the fact that the developed geopolymer could be used as a compensation material for gaps as small as 1mm.

The idea of the conducted study [15] was to establish the effectiveness of a material that would combine reasonable mechanical strength with a low viscosity allowing injectability. A metakaolin-based geopolymer and several inorganic fillers and additives were combined and tested regarding their applicability as an injection material. The experiment ascertained the effectiveness of the material to handle cracks and fill gaps.

The work of Frasson, Pelisser, and Silva (2020) have determined that the repairs made with geopolymer cement are a viable and efficient means of crack recovery. The geopolymer cement paste and an epoxy adhesive, as a reference, were used for the repairs [16]. The results showed a 13% decrease in compressive strength for unrepaired concrete, and 3,7% in concrete repaired with geopolymer. The binder presented mechanical performance similar to that of the epoxy resin on crack recovery [16].

High encouraging results were received by Yung-Chin Ding et al. [17], - the compressive strength test of the concrete substrate bonded with geopolymer paste showed up to 120% rate of repair. In comparison to Portland cement, the slag/fly ash-based geopolymer paste has very good future potential for further engineering development.

The study of geopolymers used to strengthen the masonry of historical heritage structures was further evaluated in the work of Baltazar et al (2019). The study investigated the fresh and hardened properties of grouts composed of natural hydraulic lime (NHL) and geopolymer as a useful repair and strengthening technique to intervene in old masonry buildings [18]. The experiments were conducted using a geopolymer made of fly ash, sodium hydroxide, and water. The effects of the replacement of NHL by the fly ash-based geopolymer (at the dosages of 0, 20, 50, 80, and 100%) on certain parameters, namely - stability, water absorption, compressive strength, and durability were investigated [18]. The results showed that geopolymer-based grout has several advantages based on mechanical strength, durability, and fresh stability; however, the improvement of their rheological performance proved to be a challenging task [18].

In the next work of Baltazar and Luis (2022) the experimental findings revealed that the silica-fume-based geopolymer grout has an inferior performance from a rheological point of view [19]. This finding was nevertheless compensated by the promising results in terms of mechanical strength when compared to traditional hydraulic-lime-based grout [19].

Conclusions

The improvement of the technology related to the manufacture of geopolymer materials based on industrial waste and the wide implementation of these technologies in practice will allow for solving several scientific and technical tasks, which have been summarized below:

- to obtain building materials with higher technical and construction characteristics, especially with increased durability;
- to reduce the construction industry's need for natural raw materials;
- to solve the problem of storage and rational use of industrial waste;
- to significantly reduce the energy consumption of binder production;
- to reduce the cost of production of construction materials due to the use of cheaper raw materials.

In addition, replacing Portland cement with geopolymer binders in the construction industry will significantly reduce the amount of carbon dioxide emissions into the atmosphere.

Despite the significant advantages of geopolymer binders, they are not yet widely used in construction. The creation and sustainable development of the field of geopolymer building materials requires the accumulation and systematic analysis of data on the influence of various factors on the properties. This will encourage the creation of a scientific and practical basis for the development of industrial technologies of geopolymer materials.

The unpredictability of The behavior in terms of the durability of Geopolymers can be overcome not only by a systematic study of the materials. The stated studies should be adequately supported by statistical information gathering on the effectiveness of the technologies employed based on real-life operation conditions.

Unreinforced masonry buildings in historic centers around the world have often gone unnoticed for centuries, without any protection from natural calamities. These buildings demonstrate low resistance to external influences, especially earthquakes. Earthquakes can cause severe damage to buildings and even result in the collapse of structures as a result of seismic effects on structures [20]. For this reason, repairing and strengthening damaged masonry structures is of paramount importance.

An analysis of the above studies shows that geopolymer grouts have many advantages over conventional repair materials due to their high viscosity, compressive strength, environmental friendliness, and excellent durability, as articulated in this document.

References

1. Davidovits, J. Properties of geopolymer cements: Proceedings of the First international conference on alkaline cements and concretes, 1994. pp. 131-149.

2. Charta von Venedig: Internationale Charta über die Konservierung und Restaurierung von Denkmälern und Ensembles (Denkmalbereiche). Venedig, 25. - 31. Mai 1964 (Fassung von 1989)

3. Gereon L. Kunststoffe in der Denkmalpflege? Ein kritischer Blick aus Sicht der Restaurierung. *Moderne Materialien und Konstruktionen*: Dokumentation zum 29. Kölner Gespräch zu Architektur und Denkmalpflege in Köln, Heft 37. 18. November 2019. S.21-28.

4. Kozhukova, N.I.; Chizhov, R.V.; Zhervovsky, I.V.; Strokova, V.V. Structure Formation of Geopolymer Perlite Binder Vs. Type of Alkali Activating Agent. *International Journal of Pharmacy & Technology*, vol. 8, Iss. no. 3, 2016. P. 15,339.

5. Davidovits, J. Years of successes and failures in geopolymer applications. Market trends and potential breakthroughs: Proceedings of the Geopolymer 2002 Conference. 2002. p. 29.

6. McLellan, B. C; Williams, R. P.; Lay, J.; Arie van Riessen, A. and Corder G. D. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production*, 19, 2011. P. 1080–1090.

7. Khalifeh, Mahmoud; Saasen, Arild; Hodne, Helge; Motra, Hem Bahadur. Laboratory evaluation of rock-based geopolymers for zonal isolation and permanent P&A applications. *Journal of Petroleum Science and Engineering*. 175: 2019. P. 352–362. doi:10.1016/j.petrol.2018.12.065

8. Sata, V. Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cement Concr. Compos*. 2012. Vol. 34. P. 700-708.

9. Erdogan, S.T. Properties of ground perlite geopolymer mortars. *J. Mater. Civ. Eng*. 2015. Vol. 27(7). P. 1–10.

10. Garcia-Loderio, I. Alkali-Aggregate Reaction in Activated Fly Ash Systems. *Cement and Concrete Research*. 2007. N 37. P. 175-183.

11. Kim, Y.Y. Strength and durability performance of alkali-activated rice husk ash geopolymer mortar. *Sci. World. J*. 2014. Vol. 2014. P.1–11.

12. Komnitsas, K.A. Potential of geopolymer technology towards green buildings and sustainable cities: *Procedia Engineering 21*. 2011. P. 1023-1032. doi:10.1016/j.proeng.2011.11.2108

13. M. Criado and others. Alkali Activated Fly Ash: Effect of Admixtures on Paste Rheology. *Rheologica Acta*, 48.4, 2009. P. 447–455. doi.org/10.1007/s00397-008-0345-5

14. Morgenstern, H., Kunde, C. and Raupach, M. Development of a preloadable, temperature-stable, geopolymer-based gap compensation material: ce/papers, 6, 2023. P.1238-1243. doi.org/10.1002/cepa.2238

15. Morgenstern, H., Raupach, M. Low Viscosity, High-Temperature Stable Geopolymer for Crack Injection and Cavity Filling with Optional Increase of Volume and Preload. *SynerCrete 2023*: International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of Cement-based Materials and Concrete Structures. RILEM Bookseries, vol 43. Springer, Cham. 2023. doi.org/10.1007/978-3-031-33211-1_97

16. Frasson, B. J., Pelisser, F., & Silva, B. V. Concrete crack repair analysis with metakaolin-based geopolymer cement. Revista IBRACON De Estruturas E Materiais, 13(2), 2020. P. 298–313. doi.org/10.1590/S1983-41952020000200007

17. Ding YC, Cheng TW, Dai YS. Application of geopolymer paste for concrete repair. *Structural Concrete*, v. 18, n. 4, 2017. P. 561-570. https://doi.org/10.1002/suco.201600161

18. Baltazar, L. G., Henriques, F. M. A., Temporão, D., & Cidade, M. T. Experimental Assessment of Geopolymer Grouts for Stone Masonry Strengthening. *Key Engineering Materials*, 817, 2019. P. 507–513. https://doi.org/10.4028/www.scientific.net/kem.817.507

19. Baltazar, Luis G. Performance of Silica Fume-Based Geopolymer Grouts for Heritage Masonry Consolidation. *Crystals* 12, no. 2: 2022. P. 288. https://doi.org/10.3390/cryst12020288

20. Murat Maras M. Experimental behavior of injected geopolymer grout using styrene-butadiene latex for the repair and strengthening of masonry walls. *Advances in Structural Engineering*. 24(11), 2021. P. 2484-2499. doi:10.1177/13694332211001513