# Sustainability and durability of cracked concrete with geopolymer binder

*Carina* Frangieh[1], *Marianne* Saba[1,*], *Dorra* Karmaoui[2], and *Zoubeir* Lafhaj[2]

[1]University of Balamand, Civil and Environmental Engineering Department, 100-Tripoli, Lebanon
[2]Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France

**Abstract.** In 2015, the United Nations (UN) set sustainable construction as one of the major goals when launching the 2030 Agenda for Sustainable Development. Sustainable construction improves biodiversity, minimizes pollution, protects natural resources, and makes the environment better. Within this context, it can be established by using eco-friendly materials such as geopolymers. Several studies showed that geopolymers have better properties when compared to Ordinary Portland Cement (OPC) and traditional commercial repair materials. This study investigates the ability of geopolymer paste to withstand several environments when used as a binder to repair fissured concrete. Three major types of solutions were used in this study: water, 20% NaCl solution, and 1% sulfuric acid solution. For better consistency, French Metakaolin-based geopolymer paste and Lebanese Metakaolin-based geopolymer paste were compared since they have different chemical characteristics. The results showed that for all types of samples that endured different environmental conditions, the geopolymer binder almost remained intact while the OPC severely deteriorated. As such, a comprehensive approach for more sustainable concrete was developed through durability tests that inhibited good characteristics of the geopolymer binder to solve problems related to concrete fissures/cracks worldwide.

## 1 Introduction

Sustainable construction is an innovative concept that highlights modern construction while reinforcing green and environmentally friendly properties. When Joseph Aspdin discovered Portland cement in 1824, it was considered a new technology and was later used worldwide as the main component in a concrete mix [1]. Due to its good mechanical and durable properties, concrete was used for building purposes. But, the formation of cracks in concrete structures has highlighted serious problems that need to be considered. The progressive deterioration of concrete may occur due to environmental exposure conditions, chemical degradation, physical damage, mechanical attack, aggressive gases, etc...[2]. Henceforth, researchers are not only exploring new techniques and methods to solve this problem, but they are also tackling the challenge of applying sustainable and economical repair materials [3]. Some of the known commercial repair materials used are emulsified epoxy mortars, sand epoxy mortars, and polymer-modified cement-based mortars [2]. Similarly, new repair materials are being developed and researchers have proposed the possibility of using geopolymer as a repair material. Since the major contributor to this problem is the environmental aspect, the solution should be at first eco-friendly and have the required properties better than the traditional commercial materials, as such geopolymer paste best matches this requirement [4].

Geopolymer is a durable and eco-friendly material made from a silica and alumina-rich source material such as Metakaolin and/or Ground Granulated Blast-furnace Slag (GGBFS) that reacts with a sodium or potassium-based alkali activator [5]. The geopolymerization reaction begins by dissolving the particles of the source material in a high-alkaline solution. After that, the precipitation happens and results by forming a three-dimensional solid matrix thus the formation of geopolymer [6]. During the process of geopolymerization, polysialate (Si/Al = 1), polysialate-siloxo (Si/Al = 2), and polysialate-disiloxo (Si/Al = 3) are generated [7]. Nevertheless, research forecasts geopolymer as the new technology that will replace Ordinary Portland Cement (OPC) in the construction industry due to the disadvantages foreseen by OPC [8,9]. Cement manufacturing is attributed to an- environmental concern because of large carbon dioxide emissions and excessive use of energy [6,10]. According to Pacheco-Torgal [11], the manufacturing of one ton of cement results in the creation of one ton of $CO_2$, implying that the production of cement alone contributes to global warming and climate change. Biernacki et al. [1] claimed in their article that the global production of OPC is expected to rise to 25% of global emissions by 2050. Moreover, the production of cement needs a substantial amount of energy exceeding 2.72 GJ/ton [12]. It also exploits huge amounts of natural resources such as limestone where one ton of cement requires around 2.8

* Corresponding author: marianne.saba@balamand.edu.lb

tons of raw materials [2,13]. The manufacturing of cement causes the progressive degradation of the landscape, the creation of dust, and pollution (soil, water, and air) [13-15].On the contrary, geopolymer protects natural resources [13,16], reduces $CO_2$ emissions [17,18], controls climate change [13,19], minimizes the usage of energy [5,13], and better saves the environment [19,20]. Besides that, geopolymer is prepared using industrial waste materials which makes it a sustainable and green construction material because it recycles these wastes rather than dumping them into landfills [6,13,20]. Due to the use of industrial by-products, $CO_2$ emissions are reduced by up to 80% in comparison with the traditional Portland cement technology [21,22]. However, H. U. Ahmed et al. [7] and M. M. Maras [19] stated in their article that geopolymer generates 70% less greenhouse gases compared to OPC. But the founder of geopolymer, Joseph Davidovits confirmed that "'around 0.184 tons of CO2 per ton of binder" is released during the geopolymer production process [15]. It is also regarded sustainable because it uses less energy and fuel while making geopolymer since heating is not needed [4].

However, all the studies mentioned earlier confirm the possibility that geopolymer can be considered a better repair material than the commonly used repair materials in the market. The paper aims to study the acid resistance of geopolymer as a repairing material for cracks as well as when soaked in saline water and water. A comparison was done between French Metakaolin-based geopolymer paste and Lebanese Metakaolin-based geopolymer paste with a conventional OPC mortar.

## 2 Methodology

This study expands the research conducted by Frangieh et al. [4] that investigated the mechanical properties of geopolymer pastes based on French and Lebanese Metakaolin. It resulted excellent compressive strength results compared to OPC mortar. However, it was insufficient to declare that it can replace commercial repair materials [4] . This is why these paper focuses on one of the most durable characteristics, acid resistance.

### 2.1. Preparation of OPC samples

The Ordinary Portland Cement (OPC) used in this research is formed from type I cement, standard French sand known as "sable normalisé" and water. The mix proportions are well described in Table 1. After the mortar has been mixed, it is put into (2.3 cm x 4.6 cm) cylinder molds and vibrated to release air voids. Finally, the samples are cured at room temperature by placing them in a plastic bag for 24 hours. The samples are compressed using a UTM compression machine to intentionally induce cracks before being bonded with geopolymer paste.

**Table 1.** Mix proportions of OPC samples [4]

| | Quantity used |
|---|---|
| Cement (C) (g) | 550 |
| Water (W) (mL) | 275 |
| Sand (S) (g) | 1350 |
| W/C ratio | 0.5 |
| C/S ratio | 1.2-1.3 |

### 2.2 Preparation of Geopolymer Pastes

The geopolymer paste consists of Metakaolin as source material and a sodium-based alkali activator. For greater consistency, two types of geopolymer paste with the same alkali activator are chosen with the difference in Metakaolin (French and Lebanese). The mix proportions are well detailed in Table 2. The alkali activator was prepared by mixing sodium silicate solution and sodium hydroxide pellets where the $Na_2O/SiO_2$ ratio used was 1.8. However, for the source material, the French Metakaolin was exported from a company named Imerys, and the Lebanese Metakaolin was produced in the laboratory by adding local Kaolin in a furnace under 700 °C for 5 hours [4]. After the geopolymer pastes are created, this paste is coupled within the fractured OPC samples.

**Table 2.** Mix proportions of geopolymer pastes [4]

| Ratio | Result |
|---|---|
| Solid/ Liquid | 0.78 |
| Liquid/ Solid | 1.28 |
| $Na_2O/SiO_2$ | 1.8 |

### 2.3 Testing procedure

Durability tests are essential for determining the performance of any structure in severe environments [16]. Various types of durability tests can be freeze-thaw, heat, acid resistance, water permeability, etc. However, the most significant durability test is acid resistance, saline water, and water soaking. In this experiment, the samples are submerged under 3 different solutions: water, 20% NaCl solution, and 1% sulfuric acid solution. An analysis of results was done for all the mediums on 1,7,14 and 28 days in accordance with ASTM C1012/C1012M - 18B protocol. After weighing all the specimens on different curing days, a compressive strength test was conducted to determine their strength after exposure to aggressive environments. It was performed on 2.3 x 4.6 cm specimens utilizing compression testing apparatus at a loading rate of 2.4 KN/s provided in the CIEL laboratory at the University of Balamand in Lebanon [4].

## 3 Results & Discussion

### 3.1. Durability test results

#### *3.1.1 In Water solution*

As shown in Figure 1, the weight of the Lebanese geopolymer paste specimens was higher than the French geopolymer paste specimens. Both types of geopolymer pastes have at day 1 the lowest value and then on the remaining curing days approximately similar values. This result demonstrates that the submersion of the specimens in water didn't harm or deteriorate the geopolymer paste in the specimens since the mass has slightly increased with time. However, the fact that the specimens absorbed some water during their water immersion might be responsible for the increase in weight.

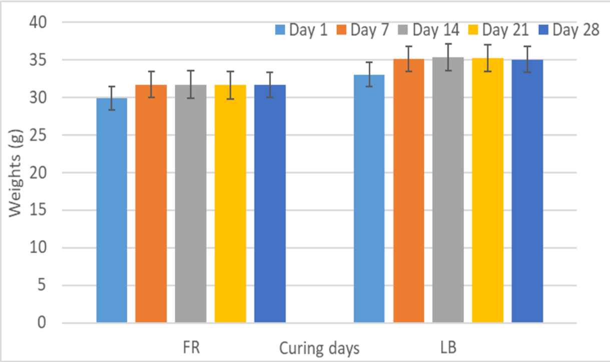


**Fig 1.** Variation of mass when submerged in water solution.

### *3.1.2 In 20% NaCl solution*

As shown in Figure 2, the French geopolymer pastes samples have higher weights compared to the Lebanese geopolymer pastes samples. In fact, for the French and the Lebanese samples, the results showed the lowest value on day 1 and then increased from day 7 till day 28. However, for both samples, a small increase was observed on days 7, 14, and 21 then slightly decreased on day 28. Similarly, to the submersion in water, no significant change in mass was foreseen for the geopolymer pastes.

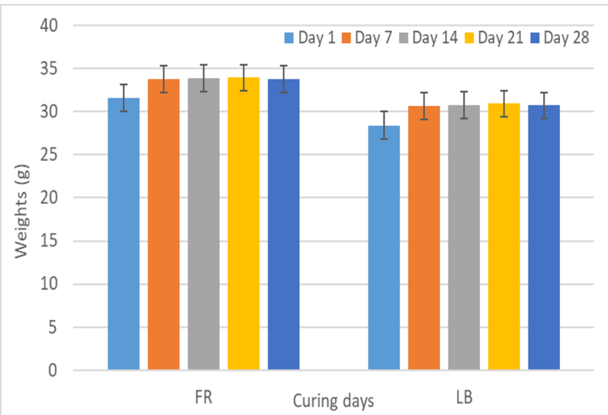


**Fig 2.** Variation of mass when submerged in saline water.

### *3.1.3 In 1% sulfuric acid solution*

The Lebanese and French samples exhibited the lowest mass after being merged in 1% sulfuric acid. Figure 3 demonstrates that both samples have slightly increased in weight although it is not regarded as a substantial increase since the absorption of acidic solution caused the weight gain. Also, a gel light substance was observed in the solution as depicted in Figure 4. As a conclusion, the geopolymer paste wasn't affected in this solution, which was deemed the harshest acidic medium in this experiment.

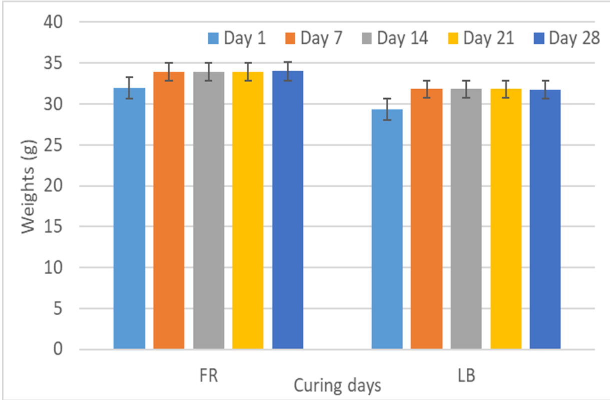


**Fig 3.** Variation of mass when submerged in 1% sulfuric acid.

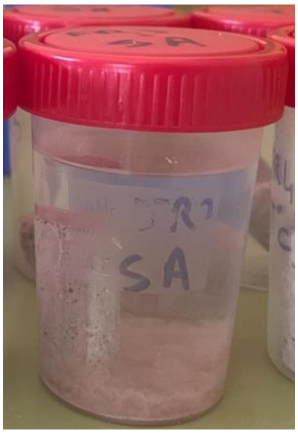


**Fig 4.** The formation of the gel after immersing a sample in sulfuric acid.

### *3.1.4 At ambient temperature*

Both Lebanese and French samples were weighted at 22°C ambient temperature for comparison purposes to the three solutions. Figure 5 illustrates the weights of the samples at ambient temperature which shows that the values remained approximately the same at all curing days.

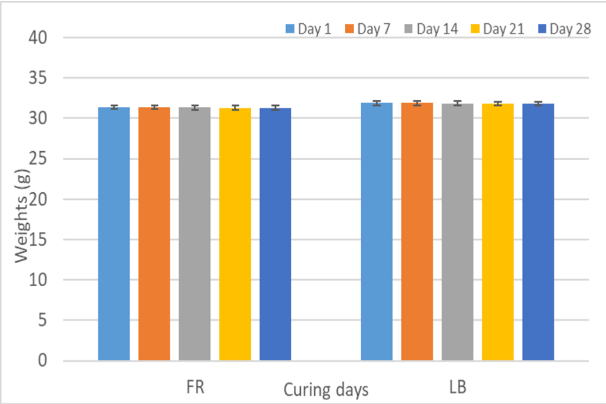


**Fig 5.** Variation of mass at ambient temperature.

### 3.1.5 For all samples

Based on Figure 6, it can be concluded that all the values are increasing by weight, and this indicates that the geopolymer pastes are not affected by the different acidic conditions. Regarding the French samples, when compared to at ambient temperature, the weight is 31.37 g on day1 but when submerged in water, 20%NaCl and 1% sulfuric acid the values on day 1 decreased to 29.87 g in water and increased to 31.56 g in 20%NaCl and 31.97 g in 1% sulfuric acid. But for the other curing days, the weights increased and remained approximately the same. On the other side, the same effect was foreseen on the Lebanese samples where the weight at ambient temperature was 31.9 g on day 1 but when merged in water, 20%NaCl and 1% sulfuric acid the values on day 1 decreased to 28.4 g in 20%NaCl and 29.38 g in 1% sulfuric acid and increased 33.03 g in. water. However, in the remaining days, an increase in the 3 solutions was shown in Figure 6. It can be concluded that the difference in mass at an early age (day 1) for all the solutions compared to ambient temperature is the absorption of the specimens from the solution immersed inside. Also, the results showed that the geopolymer paste, a collision material for the concrete cracks, was not harmed by the acidic medium. On the other side, most research has realized that OPC submerged in the same conditions has severely deteriorated. This indicates that geopolymer paste has better acid resistance than OPC thus more durable.

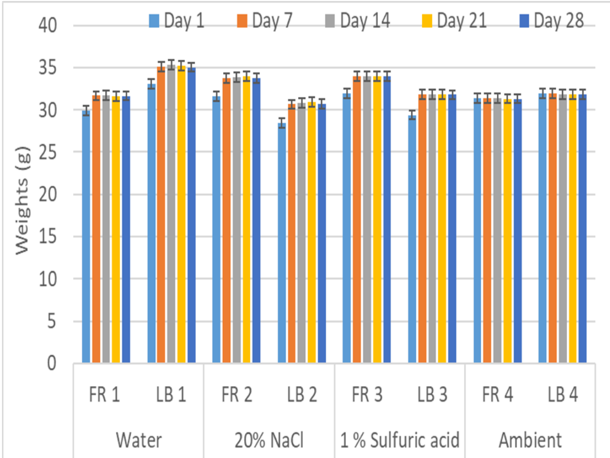


**Fig 6.** Comparison of weights with aging for all specimens.

## 3.2 Compressive strength test results

An article published by Frangieh et al. [4] studied the compressive strength of Lebanese Metakaolin-based geopolymer paste and French Metakaolin-based geopolymer paste as a binder for damaged concrete. The compressive strength result as shown in Figure 7 is compared with the compressive strength results of this experiment after submersion for 30 days as illustrated in Figure 8.

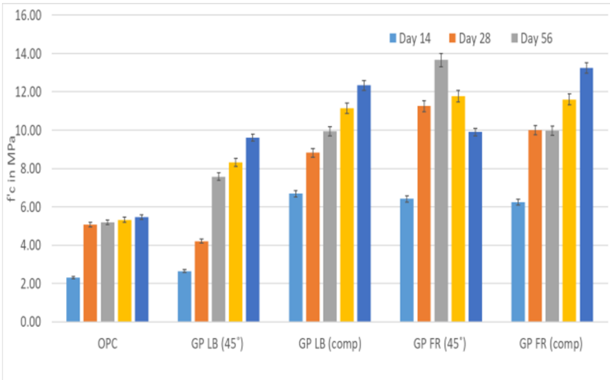


**Fig 7.** Variation of compressive strength results with aging [4].

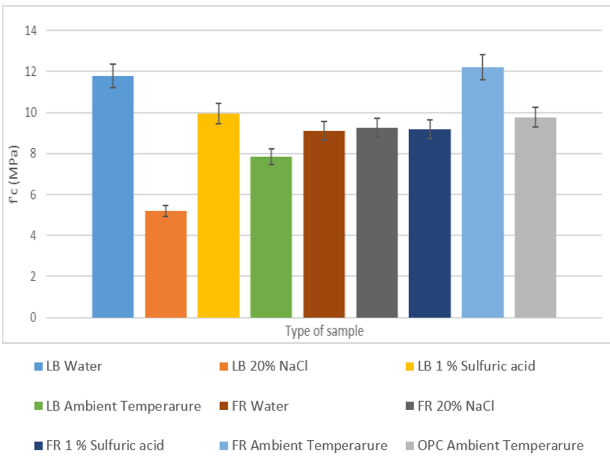


**Fig 8.** Variation of compressive strength results after acid attack.

Since the compressive testing was done after 30 days, the values to be compared from Figure 7 is only at day 28 with the results of this experiment, and an average value was taken for both type of specimens where the Lebanese sample has an average of 6.51 MPa and the French sample has an average of 10.625 MPa.
At first, the OPC sample at ambient temperature has higher compressive strength results compared to Frangieh et al. results [4]. As for the French samples, the highest compressive strength was 12.2 MPa at ambient temperature so it is higher than OPC at ambient temperature. Once the French samples were submerged in water, NaCl, and sulfuric acid, their compressive strength decreased to 9.12, 9.27, and 9.19 MPa respectively. However, if OPC was put under the same environmental conditions, research has shown that it will be damaged, and its strength will decrease less than its value at ambient temperature. In conclusion, the French geopolymer paste can withstand harmful environments better than OPC mortar since the compressive strength didn't drastically decrease like OPC mortar.

Regarding the Lebanese samples, the highest compressive strength was 11.79 MPa when immersed in a water solution. The compressive strength at ambient temperature was 7.85 MPa which is less than OPC at ambient temperature. Nevertheless, it was observed that the compressive strength has increased to 11.79 MPa in water and 9.94 MPa in sulfuric acid but has decreased to 5.2 MPa in saline solution (NaCl solution). Among the three mediums, the saline solution was the most harmful one and could be explained by the extremely harsh environmental conditions. Similarly, to the French samples, OPC has disintegrated significantly, implying that both French and Lebanese geopolymer pastes are more durable than OPC mortar itself. But, when comparing the compressive strength of the French with the Lebanese samples, it was noticed that the Lebanese geopolymer paste resisted better than the French geopolymer paste when immersed in acidic mediums.

## 4 Conclusion

The construction industry must comply with sustainability standards either by selecting new eco-friendly building materials or new green materials for rehabilitation and sustainably repairing damaged structures. Sustainability is attained when choosing geopolymer because it offers excellent mechanical and durability properties and at the same time an environmentally friendly material. Based on the experimental test results, the following conclusions are as follows:

- Both Lebanese and French geopolymer pastes showed better results under acid attack compared to OPC mortar.
- Both Lebanese and French geopolymer pastes possessed excellent durability characteristics compared to OPC mortar.
- Geopolymer paste is a green and sustainable material that can replace repairing materials in the marketplace.

The authors acknowledge IMERYS for offering the French Metakaolin and CIEL and LaMcube laboratories for offering the testing equipment's.

## References

1. J. J. Biernacki, J. W. Bullard, G. Sant, K. Brown, F. P. Glasser, S. Jones, T. Ley, R. Livingston, L. Nicoleau, J. Olek, F. Sanchez, R. Shahsavari, P. E. Stutzman, K. Sobolev, and T. Prater, J. Am. Ceram. Soc. **100,** 2746 (2017)
2. G. F. Huseien, A. R. M. Sam, and M. M. Tahir, CRC Press, (2022)
3. A. W. Wazien, M. M. A. B. Abdullah, R. A. Razak, M. M. R. Rozainy, M. F. M. Tahir, M. A. Faris, and H. N. Hamzah, EDP Sciences, **78**, 01065 (2016)
4. C. Frangieh, M. Saba, D. Karmaoui, and Z. Lafhaj,, (IOP Publishing , 012061, (2022)
5. R. Alyousef, A. A. K. Ebid, G. F. Huseien, H. Mohammad hosseini, H. Alabduljabbar, S. Poi Ngian, and A. M. Mohamed, **8**, 53 (2022)
6. C. Rahmawati, S. Aprilia, T. Saidi, and T. B. Aulia, Elkawnie,**7**, 1 (2021)
7. H. U. Ahmed, A. A. Mohammed, S. Rafiq, A. S. Mohammed, A. Mosavi, N. H. Sor, and S. Qaidi, Sustain.,**13**, 13502 (2021)
8. K. Ramujee and M. PothaRaju, Mater. Today Proc., 4, 2937 (2017)
9. M. Sumesh, U. J. Alengaram, M. Z. Jumaat, K. H. Mo, and M. F. Alnahhal, Constr.Build.Mater., **148**, 62 (2017)
10. C. Zemri and M. B. Bouiadjra, Case Stud. Constr. Mater. **12**, e00339 (2020)
11. F. Pacheco-Torgal, Introduction to Handbook of Alkali-Activated Cements, Mortars and Concretes **1**, (2015)
12. B. Feng and J. Liu, Proc. ,**10**, 1818 (2022)
13. A. F. Hashmi, M. S. Khan, M. Bilal, M. Shariq, and A. Baqi, Const. , **2**, 93 (2022)
14. G. F. Huseien, J. Mirza, M. Ismail, S. K. Ghoshal, and A. A. Hussein, Renew. Sustain. Energy Rev., **80**, 54 (2017)
15. S. Chowdhury, S. Mohapatra, A. Gaur, G. Dwivedi, and A. Soni, Mater. Today Proc., **46**, 5687 (2021)
16. G. Lavanya and J. Jegan, Adv. Mater. Sci. Eng., (2015)
17. C. Zanotti, P. H. Borges, A. Bhutta, and N. Banthia, Cem. Concr. Compos., **80**, 307 (2017)
18. S. M. Laskar and S. Talukdar, Constr. Build. Mater., **154**, 176 (2017)
19. M. M. Maras, Struct. Concr., **22**, 3173 (2021)
20. J. J. Assaad and M. Saba, Min., **13**, 186 (2023)
21. M. Nawaz, A. Heitor, and M. Sivakumar, Constr. Build. Mater., **260**, 120472 (2020)
22. Y. Ding, T. Cheng, and Y. Dai, Struct. Concr., **18**, 561 (2017)

23. M. Saba, K. J. Kontoleon, E. Zervas, and M. El Bachawati, IOP Publishing, 012043 (2021)