|  |  |
| --- | --- |
| The Effect of Using Ground Granulated Blast Furnace Slag (GGBFS) in Mortar Mixes on Setting Time |  |

**Dafid Irawan¹, Gigih Priyandoko2, Febriana D3, Firda Hani Ayuningtyas4**

,3,4 Civil Engineering Department, Faculty of Engineering, Universitas Widyagama Malang, Indonesia

2 Electrical Engineering Department, Faculty of Engineering, Universitas Widyagama Malang, Indonesia

|  |  |
| --- | --- |
| ***Abstract***  *Cement, lime, sand, and water combine to form mortar, one of the essential building materials used as a binding or adhesive agent in construction. As a crucial building material in construction, mortar often struggles with low adhesion and tensile strength under extreme weather conditions, which can lead to cracking, brittleness, and decreased durability, particularly in harsh environmental conditions. This research aThis research aims to observe the effect of varying percentages of ground granulated blast furnace slag (GGBFS) on the setting time of mortar, with the goal of improving the mechanical properties and durability The research method employs an experimental approach, creating several test samples in the laboratory using GGBFS variations of 0%, 10%, and 20%. The testing was conducted at the Brawijaya University Laboratory, including aggregate material testing, slump testing, and setting time measurement usimeasurementstest apparatus over a period of 28 days. This research utilizes the theory of the properties of GGBFS as a partial cement replacement material, which can enhance the mechanical characteristics of mortar. This theory is supported by several previous studies that demonstrate the effectiveness of GGBFS as an environmentally friendly alternative binding material in mortar mixtures. The research results show that the addition of GGBFS has a significant impact on the setting time of mortar. The ANOVA analysis results confirm this, as the calculated F (12.140) exceeds the table F (4,066). The 10% GGBFS variation showed the most optimal results with an initial setting time of 145 minutes and a final setting time of 245 minutes, faster compared to the 0% and 20% variations. In the slump test, the addition of 10% and 20% GGBFS caused a decrease in slump values to 9.7 cm and 8.7 cm, respectively.*  *This is an open-access article under the* [*CC BY-SA*](http://creativecommons.org/licenses/by-sa/4.0/) *license* | ***Keywords:***  *Mortar, GGBFS, Mortar Setting Time, Cement, ANOVA*  ***Article History:***  *Received:*  *Received:*  *Accepted:*  *Published:*  ***Corresponding Author:***  *Dafid Irawan*  *Civil Engineering Program, Faculty of Engineering, Universitas Widyagama Malang, Indonesia*  *Email:* [dafidirawan70@gmail.com](mailto:dafidirawan70@gmail.com) |

**INTRODUCTION**

Mortar is one of the important building materials playing roles as a binding material in the construction consisting of cement, lime, sand and water. However, in technological developments, the composition of mortar has experienced rapid advancement as explained in a research conducted by Ohemeng et al. [1]. In the research, an experimentation on Waste Concrete Powder (WCP) and Ground Granulated Blast Furnace Slag (GGBFS) for use as a mortar mixture was carried out. Researches on the effects of Ground Granulated Blast Furnace Slag (GGBFS) on mortar setting time have also been done as described in journals like [2], [3], [4], [5] and also in [6], [7], [8], [9].

One of the biggest problems with mortar is its low adhesion and stress tolerance in extreme weather conditions. In such a condition, it tends to crack, become fragile and less durable, especially in harsh environmental conditions. Therefore, additional materials that may improve mechanical characteristics, adhesion and resistance to environmental influences are required. GGBFS (Ground Granulated Blast Furnace Slag) is one of the mortar additives which are efficient and environmentally friendly. In research [10], it is stated that Calcium Oxide (CaO) is a reactive earth metal oxide that can function as a potential activator for GGBFS and is an environmentally friendly binder for mortar mixtures. Yao et al [11] showed a study of Mix design on metakaolin (MK) and ground granulated blast furnace slag (GGBFS) as alternative cement materials.

Işıkdağ dan Yalghuz [12] conducted a research on the development of strength and durability of geopolymer mortar (GM) which is produced using metakaolin (MK), (GGBFS), silica fume (SF), ground calcined perlite (GCP), raw perlite (RP), potassium hydroxide (KOH), sodium metasilicate (Na2SiO3), standard sand, and tap water. Meanwhile, Chen et al[13] recycled waste products for construction applications through a geopolymerization process so that it is environmentally friendly. It is shown that GGBFS contributes more to the mechanical properties of geopolymer than fly ash. The results of research made by Sharmin et al[14] revealed that there are other binding materials besides Ground Granulated Blast Furnace Slag (GGBFS), namely Waste Clay Brick Powder (WCBP) which has been proven suitable for use as a binding material. In a research conducted by Zou et al [15] it was shown that to replace Portland cement intended to reduce environmental pollution, waste brick powder (WBP) and Ground Granulated Blast Furnace Slag (GGBFS) were used. Observations made by Yang et al showed [16] that the strength of Ground Granulated Blast Furnace Slag (GGBFS) was better than normal concrete.

Of the several types of Portland cement substitute materials, in this present research, Ground Granulated Blast Furnace Slag (GGBFS) is used as a mortar mixture. In [17] it was known that in the experimental method, when Ground Granulated Blast Furnace Slag (GGBFS) is used as a mortar mixture, the result is that Ground Granulated Blast Furnace Slag (GGBFS) meets the compression strength of the type M mortar plan. In studies [11], [13], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27] Ground Granulated Blast Furnace Slag (GGBFS) was also used as a mortar binding material. Research [28] explored impacts of liquid bond ratio of geopolymer mortar with the basic material of Ground Granulated Blast Furnace Slag (GGBFS). Research in [29] showed Ground Granulated Blast Furnace Slag (GGBFS) as a binding material. From some articles above, it can be concluded that the use of Ground Granulated Blast Furnace Slag (GGBFS) as a binding material is an effective solution to improve mortar quality and performance when it is applied in construction.

This research aims to observe the effect of adding variations in the percentage of GGBFS on mortar setting time. What differentiates this research from previous ones is that no research has been conducted on the analysis of Ground Granulated Blast Furnace Slag (GGBFS) in Mortar Mixtures on Setting Time.

**1. Data Collection Method**

In this present research, an experimental method on various test samples subjected to various treatment conditions in the laboratory was adopted.

**2. Research Location**

All tests in this research were carried out at the Brawijaya University Laboratory, which is located on Jalan Veteran, Lowokwaru District, Malang City, East Java 65145. This testing was conducted for 28 days. The research location plan can be seen in Figure 1.



**Figure 1.** Research Location

**3. Tools and Materials**

The tools and materials used for this research are as follows:

Tools:

* A set of filter
* Scales/balance
* Picnometer
* Cube mortar mold
* Concrete mixer
* One set of slump tests
* aids
* Water permeability test
* One set of vicat tool

Materials:

* Fine aggregate
* Portland cement
* Water
* Ground Granulated Blast Furnace (GGBFS)

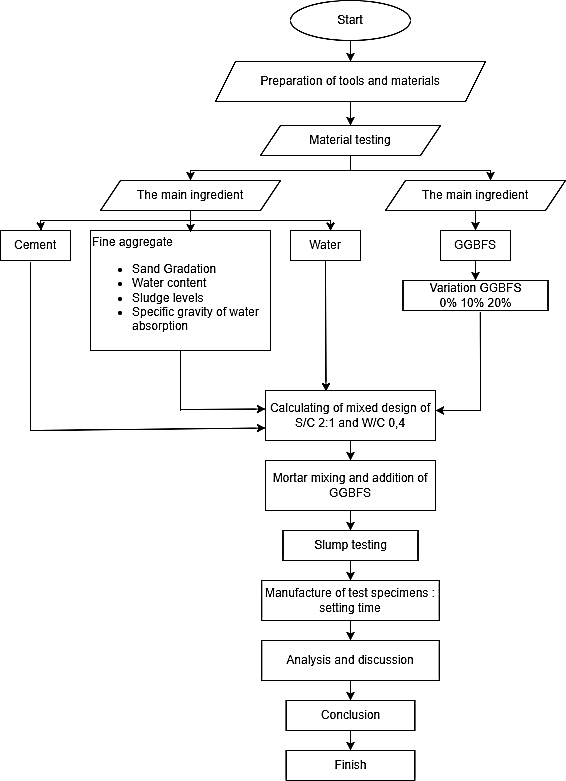
**4. Calculation of Materials Need**

Calculation of materials need may be seen in Table 1.

Table 1 Calculation of Needs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Unit weight in kg | | | | |
| Variation | PC | GGBFS | Sand | Water |
| GGBFS 0% | 7.573 | 1 | 15.146 | 3.029 |
| GGBFS 10% | 6.815 | 0.758 | 15.146 | 3.029 |
| GGBFS 20% | 6.059 | 1.514 | 15.146 | 3.029 |
| Total | 20.447 | 3.272 | 45.438 | 9.087 |

**5. Flow Diagram**

**Figure 2** displays the research flowchart. 

**Figure 2.** Flow Diagram

**Figure 2** shows the steps in the testing and preparation process of the mortar mix. It begins with the preparation of tools and materials, followed by the testing of materials divided into two main groups: the left side with cement, fine aggregate, and water, and the right side consisting of GGBFS with variations of 0%, 10%, and 20%. Next, we perform the mix design calculation using SCC 2.1 parameters and a water-cement ratio of 0.4, followed by mortar mixing and the addition of GGBFS. Next, we conduct a slump test to gauge the mix's workability, after which we prepare the test specimens and set the time. The process then concludes with an analysis and discussion of the test results. **Figure 2** illustrates the systematic process of producing mortar using variations of GGBFS (Ground Granulated Blast Furnace Slag), from preparation to conclusion. We carry out each stage sequentially and interrelatedly to ensure the quality of the research results.

**RESULTS AND DISCUSSION**

After testing, on the basis of the results, conclusions are drawn. The results of the testing in the laboratory include aggregate materials, slump test, and binding time measurement.

**1. Fine Aggregate Test Results**

After carrying out the test, results are obtained from which conclusions can then be drawn.

**Table 2** Fine Aggregate Test Results

|  |  |  |  |
| --- | --- | --- | --- |
| **Test name** | **Test result** | **Condition** | **Information** |
| Water Content | 1.60% | - |
| Sludge levels | 0.20% | Max 5% | Quality |
| Specific gravity |  | 2.5 - 2.7 | Quality |
| Bulk type | 2.67 |
| SSD type | 2.69 |
| Pseudo type | 2.7 |
| Absorption | 0.65% | - |  |

**2. Slump Test Result**

The following is a table and graph of the effect of adding cement with GGBFS on slump. It can be seen in **Table 3.**

**Table 3** Slump Test Result

Source: Calculation Results, 2023

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Composition | | | Water (kg) | Test Object | Slump (cm) |
| Cement | Sand | GGBFS |
| 1 | 2 | 0% | 2.859 | 3 | 14.8 |
| 1 | 2 | 10% | 2.859 | 3 | 9.7 |
| 1 | 2 | 20% | 2.859 | 3 | 8.7 |

**Figure 3.** Graph of slump values ​​with variations in GGBFS

From Figure 3, it can be seen that in the mixture with the addition of 10% and 20% GGBFS, the slump value of the mortar decreased by 9.7 cm and 8.7 cm.

**3. Binding Time Test Results**

After the slump test is carried out, the mortar mixture is used to test the setting time using the vicat test equipment. Tests were carried out to determine the initial setting time and final setting time of the mortar. Initial setting time of mortar Initial setting time (initial sett) must not be less than 45 minutes with a decrease of 25 mm and final setting time (final sett) must not exceed 375 minutes with a decrease of 10 mm.

**Table 4** GGBFS Setting Time 0%

|  |  |
| --- | --- |
| Drop Time | Deckline |
| (minute) | (mm) |
| 45 | 50 |
| 90 | 50 |
| 135 | 50 |
| 180 | 40 |
| 225 | 21 |
| 270 | 16 |
| 315 | 11 |
| 360 | 10 |

Source: Calculation Results, 2023

Then calculate Log Pr and Log t for each time interval and decrease at 0% GGBFS.

**Table 5** Pr Log and t Log GGBFS Testing 0%

|  |  |  |  |
| --- | --- | --- | --- |
| Drop Time | Deckline | Log Pr | Log t |
| (minute) | (mm) |
| 45 | 50 | 1.70 | 1.65 |
| 90 | 50 | 1.70 | 1.95 |
| 135 | 50 | 1.70 | 2.13 |
| 180 | 40 | 1.60 | 2.26 |
| 225 | 21 | 1.32 | 2.35 |
| 270 | 16 | 1.20 | 2.43 |
| 315 | 11 | 1.04 | 2.50 |
| 360 | 10 | 1.00 | 2.56 |

Source: Calculation Results, 2023

**Table 6** Pr Log and t Log GGBFS Testing 10%

|  |  |  |  |
| --- | --- | --- | --- |
| Drop Time | Deckline | Log Pr | Log t |
| (minute) | (mm) |
| 45 | 50 | 1.70 | 1.65 |
| 90 | 43 | 1.63 | 1.95 |
| 135 | 30 | 1.48 | 2.13 |
| 180 | 20 | 1.30 | 2.26 |
| 225 | 10 | 1.00 | 2.35 |

Source: Calculation Results, 2023

**3.1 Initial Setting Time and Final Setting Time Test Results**

The final setting time test can be carried out if the needle penetration value reaches 10 ± 1 mm while the initial tie time is 25 ± mm using the vicat tool. The summary of the results of testing for initial setting time and final setting time can be seen in **table 7.**

**Table 7** Binding Time Test Results

|  |  |  |  |
| --- | --- | --- | --- |
| GGBFS additive | Initial Sett | Final Sett | interval |
| (minute) | (minute) |
| 0% | 215 | 315 | 100 |
| 10% | 145 | 245 | 100 |
| 20% | 185 | 295 | 110 |

Source: Calculation Results, 2023

From the data from the setting time testing results, a graphic image is produced. The following is a graphic image of the test results for the initial setting time and final setting time of mortar with a mixture of GGBFS variations in mortar. This can be seen in **Figure 4.**

**Figure 4.** Graph of the Effect of GGBFS Percentage on initial setting time

**3.2 Completely Randomized Design (CRD) Mortar Setting Time**

Based on the calculation of the mortar setting, the results of the random design are obtained.

The results of the random design can be seen in **Table 7.**

**Table 7** Completely Randomized Design (CRD) Mortar setting time.

|  |  |  |  |
| --- | --- | --- | --- |
| Sample | GGBFS 0% | GGBFS 10% | GGBFS 20% |
| 1 | 3.323 | 2.912 | 3.12 |
| 2 | 3.464 | 3.112 | 3.225 |
| 3 | 3.527 | 3 | 3.29 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| SUMMARY |  |  |  |  |
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| GGBFS 0% | 3 | 10.314 | 3.438 | 0.010911 |
| GGBFS 10% | 3 | 9.024 | 3.008 | 0.010048 |
| GGBFS 20% | 3 | 9.635 | 3.211667 | 0.007358 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ANOVA |  |  |  |  |  |  |
| *Source of Variation* | *SS* | *of* | *MS* | *F* | *P-value* | *F crit* |
| Between Groups | 0.28 | 3 | 0.093331 | 12.14029 | 0.002395 | 4.066181 |
| 4,066181 | 0.062 | 8 | 0.007688 |  |  |  |
|  |  |  |  |  |  |  |
| Total | 0.341 | 11 |  |  |  |  |

From the anova results above, namely to test the hypothesis of the influence of GGBFS, it was found that the F Count was 12.140293 > the F Table of 4.066181, so the HO was rejected. The H1 was accepted, which means that GGBFS had effects on mortar setting time.

**DISCUSSION**

**1. Test Result Analysis**

Based on the slump test results shown in Table 3, there is a significant decrease in the slump value along with an increase in the GGBFS percentage in the mortar mix. The control mix (0% GGBFS) showed a slump value of 14.8 cm, while the addition of 10% and 20% GGBFS resulted in a decrease in slump values to 9.7 cm and 8.7 cm, respectively. This phenomenon can be explained through the physical characteristics of GGBFS, which has a higher specific surface area compared to Portland cement, resulting in an increased water requirement to achieve the same workability. This is in line with research [5], which shows that the fineness of GGBFS affects the rheological properties of the mixture.

**2. Binding Time Analysis**

* GGBFS (10%) produces the most optimal setting time, with an initial setting time of 145 minutes and a final setting time of 245 minutes
* GGBFS 20% shows intermediate setting times (185 minutes initial, 295 minutes final).
* The control mix has the longest setting time. (215 menit awal, 315 menit akhir)

**3. Comparison with Previous Researchers**

* The results of this study reinforce the findings of [2] regarding the effect of substituting cement with slag on setting time. We observe similarities in the pattern of setting time changes influenced by the replacement percentage
* This study also validates the findings from [6] concerning the impact of slag-based materials on mortar setting time, demonstrating that the optimal addition yields superior setting time characteristics.This study provides new insights into determining the optimal percentage of GGBFS (10%) to achieve the most efficient setting time, a topic not explicitly discussed in previous studies.
* Unlike the findings of [8], which demonstrate a delay in the setting time with an increase in slag content, this study reveals that the correct percentage of GGBFS can actually accelerate the setting time.

**CONCLUSION**

Based on research results on mortar setting time, it shows that adding the percentage of GGBFS to the mortar mixture has effects on the time needed for the mortar to harden. From the test results, the GGBFS variation with a percentage of 10% shows the most optimum results, this occurs because the initial and final setting times are fast. Meanwhile, adding a GGBFS percentage of 20% also had effects on the setting time of the mortar, but there was no increase in mortar duration as with the GGBFS percentage of 0% and there was also no acceleration in the setting time as with the GGBFS percentage of 10%. Because the F Count of 12.140 is greater than the F Table of 4.066 in the anova analysis. This shows that GGBFS has effects on the amount of time needed for the mortar to harden.

**BIBLIOGRAPHY**

[1] E. A. Ohemeng, M. S. Ramabodu, and T. D. Nena, “Utilization of Blast Furnace Slag as an Enhancer in Masonry Mortars Made with Thermally Treated Waste Concrete Powder,” *Buildings*, vol. 13, no. 10, Oct. 2023, doi: 10.3390/buildings13102616.

[2] R. Yuniarto Adi, S. Yulia Rizqi, S. Alexander Patrick Subagyo, and H. Ay Lie, “Pengaruh Substitusi Semen dengan Semen Slag pada Mortar terhadap Kebutuhan Air dan Waktu Ikat, dan Peningkatan Kuat Tekan Mortar pada Umur 14 hari dan 28 Hari,” 2020.

[3] A. Susilowati and A. G. Chaerul Imam Jurusan Teknik Sipil Politeknik Negeri Jakarta Alamat Jl Siwabessy, “Pengaruh Ground Granulated Blast Furnace Slag Sebagai Pengganti Sebagian Semen Pada Papan Serat Ringan,” 2022.

[4] R. N. Arini, N. Warastuti, M. Wahyu, and K. Darmawan, “ANALISIS KUAT TEKAN DENGAN APLIKASI GROUND GRANULATED BLAST FURNACE SLAG SEBAGAI PENGGANTI SEBAGIAN SEMEN PADA CAMPURAN BETON,” vol. 10, no. 2, 2019.

[5] J. Dai, Q. Wang, C. Xie, Y. Xue, Y. Duan, and X. Cui, “The effect of fineness on the hydration activity index of ground granulated blast furnace slag,” *Materials*, vol. 12, no. 18, Sep. 2019, doi: 10.3390/ma12182984.

[6] M. Kimsan, R. S. E. Tamburaka, S. Aminahsari, and Fitriah, “Influence of ferronickel slag powder on the performance of high-strength-mortar (setting time and compressive strength),” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Oct. 2021. doi: 10.1088/1755-1315/871/1/012016.

[7] D. Oyejobi, M. Jameel, A. Adewuyi, S. Aina, S. Avudaiappan, and N. Maureira-Carsalade, “Analyzing Influence of Mix Design Constituents on Compressive Strength, Setting Times, and Workability of Geopolymer Mortar and Paste,” *Advances in Civil Engineering*, vol. 2023, 2023, doi: 10.1155/2023/5522056.

[8] S. Li, D. Chen, Z. Jia, Y. Li, P. Li, and B. Yu, “Effects of Mud Content on the Setting Time and Mechanical Properties of Alkali-Activated Slag Mortar,” *Materials*, vol. 16, no. 9, May 2023, doi: 10.3390/ma16093355.

[9] M. Natsir Abduh, N. Pertiwi, and N. A. S. Taufieq, “The Effect of Rice Husk Ash and Sulfatic Acid Solutions on the Setting Time and Compressive Strength of Mortar,” in *Journal of Physics: Conference Series*, Institute of Physics Publishing, Jun. 2019. doi: 10.1088/1742-6596/1244/1/012046.

[10] H. S. Djayaprabha and Hermawan, “The influence of calcium oxide doses as an activator on the compressive strength and mechanical characteristics of cement-free mortar containing ground granulated blast furnace slag,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2023. doi: 10.1088/1755-1315/1195/1/012029.

[11] Z. Yao, L. Luo, Y. Qin, J. Cheng, and C. Qu, “Research on mix design and mechanical performances of MK-GGBFS based geopolymer pastes using central composite design method,” *Sci Rep*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-024-59872-0.

[12] B. Işıkdağ and M. R. Yalghuz, “Strength Development and Durability of Metakaolin Geopolymer Mortars Containing Pozzolans under Different Curing Conditions,” *Minerals*, vol. 13, no. 7, Jul. 2023, doi: 10.3390/min13070857.

[13] Y. C. Chen, W. H. Lee, and Y. C. Ding, “The use of recycled aggregate sludge for the preparation of ggbfs and fly ash based geopolymer,” *Crystals (Basel)*, vol. 11, no. 12, Dec. 2021, doi: 10.3390/cryst11121486.

[14] S. Sharmin, W. K. Biswas, and P. K. Sarker, “Evaluating Techno-Eco-Efficiency of Waste Clay Brick Powder (WCBP) in Geopolymer Binders,” *Buildings*, vol. 14, no. 3, p. 692, Mar. 2024, doi: 10.3390/buildings14030692.

[15] Z. Zou, S. Provoost, and E. Gruyaert, “Utilization of Waste Brick Powder as a Partial Replacement of Portland Cement in Mortars,” *Sustainability (Switzerland)*, vol. 16, no. 2, Jan. 2024, doi: 10.3390/su16020624.

[16] H. M. Yang, S. J. Kwon, N. V. Myung, J. K. Singh, H. S. Lee, and S. Mandal, “Evaluation of strength development in concrete with ground granulated blast furnace slag using apparent activation energy,” *Materials*, vol. 13, no. 2, Jan. 2020, doi: 10.3390/ma13020442.

[17] K. A. Sambowo, M. A. Ramadhan, and F. Igirisa, “Effect of GGBFS on Compressive Strength, Porosity, and Absorption in Mortars,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Aug. 2021. doi: 10.1088/1755-1315/832/1/012012.

[18] Y. Huo *et al.*, “Mass GGBFS Concrete Mixed with Recycled Aggregates as Alkali-Active Substances: Workability, Temperature History and Strength,” *Materials*, vol. 16, no. 16, Aug. 2023, doi: 10.3390/ma16165632.

[19] C. K. Loke, B. Lehane, F. Aslani, S. Majhi, and A. Mukherjee, “Non-Destructive Evaluation of Mortar with Ground Granulated Blast Furnace Slag Blended Cement Using Ultrasonic Pulse Velocity,” *Materials*, vol. 15, no. 19, Oct. 2022, doi: 10.3390/ma15196957.

[20] M. Á. Sanjuán *et al.*, “Radiological Characteristics of Carbonated Portland Cement Mortars Made with GGBFS,” *Materials*, vol. 15, no. 9, May 2022, doi: 10.3390/ma15093395.

[21] H. Alghamdi, A. A. Abadel, M. Khawaji, M. Alamri, and A. Alabdulkarim, “Strength Performance and Microstructures of Alkali-Activated Metakaolin and GGBFS-Based Mortars: Role of Waste Red Brick Powder Incorporation,” *Minerals*, vol. 13, no. 7, Jul. 2023, doi: 10.3390/min13070848.

[22] C. C. Hung, J. N. Chang, H. Y. Wang, and F. L. Wen, “Effect of Adding Waste Polyethylene and GGBFS on the Engineering Properties of Cement Mortar,” *Applied Sciences (Switzerland)*, vol. 12, no. 24, Dec. 2022, doi: 10.3390/app122412665.

[23] R. Karolina, J. Tarigan, H. Hardjasaputra, and R. A. D. Silalahi, “Analysis of Geopolymer Mortar Compressive Strength Based on Fly Ash and GGBFS as Patch Repair Material,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2023. doi: 10.1088/1755-1315/1195/1/012032.

[24] Y. C. Chen, W. H. Lee, T. W. Cheng, and Y. F. Li, “A Study on the Shrinkage and Compressive Strength of GGBFS and Metakaolin Base Geopolymer under Different NaOH Concentrations,” *Materials*, vol. 17, no. 5, Mar. 2024, doi: 10.3390/ma17051181.

[25] M. Dudek and M. Sitarz, “Analysis of changes in the microstructure of geopolymer mortar after exposure to high temperatures,” *Materials*, vol. 13, no. 19, Oct. 2020, doi: 10.3390/MA13194263.

[26] W. Fan *et al.*, “Durability of fibre-reinforced calcium aluminate cement (CAC)-ground granulated blast furnace slag (GGBFS) blended mortar after sulfuric acid attack,” *Materials*, vol. 13, no. 17, Sep. 2020, doi: 10.3390/ma13173822.

[27] Q. D. Nguyen and A. Castel, “Developing Geopolymer Concrete by Using Ferronickel Slag and Ground-Granulated Blast-Furnace Slag,” *Ceramics*, vol. 6, no. 3, pp. 1861–1878, Sep. 2023, doi: 10.3390/ceramics6030114.

[28] I. V. Ranga Ramanujam, K. Ramachandra Reddy, and N. Venkata Ramana, “Compressive strength of geopolymer mortar on different molarities, liquid binder, and alkaline solution ratios.,” in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2023. doi: 10.1088/1755-1315/1280/1/012012.

[29] R. A. T. Cahyani and Y. Rusdianto, “An Overview of Behaviour of Concrete with Granulated Blast Furnace Slag as Partial Cement Replacement,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Dec. 2021. doi: 10.1088/1755-1315/933/1/012006.