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American Concrete Institute
Malaysia Chapter

# MYCONCRETE

THE BULLETIN OF THE AMERICAN CONCRETE INSTITUTE - MALAYSIA CHAPTER
(E-bulletin)

## Highlight!



### Upcoming Event

ACI-Malaysia Chapter 26th General Meeting –
14th April 2023

70-1, Jalan PJS 5/30,
Petaling Jaya Commercial City (PJCC), 46150 Petaling Jaya, Malaysia
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**MyConcrete:**
**The Bulletin of the American Concrete Institute – Malaysia Chapter**

Editor:
Ms. Serina Ho Chia Yu
Hume Cement Sdn. Bhd.


70-1, Jalan PJS 5/30, Petaling Jaya Commercial City (PJCC),
46150 Petaling Jaya,
MALAYSIA

http://www.acimalaysia.org
+6014 220 7138
admin@acimalaysia.org



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# INTRODUCTION TO ACI MALAYSIA CHAPTER

American Concrete Institute - Malaysia Chapter (ACI-Malaysia) is a non-profit technical and educational society representing ACI Global in Malaysia, which is one of the world's leading authorities on concrete technology. Our members are not confined to just engineers; in fact, our invitation is extended to educators, architects, consultants, corporate, contractors, suppliers, and leading experts in concrete related field. The purpose of this Chapter is to further the chartered objectives for which the ACI was organized; to further education and technical practice, scientific investigation, and research by organizing the efforts of its members for a non-profit, public service in gathering, correlating, and disseminating information for the improvement of the design, construction, manufacture, use and maintenance of concrete products and structures. This Chapter is accordingly organized and shall be operated exclusively for educational and scientific purposes.

**Objectives of ACI-Malaysia are:**

- ACI is a non-profitable technical and educational society formed with the primary intention of providing more in-depth knowledge and information pertaining to the best possible usage of concrete.

- To be a leader and to be recognized as one of Malaysia's top societies specializing in the field of concrete technology by maintaining a high standard of professional and technical ability supported by committee members comprising of educators, professionals and experts.

- Willingness of each individual member/organization to continually share, train and impart his or her experience and knowledge acquired to the benefit of the public at large.

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*ii) All application to be made direct to companies and would be subject to their terms and conditions.*

# Upcoming Events

AMERICAN CONCRETE INSTITUTE-MALAYSIA CHAPTER

## 26TH ANNUAL GENERAL MEETING


14th April 2023, Friday

5.00 PM - AGM
7.00 PM - Dinner

Armada Hotel, Petaling Jaya

### DINNER FEE

Member: RM60.00
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*Please send RSVP and payment before 7th April 2023 in the attached form.

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# Preceding Events

# Preceding Events

# ARTICLE

## Recent Update On Geopolymer Research As Construction Materials


Noor Fifinatasha Shahedan

Liew Yun Ming

Heah Cheng Yong

Mohd Mustafa Al Bakri Abdullah

Center of Excellence Geopolymer and Green Technology
Universiti Malaysia Perlis (UniMAP)
Perlis, Malaysia
Environment Engineering Program, Curtin University Malaysia, Sarawak, Malaysia


Recycling and reusing waste materials have become an increasingly important research area in recent years [1] – [3]. The development of geopolymer research is to step ahead towards searching for green materials with the purpose to minimize or replace the use of ordinary Portland cement (OPC) and emissions of carbon dioxide ($CO_2$) so as not to risk the needs of future generations [4] – [6]. The production method applied is significant and user and eco-friendly with lower consumption of energy.

The binder materials used for geopolymer products are mostly the industrial waste or by-products containing high content of silica (Si) and alumina (Al) which acted as precursor for geopolymerization [2]. The potential of source materials in a wide range of slag, natural clay, waste and natural Al–Si minerals possibly will provide as potential source materials for the production of geopolymer [1].

In addition, the current research on geopolymer demonstrates how geopolymer products display superior properties good for many applications including as a new building materials (lightweight concrete, insulating concrete, lightweight brick, lightweight aggregate, a new steel fiber reinforced concrete), a new materials for road base application, as a repair materials, a new materials for corrosion application, a new filler in piping application, as underwater concrete materials, a low sintering temperature ceramic, as reinforced material in solder alloy, lightweight ceramic application, high strength paste application and also as soil stabilisation agent [1] – [8], [13], [19].

The advancement made in the various research of science and technology has helped us to have equivalence or a better quality of existing product [1] – [8]. The characteristic and performance of geopolymer products has proved for better thermal insulation properties, higher fire resistance, lower processing temperature, low permeability, good chemical resistance, excellent in acid and salt environment [8]. There are a few current geopolymer researches that can be highlighted such as a new finding on high strength paste application, self-fluxing for low-sintering ceramic and insulation concrete.

The high strength paste development of solely ground granulated blast furnace slag geopolymers (GGBFS) with various solid/liquid and alkaline activator ratios had been determined by performing a number of compressive strength tests (Figure 1) [4]. It was found that GGBFS with 3.0 solid/liquid ratio and 2.5 alkaline activator ratios resulted in high compressive strength at 168.7 MPa after 28 days of curing. The microstructure analysis of the GGBFS geopolymers using SEM, FTIR and XRD revealed the formation of tobermorite and calcite ($CaCO_3$) phases within a threedimensional system. It displayed that the calcium concentration was higher at silica and alumina regions, which described the formation of tobermorite and $CaCO_3$ as the contributing factor towards high compressive strength.

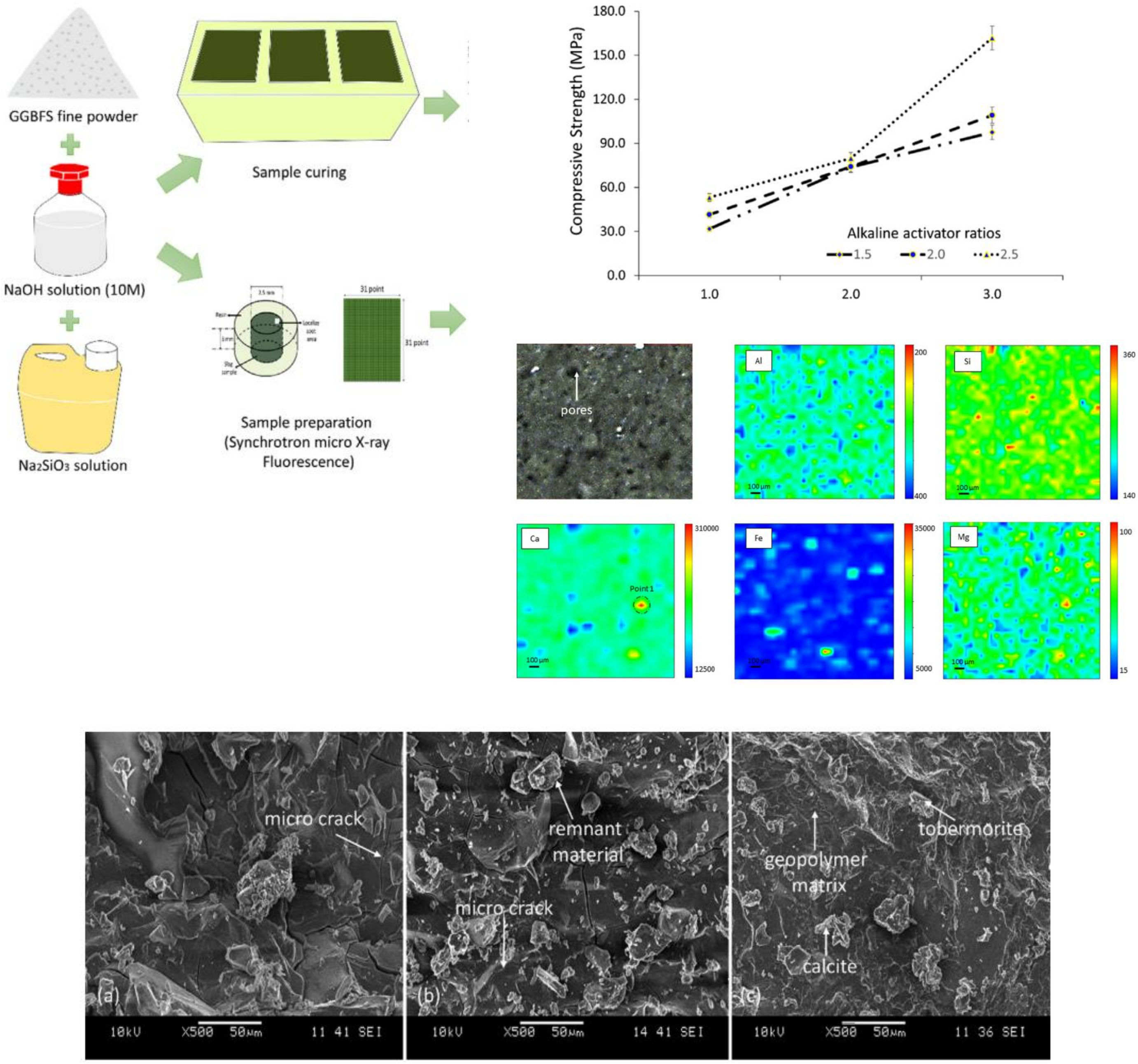



Figure 1: Mechanical and microstructure of solely GGBFS based geopolymer [4]

Self-fluxing low-sintering geopolymer ceramic was prepared with a ratio of solid to liquid 2:1 and cured at 60 ˚C for 14 days [5]. The cured geopolymer was sintered at different temperatures: 800, 900, 1000, and 1100˚C. Sintering at 900 ˚C resulted in the highest compressive strength (Figure 2) due to the formation of densified microstructure, while higher sintering temperature led to the formation of interconnected pores. Thermal analysis indicated the stability of sintered kaolin–GGBS geopolymer when exposed to 1100˚C, proving that kaolin can be directly used without heat treatment in geopolymers. The geopolymerization process facilitates the stability of cured samples when directly sintered, as well as plays a significant role as a self-fluxing agent to reduce the sintering temperature when producing sintered kaolin–GGBS geopolymers.

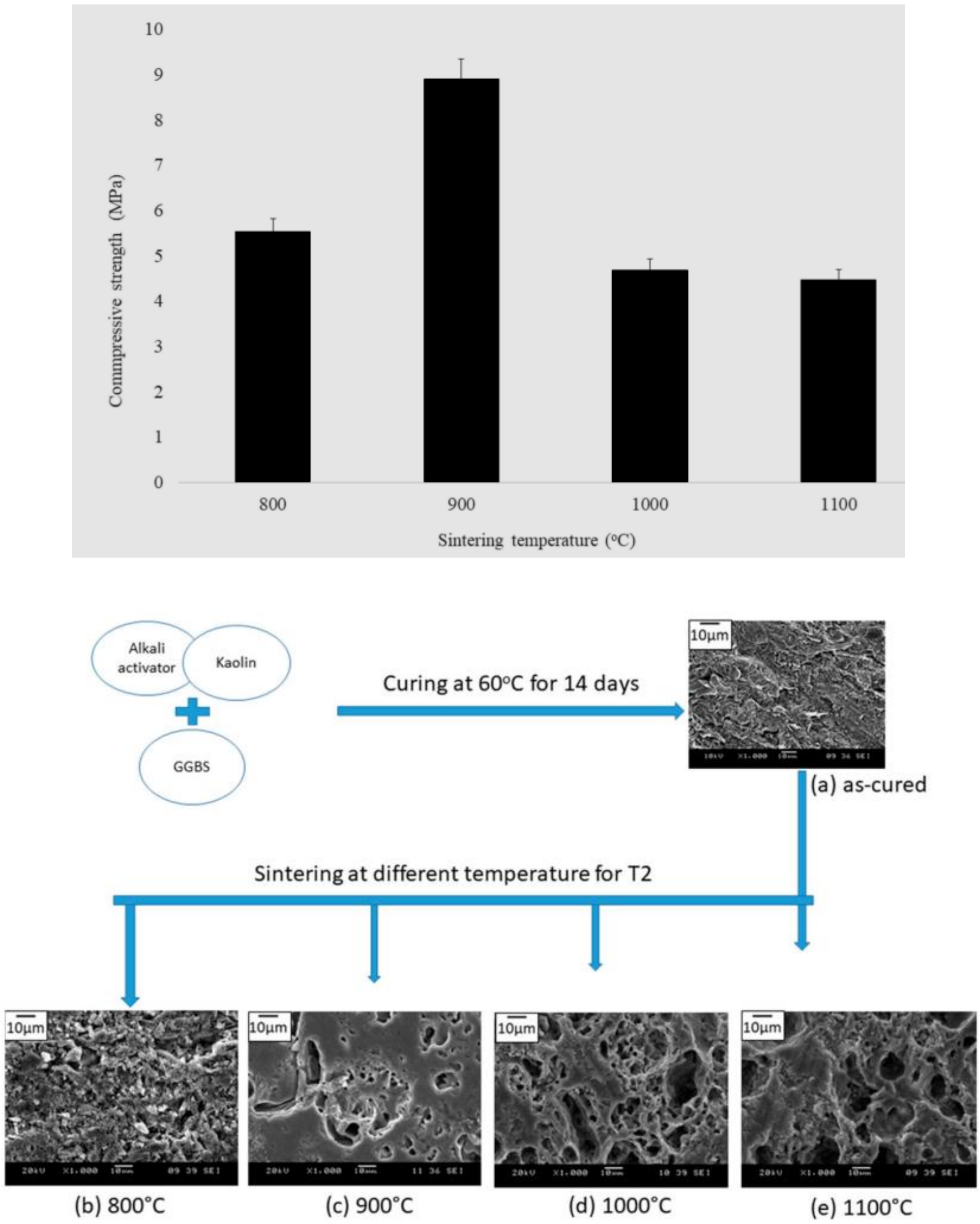



Figure 2: Effect of sintering temperature on the compressive strength and microstructure ((a) as-cured, (b) 800 ˚C, (c) 900 ˚C, (d) 1000 ˚C, and (e) 1100 ˚C) of sintered kaolin-GGBS geopolymer [5]

A novel geopolymer concrete embedded with glass bubble as its thermal insulating material, fly ash as its precursor material, and a combination of sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$) as its alkaline activator to form a geopolymer system (Figure 3) [6]. The workability, density, compressive strength (per curing days), and water absorption of the sample loaded at 10% glass bubble (loading level determined to satisfy the minimum strength requirement of a load-bearing structure) were 70 mm, 2165 kg/m$^3$, 52.58 MPa (28 days), 54.92 MPa (60 days), and 65.25 MPa (90 days), and 3.73 %, respectively. The thermal conductivity for geopolymer concrete decreased from 1.47 to 1.19 W/mK, while the thermal diffusivity decreased from 1.88 to 1.02 mm$^2$/s due to increased specific heat from 0.96 to 1.73 MJ/m$^3$K. The improved physicomechanical and thermal (insulating) properties resulting from embedding a glass bubble as an insulating material into geopolymer concrete resulted in a viable composite for use in the construction industry.

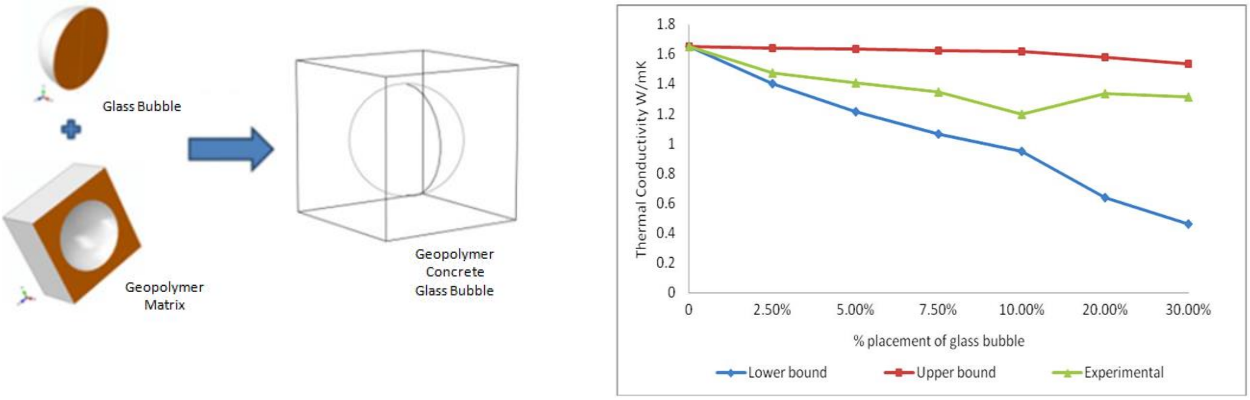
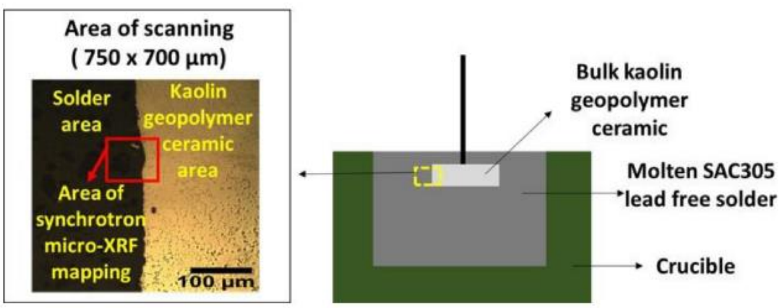



Figure 3: A novel geopolymer concrete embedded with glass bubble as its thermal insulating material [6]

Geopolymer in form of powder can be used to produce geopolymer ceramics through a sintering process yielding crystalline phases, which require slightly lower sintering temperatures [9-12]. Geopolymer ceramic is made up of elements that can act as additional nucleation sites in solder alloy, improving their properties. Several hypotheses on the incorporation of ceramic particles into existing solder alloys have been proposed. One research has studied on the effects of different weight percentages (0, 0.5, 1.0, 1.5 and 2.0 wt.%) of kaolin geopolymer ceramic (KGC) on the microstructure formation, thermal properties, spreadability and joint strength in Sn-3.0Ag-0.5Cu (SAC305) lead-free solder alloys in order to develop a new composite solder system [13]. The spreadability of the KGC reinforced SAC305 composite solder is significantly increased in the spreadable area with a higher strength of solder joint (Figure 4). Significantly, the results obtained prove that 1.0 wt. % KGC addition gives better performance in terms of microstructure formation, thermal properties, spreadability and joint strength.



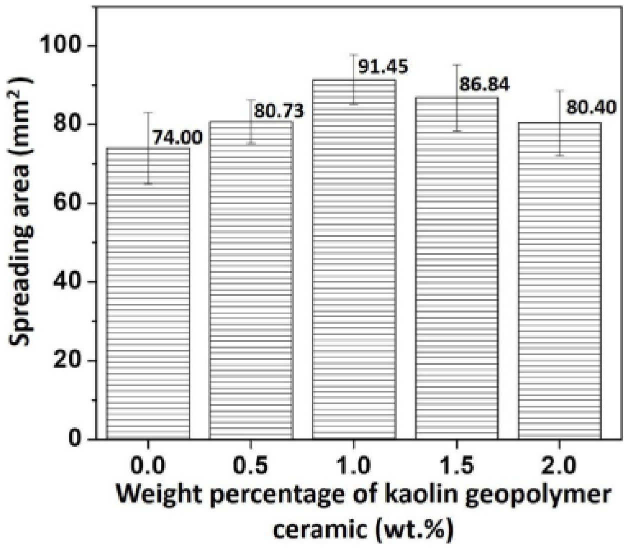



Figure 4: Schematic diagram for the experimental setup dipping of bulk kaolin geopolymer ceramic in SAC305 lead free solder and spreadability of SAC305 lead free solder with different weight percentages of KGC on a copper substrate [13]

Geopolymers have demonstrated impressive engineering properties to overcome the problem of damaged (collapsed, cracked, and decreased soil strength) road pavement structures built on clay soil due to clay soil properties [14–18]. One study was conducted to investigate soil stabilisation using GGBS and fly ash-based geopolymer processes further [19]. The results showed that the highest strength obtained was 3.15 MPA with a GGBS to alkaline activator ratio of 1.5 and $Na_2SiO_3$ to NaOH ratio of 2.0 at 7 days curing time (Figure 5). Based on the compression test results, the geopolymer soil with GGBS and fly ash could be used as the road subgrade since the values achieved were more than 0.8 MPa. This indicates that the soil stabilization using fly ash and GGBS based geopolymer has proven effective in increasing the strength of the soil according to the ASTM D4609 standard and Design Guideline for Alternative Pavement Structures (Low Volume Roads) of Malaysia Public Work Department (PWD). These findings are useful in enhancing knowledge in the field of soil stabilization-based geopolymer, especially for applications in pavement construction. In addition, it can be used as a reference for academicians, civil engineers, and geotechnical engineers.

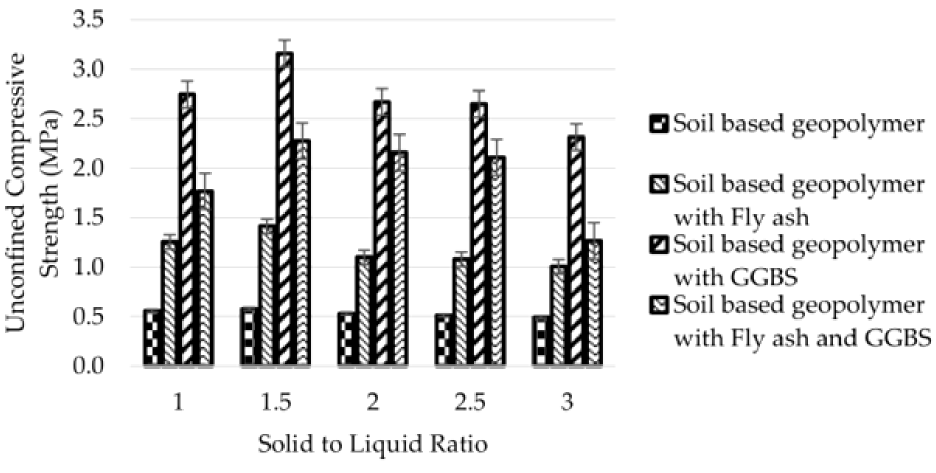


Figure 5: The effect of different solid to liquid (S/L) ratios of soil based geopolymer, soil based geopolymer with fly ash, soil based geopolymer with GGBS, and soil based geopolymer with fly ash and GGBS on compression strength at 7 days curing

Ceramics have become more essential in industry because to their superior mechanical and physical qualities [20]. The goal for developing fly ash geopolymer ceramics was to overcome the issue associated with traditional technical ceramics such as alumina, silicon, carbide, and aluminium nitride, which shatter easily under mechanical or thermo-mechanical pressures. One research has studied the development of a new material for the fabrication of geopolymer as a lightweight ceramic precursor and the advancement of green technology [21]. The image of fly ash geopolymer sample surface (Figure 6(a)) showed heterogeneous elements and contained more unreacted particles. Figure 6(b) shows at solid liquid to liquid ratios 1.0, large sintered area was formed due to the fly ash particle begin to fuse together where it demonstrates incomplete geopolymerization. Figure 6(c) at solid to liquid ratio 2.0, the matrix of fly ash were started to fuse together and the appearance of pores started to presence. However, at solid to liquid ratio 3.0 (Figure 6(d)), the pores started to increase and leave many pores in the structure. The solids to liquid ratio affect the amount of pores in the pastes which directly influences the strength and density of geopolymer ceramics. Microstructure image shows smoother and complete geopolymer matrix which gives denser structure as supported by the excellent density.

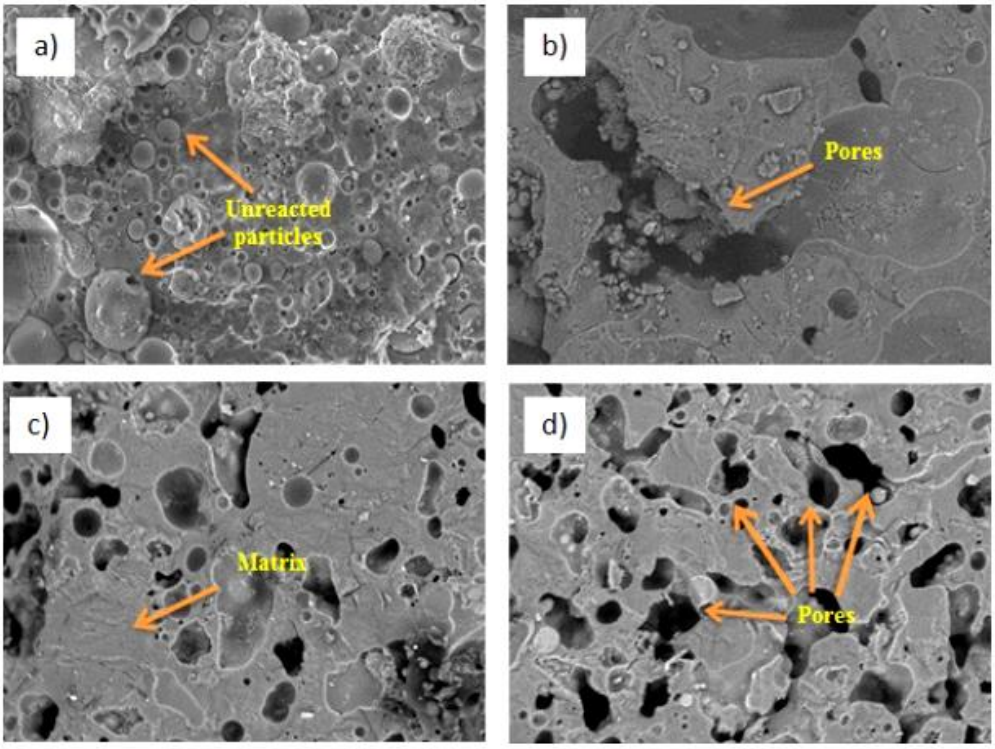



Figure 6: Microstructural images of a) fly ash geopolymer and fly ash geopolymer ceramics with solid to liquid ratio of b) 1.0, c) 2.0, and c) 3.0 [21]

In conclusion, this article introduces current geopolymer research of product development process and their performance. Current geopolymer research is important to develop a new product which is environmental friendly, robust and safe for intended use by any application.

**Reference**


1. Nergis, D. B., Abdullah, M. M. A. B., Vizureanu, P., & Tahir, M. M. (2018, June). Geopolymers and their uses. In IOP Conference Series: Materials Science and Engineering (Vol. 374, No. 1, p. 012019). IOP Publishing.
2. Abdullah, M. M., Ming, L. Y., Yong, H. C., & Tahir, M. F. (2018). Clay-based materials in geopolymer technology. Cement Based Materials, 239.
3. Jaya, N. A., Yun-Ming, L., Cheng-Yong, H., Abdullah, M. M. A. B., & Hussin, K. (2020). Correlation between pore structure, compressive strength and thermal conductivity of porous metakaolin geopolymer. Construction and Building Materials, 247, 118641.
4. Aziz, I. H., Abdullah, M. M. A. B., Salleh, M. M., Azimi, E. A., Chaiprapa, J., & Sandu, A. V. (2020). Strength development of solely ground granulated blast furnace slag geopolymers. Construction and Building Materials, 250, 118720.
5. Jamil, N. H., Abdullah, M., Al Bakri, M., Pa, F. C., Mohamad, H., Ibrahim, W. M. A. W., ... & Ibrahim, N. (2021). Self-fluxing mechanism in geopolymerization for low-sintering temperature of ceramic. Materials, 14(6), 1325.
6. Shahedan, N. F., Abdullah, M. M. A. B., Mahmed, N., Kusbiantoro, A., Tammas-Williams, S., Li, L. Y., ... & Nabiałek, M. (2021). Properties of a New Insulation Material Glass Bubble in Geo-Polymer Concrete. Materials, 14(4), 809.
7. Zaidi, F. H. A., Ahmad, R., Abdullah, M. M. A. B., Mastura, W., & Syauqi, A. (2020, May). The Effect of Seawater on The Strength, Microstructure and Elemental Distribution of Fly Ash/Kaolin Based Underwater Geopolymer. In IOP Conference Series: Materials Science and Engineering (Vol. 864, No. 1, p. 012014). IOP Publishing.
8. Bouaissi, A., Li, L. Y., Moga, L. M., Sandu, I. G., Abdullah, M. M. A. B., & Sandu, A. V. (2018). A review on fly ash as a raw cementitious material for geopolymer concrete. Rev. Chim, 69(7), 1661-1667.
9. Jaya, N. A., Abdullah, M. M. A. B., Ghazali, C. M. R., Hussain, M., Hussin, K., & Ahmad, R. (2016). Kaolin geopolymer as precursor to ceramic formation. In MATEC Web of Conferences (Vol. 78, p. 01061). EDP Sciences.
10. Jaya, N. A., Al Bakri, A. M., Ghazali, C. M. R., Binhussain, M., Kamarudin, H., & Ahmad, R. (2016). Characterization and Microstructure of Kaolin-based ceramic using geopolymerization. In Key Engineering Materials (Vol. 700, pp. 3-11). Trans Tech Publications Ltd.
11. Liew, Y. M., Heah, C. Y., Li, L. Y., Jaya, N. A., Abdullah, M. M. A. B., Tan, S. J., & Hussin, K. (2017). Formation of one-part-mixing geopolymers and geopolymer ceramics from geopolymer powder. Construction and Building Materials, 156, 9-18.
12. Jaya, N. A., Al Bakri Abdullah, M. M., & Ahmad, R. (2015). Reviews on clay geopolymer ceramic using powder metallurgy method. In Materials Science Forum (Vol. 803, pp. 81-87). Trans Tech Publications Ltd.
13. Zaimi, N. M., Salleh, M. M., Abdullah, M. M. A. B., Ahmad, R., Mostapha, M., Yoriya, J. Chaiprapa, G. Zhang, and D. M. Harvey. (2020). Effect of kaolin geopolymer ceramic addition on the properties of Sn-3.0 Ag-0.5 Cu solder joint. Materials Today Communications, 25, 101469.

14. Thomas, A., Tripathi, R. K., & Yadu, L. K. (2018). A laboratory investigation of soil stabilization using enzyme and alkali-activated ground granulated blast-furnace slag. Arabian Journal for Science and Engineering, 43(10), 5193-5202.
15. Tigue, A. A. S., Malenab, R. A. J., Dungca, J. R., Yu, D. E. C., & Promentilla, M. A. B. (2018). Chemical stability and leaching behavior of one-part geopolymer from soil and coal fly ash mixtures. Minerals, 8(9), 411.
16. Canakci, H., Güllü, H., & Alhashemy, A. (2019). Performances of using geopolymers made with various stabilizers for deep mixing. Materials, 12(16), 2542.
17. Singhi, B., Laskar, A. I., & Ahmed, M. A. (2016). Investigation on soil–geopolymer with slag, fly ash and their blending. Arabian Journal for science and engineering, 41(2), 393-400.
18. Zaliha, S. Z., Al Bakri, A. M., Kamarudin, H., & Fauziah, A. (2015). Characterization of soils as potential raw materials for soil stabilization application using geopolymerization method. In Materials Science Forum (Vol. 803, pp. 135-143). Trans Tech Publications Ltd.
19. Abdila, S. R., Abdullah, M. M. A. B., Ahmad, R., Rahim, S. Z. A., Rychta, M., Wnuk, I., Nabiałek, M., Muskalski, K., Tahir, M.F.M., Isradi, M. and Gucwa, M. (2021). Evaluation on the mechanical properties of ground granulated blast slag (GGBS) and fly ash stabilized soil via geopolymer process. Materials, 14(11), 2833.
20. Ahmad, R., Abdullah, M. M. A. B., Hussin, K., Sandu, A. V., Binhussain, M., & Jaya, N. A. (2016). Processing and properties of polymer filled geopolymer ceramics fabricated via powder metallurgy method: A review. Rev. Adv. Mater. Sci, 44(1), 26-32.
21. Ahmad, R., Abdullah, M. M. A. B., Ibrahim, W. M. W., Sandu, A. V., Zailani, W. W. A., & Nahar, S. N. S. (2019, August). Influence of Solid-To-Liquid Ratio on Properties of Fly Ash Geopolymer Ceramics. In IOP Conference Series: Materials Science and Engineering (Vol. 551, No. 1, p. 012083). IOP Publishing.

Reprint from CI Magazine, Volume 42, No 10, Page 47-52

# Doing More and Doing Better with Fiber-Reinforced Shotcrete

## Design and testing comparison

by Antoine Gagnon and Marc Jolin

Over the years, fiber-reinforced shotcrete (FRS) has proven to be a very effective and versatile material. It plays an essential and often unique role in ground support systems in mines and many tunneling projects, and it makes possible the safe and economical construction of various civil structures. Simply put, FRS performs well in situations where installing conventional reinforcing bars or cast fiber-reinforced concrete (FRC) would be complex and tedious or simply unsafe. However, we believe that FRS does not get the consideration it deserves. This article will discuss how FRS can achieve more recognition and how we can do better in exploiting its impressive properties and capturing its full potential.

### What Makes FRS So Interesting

FRS is a composite material created by pneumatically projecting a concrete mixture and fibers onto a surface. More formally, a mixture of cement, water, aggregate, and admixtures are combined with discrete, discontinuous filaments comprised of a material with a high tensile strength and/or a high toughness. The performance of FRS obviously comes from the quality of the shotcrete (its constituents and process) and the performance of the fibers, but also from the interaction between the fibers and the shotcrete matrix. Unfortunately, the latter aspect is too often overlooked when designing an FRS mixture.

FRS is subject to the actions that are specific to shotcrete. In the process of placing shotcrete, the material is sprayed at high velocity and builds up on a receiving surface. The consolidation energy of the material impacting the surface produces compaction that allows shotcrete ingredients to work together efficiently through a strong packing density.[1] Also, the impact tends to give a preferential orientation to the fibers that is generally beneficial in the structure because the fibers are mainly oriented in a plane that is perpendicular to the nozzle axis and parallel to the surface sprayed.2,3 We recently studied this in our Shotcrete Laboratory at Université Laval, Québec City, QC, Canada, using the fiber orientation factor α, which is the average, for all possible fiber orientations, of the projected fiber length in the tensile stress direction to the fiber length itself.4 For a standard wet-mix shotcrete mixture, we found that $\alpha = 0.648$ for tension in a plane perpendicular to the nozzle and $\alpha = 0.223$ for tension in a plane perpendicular to the nozzle axis. Because cracks generally form perpendicularly to the former plane, it is clear that most of the fibers in FRS are in the best position to effectively transfer stress across a crack.

The flexibility of the shotcrete placement process also allows the buildup of a uniform thickness of FRS on surfaces that are naturally uneven. Because it is designed to adhere to vertical and even overhead surfaces, shotcrete does not need to be supported by formwork. For example, it is possible to follow the shape of an excavation without having to unnecessarily overfill the cavities. This is particularly costeffective and allows for fast construction and fast reentry of work personnel in underground environments. Compared to other construction methods and other ground support systems, it is generally considered much faster and much simpler.5

Getting the most out of FRS is about finding the right “composite” for the situation or application considered. It is also a question of finding the optimal interaction between fibers and shotcrete. This varying combination allows for a wide range of possibilities in terms of mixtures and applications. Fortunately, our level of understanding has improved over the past decades—the rheology and the placement process of shotcrete are now better controlled, which opens the doors to many new applications. It is also possible to use the information that applies more generally to FRC by adapting it to the context of the shotcrete placement process. After all, FRS is FRC.

## The Consideration That It Deserves

Because FRS helps us achieve so much in so many contexts, it seems appropriate to take some time to make sure it is specified to perform at its best. As for all concrete, this means that special care should be given to the choice of ingredients, mixture proportions, testing methods, and design approaches.

For shotcrete, the right choice of ingredients is essential to achieve the desirable properties in both fresh and hardened states. The aggregate size distribution is a key parameter in this matter; a good distribution will make a mixture that is both pumpable and sprayable. This is particularly important for FRS, as the introduction of fibers tends to reduce the workability of shotcrete. Whenever possible, it is better to focus on good base materials to reach the right pumping and spraying behaviors rather than having to rely only on chemical admixtures and risk incorrect use and unnecessary costs.[6,7]

FRS should be considered a "dynamic" material because the proportions of its components may change during the placement process. The effect of rebound—shotcrete material that bounces away from the surface—is responsible for this shift of proportions. In fact, this phenomenon is usually minimized by adequate tuning of the equipment and by maintaining a proper consistency of the material. This is always true for shotcrete, but it can also affect the fiber content when working with FRS because fibers behave like elongated aggregates and can bounce off the surface.[8] Indeed, one must understand that the final fiber content of the in-place material is usually different from the initial fiber content.[2,9]

FRS is used in a wide range of contexts with different loading conditions. It is sometimes used in challenging environments where the loading conditions are complex; deep mines and highly stressed ground openings are great examples. Therefore, it is essential to give appropriate consideration to the test method that will be used for the evaluation of FRS. This is particularly true considering the number of standard test methods available:

- ASTM C1399/C1399M, "Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete";
- ASTM C1550, "Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)";
- ASTM C1609/1609M, "Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)";
- UNE 83-515, "Fibre Reinforced Concrete. Determination of Cracking Strength, Ductility and Residual Tensile Strength. Barcelona Test"[10];
- EN 14488-5[11] for determination of energy absorption capacity of fiber-reinforced slab specimens;
- EN 14651[12] for measuring the flexural tensile strength;
- "EFNARC Three Point Bending Test on Square Panel with Notch"[13];
- Norwegian round panel test[14]; and
- Grimstad and Barton.[15]

It is crucial to understand what information will be produced and how it will be used. Will it be used to compare with a design value, or will it be used as a quality indicator? Because different test methods do not test samples under the same conditions, it is generally hard to compare test methods directly, even though it may seem convenient. Although a given test method may show an increase in performance of a mixture, a second test method may not. This means that performance results from one test method are often not comparable to results from another test method. Finding the right test method to be used and the right way to use the information are essential steps for ensuring correct conclusions and appropriate decisions.

Particularly when working with FRS, it is important to consider and understand the idea behind the testing procedure selected. Testing a material is the same as asking a question. For example: How does this material react under the specific conditions of this test method? Subsequently, an answer to the question can be retrieved from the results, and this answer can be shared or used for design or performance evaluation. Essentially, it is crucial to understand the test (question) that is being run (asked) and the result (answer) that is collected.

For example, the compressive strength is a commonly evaluated characteristic of concrete, and it is generally a good indicator of the quality of the placement of shotcrete and the quality of its ingredients. In some applications, the compressive strength can be the only performance specification for shotcrete.[16] However, it is generally not a good indicator of the performance of FRS. In the typical range of fiber contents found, the compressive strength of FRS is not affected by the fibers.[1] Also, having the strongest concrete mixture (that is, the highest compressive strength) is not the correct approach to obtaining an FRS with the best properties (highest energy absorption, for example). In fact, the behavior of this composite comes from the interaction between the fiber and the concrete. Indeed, in an FRS composite system, a fiber that slowly pulls out of the concrete will dissipate more energy than a fiber that breaks because it is too strongly anchored. Focusing on making a strong(er) concrete is not necessarily the best way to reach an ideal composite action.

Finally, as for concrete in general, the attention given to the sampling procedure is not only necessary but also beneficial in making the appropriate decisions. As it was explained previously, the placement process of shotcrete has a strong effect on the characteristics of the in-place material. Thus, creating test specimens that are representative of the actual structure is an important aspect of the design steps, quality control, and quality assurance. This is particularly important for FRS because the rebound of fibers and their orientation in the structure can affect the performance of the material. Luckily, many documents focus on this aspect and give guidance on the sampling procedure of shotcrete.

As a matter of fact, ACI technical committees have published multiple documents that can guide engineers, researchers, concrete producers, and contractors in the way they approach FRS. First, ACI 506R, "Guide to Shotcrete,"[16] is a general reference document that provides tools on the appropriate production, placement, and testing of shotcrete. Second, ACI 506.1R, "Guide to Fiber-Reinforced Shotcrete,"[8] gives specific details about the use of fibers in shotcrete. Finally, ACI Committee 544, Fiber Reinforced Concrete, offers a number of documents on the subject of FRC, including a lot of information that applies to FRS.[17-23]

## Laboratory Experience

Results from a recent research program well represent the affirmation by which different wet-mix shotcrete designs respond differently to different test procedures. In this series of experiments, three different FRS mixtures were tested following two test methods on panels that are commonly used in the industry for the design and testing of FRS: ASTM C1550 and EN 14488-5.[11] In both test methods, a shotcrete panel is subjected at its center to a load controlled by deflection rate (Fig. 1). The peak load and energy absorption (toughness) of the FRS samples are measured in both of these procedures.

The concrete batches for all test panels had the same mixture proportions and steel fiber dosage of 25 kg/m$^3$ (shown in Table 1). However, Mixtures A, B, and C incorporated Bekaert Dramix® 3D-45/35 BL, Dramix® 4D-65/35 BG, and Dramix® 5D-65/60 BG steel fibers (shown in Table 2). A priori, these fibers should create different behaviors with the same concrete mixture proportions, as the fibers' geometries, tensile strengths, and anchoring systems are different. Based on the fibers' properties, we would expect Mixture C to have better performance than Mixture B, and we would expect Mixture B to have better performance than Mixture A.

Fig. 1: Setup for bending tests: (a) ASTM C1550; and (b) EN 14488-5[11] test methods

The results summarized in Table 3 show that the ASTM C1550 and EN 14488-5[11] test methods do not reflect identical increases in performance. Regardless of the absolute values of energy absorption, the trend is different from one test method to another. By normalizing the value of energy absorption at maximum deflection with Mixture A as a reference, it is possible to highlight this trend (Fig. 2). ASTM C1550 shows a lower increase in performance relative to the lowest value (Mixture A) compared to the increase shown with EN 14488-5.[11] This shows that one FRS mixture could be preferred over another, depending on the test method used to characterize the material. The results also indicate that the design process could be affected, again depending on the test method used.

The results support the idea that, because of the loading conditions, some test methods tend to be more sensitive to the fiber type, the fiber dosage, the compressive strength of the concrete, or the interaction between the shotcrete and the fibers. In this case, the EN 14488-5 test method showed a clear strength advantage of Mixture C over the other mixtures, with a 110% increase with regard to Mixture A. In contrast, the ASTM C1550 test method shows only a 71% strength advantage of Mixture C over Mixture A. It is possible that, for that specific shotcrete mixture, the square panel on continuous support (EN 14488-5[11]) is more sensitive to the fiberanchoring system. These test method conditions could increase the deflection hardening behavior of Mixture B and Mixture C (both contain fibers with efficient anchoring systems). The anchor systems could also help to maintain a steady load capacity up to a 25 mm (1 in.) deflection, making the energy absorption value higher.

These conclusions mean that the choice of test method is important, as it can influence the decisions in different steps of a construction process, particularly during design. The test

### Table 1:
Mixture proportions for Mixtures A, B, and C

| Material | Quantity |
|---|---|
| Cement, kg/m$^3$ (lb/yd$^3$) | 377 (635) |
| Silica fume, kg/m$^3$ (lb/yd$^3$) | 29 (49) |
| Fly ash , kg/m$^3$ (lb/yd$^3$) | 72 (121) |
| Fine aggregate, kg/m$^3$ (lb/yd$^3$) | 1060 (1787) |
| Coarse aggregate, kg/m$^3$ (lb/yd$^3$) | 568 (957) |
| Water, kg/m$^3$ (lb/yd$^3$) | 213 (359) |
| Steel fiber, kg/m$^3$ (lb/yd$^3$) | 25 (42) |
| Air-entraining admixture, mL/m$^3$ (fl oz/yd$^3$) | 400 (10.3) |
| Water-reducing admixture, mL/m$^3$ (fl oz/yd$^3$) | 400 (10.3) |

**Table 2:**
**Bekaert fiber properties in Mixtures A, B, and C**

| Fiber properties | Mixture A | Mixture B | Mixture C |
|---|---|---|---|
| Type | Dramix 3D-45/35 BL | Dramix 4D-65/ 35 BG | Dramix 5D-65/60 BG |
| Length, mm (in.) | 35 (1.4) | 35 (1.4) | 60 (2.4) |
| Aspect ratio | 45 | 65 | 65 |
| Tensile strength, Mpa (psi) | 1225 (177,700) | 1850 (268,300) | 2300 (333,600) |
| Anchoring system | 3-face hook | 4-face hook | 5-face hook |

**Table 3:**
**Summarized results from properties at fresh state and hardened state (28 days)**

| Properties | | Mixture A | Mixture B | Mixture C |
|---|---|---|---|---|
| Slump per ASTM C143/C143M, mm (in.) | | 120 (4.75) | 100 (4.00) | 55 (2.25) |
| Air content per ASTM C231/C231M before pumping and spraying, % | | 6.8 | 9.4 | 7.4 |
| Average compressive strength per ASTM C1604/C1604M, MPs (psi) | | 49.0 (7110) | 45.4 (6580) | 51.7 (7500) |
| Average peak load per ASTM C1550, N | | 29,600 | 27,100 | 30,420 |
| Average energy absorption per ASTM C1550, J | 5 mm (0.2 in.) deflection | 90 | 101 | 118 |
| | 10 mm (0.4 in.) deflection | 115 | 183 | 245 |
| | 20 mm (0.8 in.) deflection | 244 | 300 | 409 |
| | 40 mm (1.6 in.) deflection | 349 | 456 | 597 |
| Average peak load per EN 14488511, kN | | 61 | 67 | 91 |
| Average energy absorption per EN 14488-511 at 25 mm (1 in.) deflection, J | | 1010 | 1470 | 2120 |

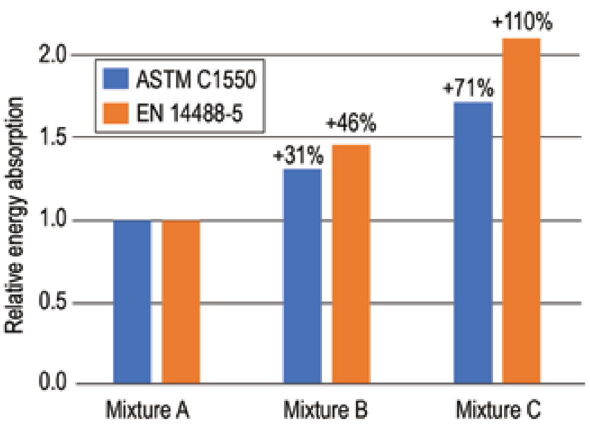



**Fig. 2: Relative energy absorption values from ASTM C1550 and EN 14488-5 testing at maximum deflection for FRS with three different fibers at the same dosage**

method should represent the actual loading conditions in which FRS will be used to truly evaluate its performance. It also means that, once a test method has been chosen for a project, it should be the only test method used throughout the entire project, from the initial design of the mixture to the quality control on-site—unless a clear correlation has been identified for a specific mixture.

Obviously, difficulties arise when the time comes to select an appropriate test method to work with. Before doing so, the engineer must not only reflect on the objective(s) of the test (including design, quality assurance, quality control, and research and development) but also identify a test method that will allow the engineer to truly discriminate between successful and meaningful results.

## Conclusions

There is no doubt that FRS is applied using a unique placement process that yields a complex material. The rheology of the fresh shotcrete, the pumping aspects, and the consolidation process are all examples of what influences the in-place material. Although a good understanding is required to design and specify shotcrete, the knowledge is fortunately there for us to use. Besides, the complexity surrounding FRS is what makes it so versatile and useful. Indeed, when using the proper tools and materials, the possibilities are endless. Therefore, it is essential to use the information that is available and give FRS the consideration that it deserves. Many challenges we must overcome remain, but this is how we will be able to use this effective tool at its full potential.

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## References


1. Bentur, A., and Mindess, S., *Fibre Reinforced Cementitious Composites*, second edition, CRC Press, Boca Raton, FL, 2006, 624 pp.
2. Armelin, H.S., and Helene, P., "Physical and Mechanical Properties of Steel-Fiber Reinforced Dry-Mix Shotcrete," *ACI Materials Journal*, V. 92, No. 3, May-June 1995, pp. 258-267.
3. "Guideline on the Applicability of Fibre-Reinforced Shotcrete for Ground Support in Mines," *MIGS III WP 24 Report*, Nordic Rock Tech Centre, 2019, 53 pp.
4. Soroushian, P., and Lee, C.-D., "Distribution and Orientation of Fibers in Steel Fiber Reinforced Concrete," *ACI Materials Journal*, V. 87, No. 5, Sept.-Oct. 1990, pp. 433-439.
5. Vandewalle, M., "Use of Steel Fibre Reinforced Shotcrete for the Support of Mine Openings." *Journal of the South African Institute of Mining and Metallurgy*, V. 98, No. 3, May/June 1998, pp. 113-120.
6. Burns, D., "Characterization of Wet-Mix Shotcrete for Small Line Pumping," MS thesis, Department of Civil Engineering, Université Laval, Québec City, QC, Canada, 2008, 119 pp.
7. Jolin, M.; Melo, F.; Bissonnette, B.; Power, P.; and Demmard, E., "Evaluation of Wet-Mix Shotcrete Containing Set-Accelerator and Service Life Prediction," *Proceedings: Shotcrete for Underground Support XII*, M. Lu, O. Sigl, and G. Li, eds., Singapore, Oct. 2015, 13 pp.
8. ACI Committee 506, "Guide to Fiber-Reinforced Shotcrete (ACI 506.1R-08)," American Concrete Institute, Farmington Hills, MI, 2008, 14 pp.
9. Jolin, M.; Lemay, J.-D.; Ginouse, N.; Bissonnette, B.; and Blouin-Dallaire, É., "The Effect of Spraying on Fiber Content and Shotcrete Properties," *Proceedings: Shotcrete for Underground Support XII*, M. Lu, O. Sigl, and G. Li, eds., Singapore, Oct. 2015, 15 pp.
10. UNE 83515:2010, "Hormigones con Fibras. Determinación de la Resistencia a Fisuración, Tenacidad y Resistencia Residual a Tracción. Método Barcelona" (Fibre Reinforced Concrete. Determination of Cracking Strength, Ductility and Residual Tensile Strength. Barcelona Test), Asociación Española de Normalización y Certificación (AENOR), Madrid, Spain, 2010, 10 pp.
11. EN 14488-5, "Testing Sprayed Concrete—Part 5: Determination of Energy Absorption Capacity of Fibre Reinforced Slab Specimens," European Committee for Standardization, Brussels, Belgium, 2006, 10 pp.
12. EN 14651, "Test Method for Metallic Fibre Concrete. Measuring the Flexural Tensile Strength (Limit of Proportionality [LOP], Residual)" European Committee for Standardization, Brussels, Belgium, 2007, 19 pp.
13. "EFNARC Three Point Bending Test on Square Panel with Notch," EFNARC, June 2011, 12 pp.
14. "Publication No. 7: Sprayed Concrete for Rock Support," Norwegian Concrete Association, Oslo, Norway, 2011, 103 pp.
15. Grimstad, E., and Barton, N., "Updating the Q-System for NMT," *Sprayed Concrete: Modern Use of Wet Mix Sprayed Concrete for Underground Support*, R. Kompen, O. Opsahl, and K. Berg, eds., International Symposium on Sprayed Concrete, Fagernes, Norway, Oct. 1993, 464 pp.
16. ACI Committee 506, "Guide to Shotcrete (ACI 506R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 52 pp.
17. ACI Committee 544, "Report on the Measurement of Fresh State Properties and Fiber Dispersion of Fiber-Reinforced Concrete (ACI 544.2R-17)," American Concrete Institute, Farmington Hills, MI, 2017, 20 pp.
18. ACI Committee 544, "Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete (ACI 544.3R-08)," American Concrete Institute, Farmington Hills, MI, 2008, 12 pp.
19. ACI Committee 544, "Guide to Design with Fiber-Reinforced Concrete (ACI 544.4R-18)," American Concrete Institute, Farmington Hills, MI, 2018, 39 pp.
20. ACI Committee 544, "Report on the Physical Properties and Durability of Fiber-Reinforced Concrete (ACI 544.5R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 31 pp.
21. ACI Committee 544, "Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs (ACI 544.6R-15)," American Concrete Institute, Farmington Hills, MI, 2015, 38 pp.
22. ACI Committee 544, "Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete (FRC) (ACI 544.8R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 22 pp.
23. ACI Committee 544, "Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete (ACI 544.9R-17)," American Concrete Institute, Farmington Hills, MI, 2017, 48 pp.


Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.


ACI member **Antoine Gagnon** is a PhD Student in the Department of Civil and Water Engineering at Université Laval, Québec City, QC, Canada. His research focuses on the development of tools for the design and testing of fiber-reinforced shotcrete for ground support. He has worked on shotcrete research projects with different companies in the industry. He is Chair of ACI Subcommittee 506-B, Shotcreting-Fiber-Reinforced, and a member of ACI Committees 506, Shotcreting, and 544, Fiber Reinforced Concrete. He received his bachelor's degree and his master's degree in civil engineering from Université Laval.

**Marc Jolin**, FACI, is a Professor in the Department of Civil and Water Engineering at Université Laval. He is Chair of ACI Subcommittee 506-L, Liaison Subcommittee; past Chair of ACI Committees 506, Shotcreting, and C660, Shotcrete Nozzleman Certification; Secretary of ACI Committee C661, Shotcrete Inspector Certification; and an ACI Examiner for Shotcrete Nozzleman Certification (wet- and dry-mix processes). Jolin is also a member of the American Shotcrete Association. He received his PhD from the University of British Columbia, Vancouver, BC, Canada.

# CASE STUDY

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# A Step Toward Practical Geopolymer Concrete

## Laboratory investigations and a field demonstration show promise

by Faris Matalkah and Parviz Soroushian

Geopolymers are inorganic binders based on alkali aluminosilicate chemistry, which is prevalent among natural rocks.[1] Geopolymerization is the process of transforming an aluminosilicate precursor in powder form (for example, coal fly ash) into a largely amorphous binder by the addition of alkaline (for example, sodium hydroxide and sodium silicate) solutions.[2,3] The amorphous binder is comprised largely of alkali aluminosilicate hydrates and produces concrete with moisture resistance, chemical stability, fire resistance, and sustainability attributes.[2,4,5]
This alternative inorganic binder chemistry has been investigated extensively in the laboratory.[6-8] Researchers working in this field come from a wider breadth of backgrounds when compared with those typically conducting research on portland cement concrete. Many chemists and materials scientists who have been working in this field view geopolymer as a replacement for a host of materials, including organic polymers and ceramics.[9,10] While this multidisciplinary approach to geopolymer matrices and concrete materials laid a scientifically sound basis for future developments, it has left some practical issues ignored. In general, limited field work has been done with geopolymer concrete, so the rheology of geopolymer concrete in field applications has received limited attention.[11,12] Dimensional stability of geopolymer concrete is another topic that needs to be investigated more thoroughly.
In the work reported herein, we developed a geopolymer formulation in the laboratory and evaluated the mixture under scaled-up production and field application conditions. This allowed us to identify issues that need to be addressed for improving the compatibility of geopolymer concrete with mainstream construction practices.

## Materials and Methods

The coal fly ash used in our laboratory investigations was obtained from a power plant in Lansing, MI. For activators, we used a chemical grade sodium hydroxide and a sodium silicate solution. The sodium hydroxide pellets had 98% purity, from Sigma Aldrich. We dissolved them in tap water to produce a molarity of 14 M. The sodium silicate solution was acquired from PQ Corporation, Malvern, PA. This solution comprised 28.7% $SiO_2$, 8.9% $Na_2O$, and 62.4% $H_2O$, with density of 1.39 g/cm$^3$ and a pH of 11.30. We used citric acid, in powder form, as set retarder. This material had 98% purity and was also purchased from Sigma Aldrich. Natural sand and crushed limestone, with maximum particle sizes of 4.75 and 19 mm (187 and 748 mil), respectively, were used as fine and coarse aggregates. Table 1 presents the base concrete mixture design used in the laboratory investigations and the field demonstration project. We used this base mixture in our investigation of the set retardation effects of citric acid (used at different dosages).
The fresh mixture workability was measured per ASTM C143/C143M, "Standard Test Method for Slump of Hydraulic-Cement Concrete." Initial and final setting times were measured per ASTM C403/C403M, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." For strength tests, fresh concrete mixtures were placed in 75 x 150 mm (3 x 6 in.) cylindrical molds that were consolidated via external vibration at medium intensity for 2 minutes. The molded specimens were sealed and stored at room temperature for 24 hours, after which they were demolded and subjected to five curing conditions. Specimens in Set 1 and 2 were cured at room temperature in sealed and unsealed conditions, respectively. Set 3 and 4 were

**Table 1:**
**Geopolymer concrete mixture proportions**

| Material | Quantity kg/m³ (lb/yd³) |
|---|---|
| Coal fly ash | 500 (840) |
| NaOH solution (14 M) | 125 (210) |
| Na2SiO3 solution | 125 (210) |
| Natural sand (4.75 mm [No. 4] MSA*] | 750 (1265) |
| Crushed limestone (19 mm [3/4 in.] MSA*) | 568 (957) |

*Maximum size aggregate

subjected to 48 hours of steam curing at 80°C (176°F) in sealed and unsealed conditions, respectively. Set 5 specimens were cured in water at room temperature to evaluate the moisture stability of the resultant hydrates. The specimens were then stored at 50% relative humidity and at room temperature, and they were tested at 7 days of age. Scanning electron microscopic (SEM) images and energy-dispersive X-ray spectroscopy (EDS) were captured of coal fly ash and the hardened geopolymer paste using a JEOL JSM-6610LV scanning electron microscope. X-ray fluorescence (XRF) spectroscopy methods were employed to assess the chemical composition of the fly ash.

## Laboratory Test Results

Laboratory tests were performed to characterize the fly ash and investigate the effects of various dosages of citric acid (a set retarder) on setting time and compressive strength.

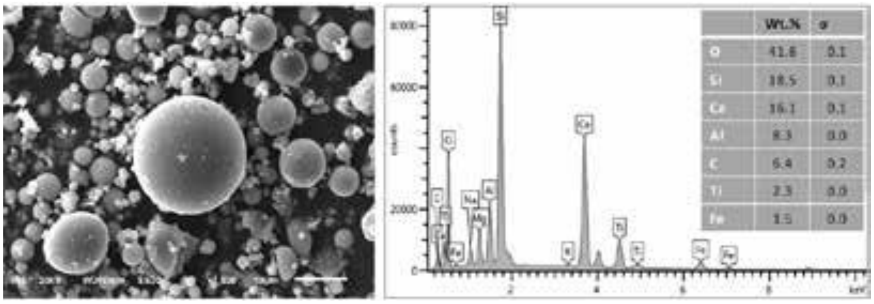

**Fig. 1: SEM image and EDS spectra of coal fly ash used in this investigation**

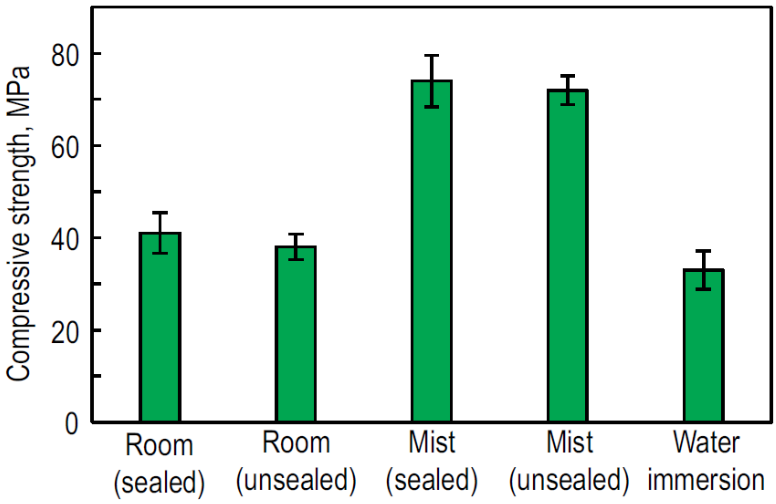


**Fig. 2: Effect of curing conditions on the 7-day compressive strength (mean values and 95% confidence intervals) (Note: 1 MPa = 145 psi)**

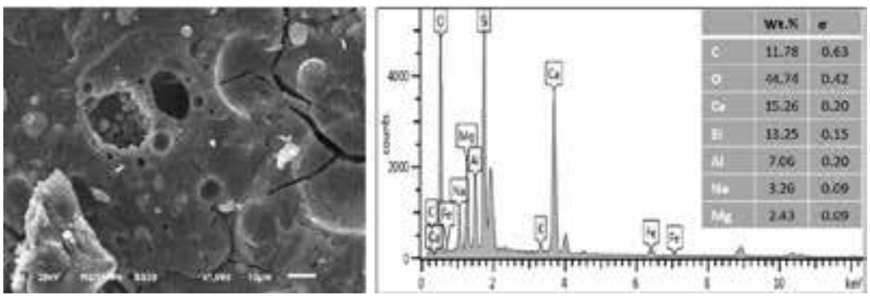

**Fig. 3: SEM image and EDS spectrum of coal ash-based geopolymer binder**

The chemical composition of the coal fly ash, measured using XRF spectroscopy, comprised silicon and aluminum oxides (about 45% by weight) with a silicon to aluminum oxide ratio of about 2 (30.6% $SiO_2$ and 15.1% $Al_2O_3$). The calcium oxide content of fly ash was about 22%, qualifying it as Class C fly ash per ASTM C618, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." The iron oxide content was 16.8% by weight, and the $Na_2O$ and $K_2O$ contents totaled less than 3%. The loss on ignition of the fly ash was 1.2%.

Figure 1 presents an SEM image and the local EDS (local chemistry) data for the fly ash. As expected, the particles are spherical, and the local chemistry roughly represents that of the bulk fly ash evaluated via XRF spectroscopy.

Figure 2 shows the compressive strength test results obtained with different curing conditions. Room temperature cured specimens showed compressive strengths of about 40 MPa (5800 psi), whereas the steam-cured specimens showed strengths exceeding 70 Mpa (10,150 psi). This agrees with previous work which shows that steam curing benefits the dissolution rate of coal fly ash in alkaline solution and accelerates the geopolymerization process.[13]

Sealed and unsealed specimens were found to produce similar compressive strengths for both room temperature and steam curing conditions. Curing by immersion in water at room temperature lowered the compressive strength by 14% when compared to curing in air at room temperature.

Figure 3 shows an SEM image and the corresponding EDS spectrum of the binder after 28 days of room-temperature curing in air. The microstructure comprises a geopolymer gel that embodies the nonhydrated cores of fly ash particles. The gel exhibits relatively low porosity.

The microcracks observed in this image could have resulted from the extreme drying of the specimens prior to SEM imaging. The EDS data points at the formation of a Ca-rich geopolymer binder (calcium aluminosilicate hydrate C-A-S-H).[14]

The local Ca-to-Si ratio is close to 1, compared to 2-3 for the C-S-H gel resulting from hydration of portland cement.[15]

Table 2 presents the initial and final setting times and the compressive strength values for mixtures with different concentrations of citric acid. The addition of citric acid to a geopolymer retards the rate of hydration reactions and therefore lowers the early-age compressive strength of the resultant concrete. The delay could be due to the formation of carboxylate complexities via interactions between the $Ca^{+2}$ ions liberated from fly ash and the carboxylic acid groups of citric acid.[16]

While the addition of 2.5% citric acid by weight of fly ash roughly doubled the initial and final setting times for our mixture, it resulted in only a 10% decrease in compressive strength. A 5% dosage of citric acid almost tripled the initial setting time relative to the control mixture, and it boosted the final setting time by a factor of almost 2.6. However, that dosage resulted in a 26% drop in compressive strength relative to the control mixture.

## Field Demonstration

Laboratory investigations verified satisfactory performance of the geopolymer concrete. The concrete mixture design evaluated in the laboratory (Table 1) was used to cast a section of a sidewalk on the campus of Michigan State University (MSU), in July 2015. To control the setting time, the concrete was batched with 2.5% citric acid by weight of fly ash. Coal fly ash was added to the truck in the concrete plant, directly from the silo (Fig. 4(a)). To reduce the quantity of alkaline solutions used to activate the coal fly ash in the field, the sodium silicate solution and citric acid were added to the truck at the plant (Fig. 4(b)). The sodium hydroxide solution was pumped into the truck soon after it arrived at the jobsite (Fig. 4(c)). Due to a relatively rapid loss of workability, 75 kg/$m^3$ (126 lb/$yd^3$) extra water was added to the geopolymer mixture at the jobsite.

The geopolymer concrete was used to cast a 2.4 x 12 m (7.9 x 39 ft), 150 mm (6 in.) thick section of sidewalk. The fresh concrete workability was measured at the site using the slump test (Fig. 5(a)) per ASTM C143/C143, “Standard Test Method for Slump of Hydraulic-Cement Concrete.” The

**Table 2:**
**Setting times and 7-day compressive strength values for fly ash geopolymer with different citric acid dosages**

| Citric acid addition, % of fly ash by weight | Setting time, minutes | | 7-day compressive strength, MPa (psi) |
|---|---|---|---|
| | Initial | Final | |
| 0 (Control) | 14 | 48 | 43.2 (6270) |
| 2.5 | 32 | 77 | 38.1 (5530) |
| 5.0 | 41 | 124 | 31.8 (4610) |

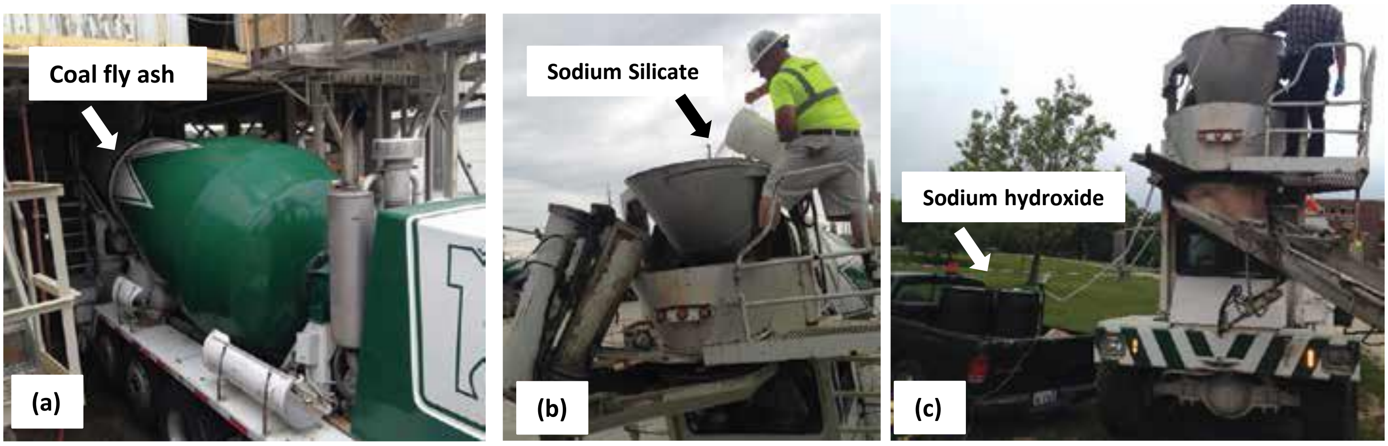


Fig. 4: Field trial of geopolymer concrete: (a) loading coal fly ash to a concrete truck; (b) adding sodium silicate solution at the plant; and (c) pumping sodium hydroxide solution into a mixer at the jobsite


Fig. 5: Field trial operations with geopolymer concrete: (a) slump test; (b) spreading; and (c) finishing

average slump was 75 mm (3 in.). Concrete test cylinders were consolidated using external vibration. The specimens were cured in a sealed condition at room temperature. Workers reported that the fresh geopolymer concrete mixture required more effort to spread than normal portland cement concrete (Fig. 5(b)). This agrees with previous studies, which have shown that fresh geopolymer pastes are more cohesive than fresh portland cement pastes, with higher values of yield stress and viscosity.[17] However, the geopolymer concrete sidewalk was finished using the same tools and procedures that would be used with normal portland cement concrete (Figure 5(c)).

Figure 6 presents the trends in compressive strength development for the geopolymer concrete specimens taken from the concrete truck. After 3 days, the compressive strength values were relatively low at about 8 MPa (1160 psi). Although the 7-day compressive strength measured in laboratory specimens reached about 38 MPa (5530 psi), the field trial mixture reached only 12 MPa (1740 psi) in 7 days. The significantly lower strength of the concrete produced for the field trial is likely the result of the water addition used to adjust the slump and avoid loss of workability. As shown in Fig. 6, however, the compressive strength increased continuously with time. The strength reached about 30 MPa (4350 psi) after 28 days, which is the compressive strength of normal portland cement concrete used in similar applications. After 120 days, the compressive strength of geopolymer concrete reached about 55 MPa (7980 psi). The observed rise in compressive strength from 28 to 120 days exceeds the rise expected for normal portland cement concrete over the same period.

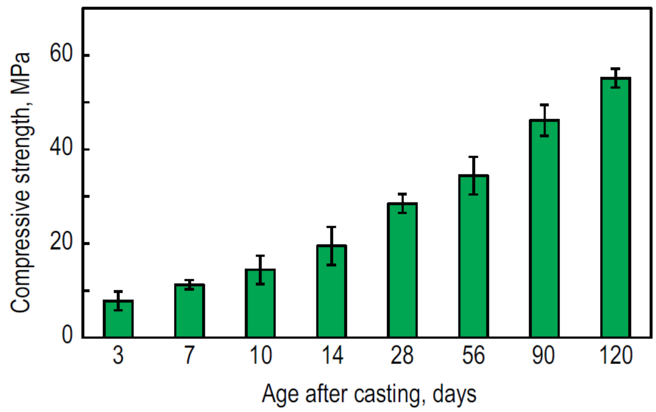


**Fig. 6: Compressive strength test results for geopolymer concrete specimens taken from a concrete truck (Note: 1 MPa = 145 psi)**

## Conclusions

A geopolymer concrete mixture based on alkali-activated coal fly ash was developed to provide a viable balance of fresh mixture workability, setting time, and compressive strength (with room-temperature curing). The resulting mixture was used to construct a section of a sidewalk on the campus of MSU. Based on the laboratory investigations and the field experience, we can report that:

- Sealed specimens cured at room temperature had slightly greater compressive strength than specimens exposed to ambient air. Immersion of specimens in water reduced compressive strength by 14% relative to sealed specimens;
- Citric acid was found to be effective in increasing the initial and final setting times. The addition of citric acid at a dosage of 2.5% by weight of fly ash provided setting times and compressive strength comparable with those obtained using portland cement;
- The geopolymer concrete exhibited a relatively rapid loss of workability. The relatively high viscosity and surface adhesion characteristics of the fresh geopolymer concrete also caused difficulties in finishing the concrete. To facilitate spreading and finishing of the geopolymer concrete, water had to be added in the field; and
- The specimens produced during the field trial developed strength more slowly than specimens prepared in laboratory under controlled conditions. Compressive strength continued to increase over the 120 days that strength was monitored.

We recommend more research on the fresh attributes of geopolymer concrete. While the rheological attributes of geopolymer concrete are somewhat different from those of portland cement concrete, this and other studies show that proper use of water reducers and viscosity modifying admixtures could allow the use of conventional concrete construction practices with geopolymer concrete.

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## References

1. Krivenko, P.V., “Alkaline Cements,” *Proceedings of the First International Conference on Alkaline Cements and Concretes*, V. 1, Kiev, Ukraine, 1994, pp. 11-129.
2. Somna, K.; Jaturapitakkul, C.; Kajitvichyanukul, P.; and Chindaprasirt, P., “NaOH-Activated Ground Fly Ash Geopolymer Cured at Ambient Temperature,” *Fuel*, V. 90, No. 6, June 2011, pp. 2118-2124.
3. Swanepoel, J.C., and Strydom, C.A., “Utilisation of Fly Ash in a Geopolymeric Material,” *Applied Geochemistry*, V. 17, No. 8, Aug. 2002, pp. 1143-1148.
4. Cheng, T.W., and Chiu, J.P., “Fire-Resistant Geopolymer Produced by Granulated Blast Furnace Slag,” *Minerals Engineering*, V. 16, No. 3, Mar. 2003, pp. 205-210.
5. Chindaprasirt, P.; Chareerat, T.; and Sirivivatnanon, V., “Workability and Strength of Coarse High Calcium Fly Ash Geopolymer,” *Cement and Concrete Composites*, V. 29, No. 3, Mar. 2007, pp. 224-229.
6. Duxson, P.; Fernández-Jiménez, A.; Provis, J.L.; Lukey, G.C.; Palomo, A.; and van Deventer, J.S.J., “Geopolymer Technology: The Current State of the Art,” *Journal of Materials Science*, V. 42, No. 9, May 2007, pp. 2917-2933.

7. Van Deventer, J.S.J.; Provis, J.L; and Duxson, P., "Technical and Commercial Progress in the Adoption of Geopolymer Cement," *Minerals Engineering*, V. 29, Mar. 2012, pp. 89-104.
8. Komnitsas, K.A., "Potential of Geopolymer Technology Towards Green Buildings and Sustainable Cities," *Procedia Engineering*, V. 21, 2011, pp. 1023-1032.
9. Davidovits, J., "Geopolymers and Geopolymeric Materials," *Journal of Thermal Analysis*, V. 35, No. 2, Mar. 1989, pp. 429-441.
10. He, P.; Jia, D.; Wang, M.; and Zhou, Y., "Effect of Cesium Substitution on the Thermal Evolution and Ceramics Formation of Potassium-Based Geopolymer," *Ceramics International*, V. 36, No. 8, Dec. 2010, pp. 2395-2400.
11. Ilyin, V.P., "Durability of Materials Based on Slag-Alkaline Binders," *Proceedings of the First International Conference on Alkaline Cements and Concretes*, Kiev, Ukraine, 1994, pp. 789-836.
12. Ozyildirim, H.C., "A Field Investigation of Concrete Overlays Containing Latex, Silica Fume, or Pyrament Cement," *No. FHWA/VA-96-R23*, Virginia Transportation Research Council, Charlottesville, VA, 1996, 28 pp.
13. Kovalchuk, G.; Fernández-Jiménez, A.; and Palomo, A., "Alkali-Activated Fly Ash: Effect of Thermal Curing Conditions on Mechanical and Microstructural Development– Part II." *Fuel*, V. 86, No. 3, Feb. 2007, pp. 315-322.
14. Huseien, G.F.; Mirza, J.; Ismail, M.; and Hussin, M.W., "Influence of Different Curing Temperatures and Alkali Activators on Properties of GBFS Geopolymer Mortars Containing Fly Ash and Palm-Oil Fuel Ash," *Construction and Building Materials*, V. 125, Oct. 2016, pp. 1229-1240.
15. Escalante-Garcia, J.I.; Mendoza, G.; and Sharp, J.H., "Indirect Determination of the Ca/Si Ratio of the CSH Gel in Portland Cements," *Cement and Concrete Research*, V. 29, No. 12, Dec. 1999, pp. 1999-2003.
16. Sugama, T., and Brothers, L.E., "Citric Acid as a Set Retarder for Calcium Aluminate Phosphate Cements," *No. BNL—73600-2005-IR*, Brookhaven National Laboratory, Upton, NY, 2005, 33 pp.
17. Romagnoli, M.; Leonelli, C.; Kamse, E.; and Gualtieri, M.L., "Rheology of Geopolymer by DOE Approach," Construction and Building Materials, V. 36, Nov. 2012, pp. 251-258.

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Selected for reader interest by the editors.

**Faris Matalkah** is an Assistant Professor of civil engineering at Yarmouk University, Irbid, Jordan. He received his PhD in materials and structural engineering from MSU, East Lansing, MI. His research interests include development of sustainable, energy efficient, and low cost cementitious materials

**Parviz Soroushian**, FACI, is a Professor of civil and environmental engineering at MSU. His research focuses on advanced and environmentally friendly structural materials. His background includes research and development of technologies concerning structural applications of nanocomposites, reinforcing fibers for composites, and structural systems. Soroushian is a licensed professional engineer in Michigan. He is also a Fellow of the American Society of Civil Engineers. He received his PhD from Cornell University, Ithaca, NY.

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