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A critical review of slag and fly-ash based geopolymer concrete

Tülin Akçaoğlu*[1], Beste Çubukçuoğlu[2a] and Ashraf Awad[1b]

[1]*Department of Civil Engineering, Faculty of Engineering, Eastern Mediterranean University, Gazimagusa - North Cyprus, via Mersin 10, Turkey*
[2]*Department of Civil Engineering, Faculty of Civil and Environmental Engineering, Near East University, Nicosia - North Cyprus via Mersin 10, Turkey*

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Abstract. Today, concrete remains the most important, durable, and reliable material that has been used in the construction sector, making it the most commonly used material after water. However, cement continues to exert many negative effects on the environment, including the production of carbon dioxide (CO2), which pollutes the atmosphere. Cement production is costly, and it also consumes energy and natural non- renewable resources, which are critical for sustainability. These factors represent the motivation for researchers to examine the various alternatives that can reduce the effects on the environment, natural resources, and energy consumption and enhance the mechanical properties of concrete. Geopolymer is one alternative that has been investigated; this can be produced using aluminosilicate materials such as low calcium (class F) FA, Ultra-Fine GGBS, and high calcium FA (class C, which are available worldwide as industrial, agricultural byproducts.). It has a high percentage of silica and alumina, which react with alkaline solution (activators). Aluminosilicate gel, which forms as a result of this reaction, is an effective binding material for the concrete. This paper presents an up-to-date review regarding the important engineering properties of geopolymer formed by FA and slag binders; the findings demonstrate that this type of geopolymer could be an adequate alternative to ordinary Portland cement (OPC). Due to the significant positive mechanical properties of slag-FA geopolymer cements and their positive effects on the environment, it represents a material that could potentially be used in the construction industry.

Keywords: geopolymer cement; ordinary Portland cement; FA; slag; sustainability

1. Introduction

Cement production emissions, such as carbon dioxide (CO_2), are regarded as one of the primary causes of global warming and climate change. Table 1 indicates that cement is the most commonly used material in the construction industry and that cement production has increased across the world since 2016. However, in addition to the immense energy consumption related to cement production, emissions, odors, and noise pollution are also negative consequences that should be considered. Emissions include CO_2, NOX, SOX, VOCs, particulate matter, among others (Devi *et al*. 2017). Global greenhouse (GHG) emissions are increasing rapidly, and the carbon dioxide produced by the construction industry and other industries comprises 70% of GHG emissions, which have been estimated to be 35.8 gigatonne (Gt) CO_2 for 2016; the growth rate of these emissions has changed drastically during the past three years, and global industrial and economic growth have produced these emissions in enormous quantities, as the global gross domestic product has increased by 2 to 3% each year (UNEP 2017).

To mitigate the increasing carbon dioxide emissions and other greenhouse gases and to prevent global warming and environmental pollution, researchers have focused on offering alternatives to reduce cement production. Consequently, many efforts have been devoted to the investigation of supplementary cementing materials (SCM) and geopolymers' performance. The average rate of cement replacement by SCM is around 20%, and the most common SCMs include fine limestone, granulated blast-furnace slags (GBFS), and coal FAs (FA). GBFS and FA are not available with the required properties in large quantities; they constitute around 15 to 25% of cement production, and this percentage is not expected to increase. However, researchers have recently developed a supplementary cement materials system with low carbon dioxide formed from a binder of calcined clays with ground limestone; this binder is not expensive and it is available using materials that could replace cement by up to 50% without any significant loss in the performance of the concrete (UNEP 2017).

The use of geopolymers is a new trend in the cement industry, which could mitigate several problems related to health and the environment that result from traditional cement production. This review paper investigates slag and FAFA-based geopolymer concrete, which uses slag and FAFA to completely replace Portland cement as the cementing material. Unlike ordinary Portland cement (OPC) concrete, geopolymer concrete does not require

*Corresponding author, Associate Professor
E-mail: tulin.akcaoglu@emu.edu.tr
[a]Assistant Professor
E-mail: beste.cubukcuoglu@neu.edu.tr
[b]Ph.D. Candidate
E-mail: eng_ashrafawad@hotmail.com

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Table 1 World Production and Capacity of Cement (in million metric tons) (Oss 2018)

	Cement production[e]		Clinker capacity[e]	
	2016	2017	2016	2017
United States (includes Puerto Rico)	85,000	86,300	107,000	109,000
Brazil	57,000	54,000	60,000	60,000
China	2,400,000	2,400,000	2,000,000	2,000,000
Egypt	55,000	58,000	46,000	48,000
India	280,000	270,000	280,000	280,000
Indonesia	63,000	66,000	78,000	78,000
Iran	55,000	56,000	79,000	80,000
Japan	53,300	53,000	53,000	53,000
Korea, Republic of	57,000	59,000	50,000	50,000
Russia	56,000	58,000	80,000	80,000
Saudi Arabia	62,000	63,000	75,000	75,000
Turkey	75,400	77,000	80,000	82,000
Vietnam	77,300	78,000	90,000	90,000
Other countries (rounded)	724,000	750,000	625,000	721,000
World total (rounded)	4,100,000	4,100,000	3,700,000	3,800,000

Portland cement to bond aggregates; it uses geopolymer cement as the cementing material. Davidovits *et al*. (2014) coined the term "geopolymer" in 1979 and initiated the investigation to determine which mineral polymers could be used for producing geopolymer cement; they defined geopolymer cement as a binding system that hardens at room temperature (Davidovits *et al*. 2014). One type of geopolymer cementitious binder is FAFA-slag-based geopolymer cement.

2. The mechanical properties of geopolymer concrete

2.1 Compressive strength

Several tests have been conducted by Chen *et al*. (2015) for three different combinations of slag-FAFA geopolymer concrete (slag-to-FAFA ratios were 25/75, 50/50, and 75/25); these tests demonstrated that slag-FAFA geopolymer concrete specimens are characterized by high early strength relative to Ordinary Portland Cement (OPC) concrete. Takekar *et al*. (2017) discovered that when FAFA was replaced at different levels (0%, 25%, 50%, 75%, and 100%) by ground granulated blast furnace slag (GGBS), heat curing of geopolymer concrete was eliminated. Geopolymer concrete displays improved results relative to conventional concrete. The rate of strength gain of geopolymer concrete is high at an early phase; however, geopolymer concrete is more beneficial, economical, and eco- friendly.

Regarding the relationship between slag content and the mechanical properties of the fly ash-slag geopolymer concrete, Rashad (2013) concluded that all of the mechanical properties of FA-slag- based geopolymer concrete improve when the slag content is increased. Mahendran (2016) demonstrated that copper slag percentages significantly affect the strength of the FA-based geopolymer concrete; the strength of the geopolymer concrete with copper slag as a fine aggregate was increased by a factor of 1.35, as opposed to the control concrete, which increased by 1.51. When cured in ambient and oven curing, the maximum compressive strength of oven-cured geopolymer concrete was found to be 58.95 Mpa, whereas in ambient-cured geopolymer, the compressive strength was 40.78 Mpa. Lastly, it was concluded that when the percentage of the copper slag was increased in the geopolymer concrete, the compressive strength also increased. Criado *et al*. (2016) explained that the significant strength increase in the FA-slag geopolymers with the increased contents of slag occurs due to the strong load-bearing C-A-S-H type gel formed.

Regarding the relationship between FA content and the mechanical properties of the FA-slag geopolymer concrete, Rajini *et al*. (2014) concluded that increasing the FA content in the mix, irrespective of the curing periods, decreases the compressive strength of the Slag-FA geopolymer concrete. For the different tested proportions (FA to slag ratios were 0/100, 25/75, 50/50, and 100/0), the compressive strength increased with age; the results indicate that the maximum compressive strength of geopolymer concrete was associated with FA0-GGBS100 (0% FA and 100%GGBS), irrespective of the curing period. After a 7- day curing period, the rate of gain in compressive strength of geopolymer concrete was The previous conclusion also contradicts those of other researchers, who have determined that the optimum compressive strength could be achieved when the majority of the binder mix is FA, as Ghosh and Rasayan (2018), Shah (2017), Arun *et al*. (2018) revealed. They discovered that a 70/30 ratio (FA/slag) achieves the maximum compressive strength of FA-slag geopolymer. Srinivas and Rao (2016) as well as Mithanthaya and Rao (2015) revealed that an 85/15 ratio (FA/slag) achieves the optimal compressive strength, and Pilehvar *et al*. (2018) observed that the addition of 40% GGBS of the FA-based geopolymer increases the compressive strength of geopolymer concrete; they also noted that there is no existing mix-design code. Therefore, it is necessary to review the results that have been yielded around the world.

Other researchers have revealed that equal proportions of FA and slag achieve the optimal compressive strength. For example, Thakkar *et al*. (2014) and Abhilash *et al*. (2016) concluded that the maximum compressive strength of the FA-slag geopolymers could be achieved at a 50/50 (FA/slag) ratio, with 28 days of curing. Additionally, Mehta *et al*. (2016) demonstrated that the compressive strength of GPC, with equal proportions of FA and GGBS, was comparable to the control specimen (OPC) after 28 days (slag to FA ratios were 0/100, 25/75, 50/50, and 75/25). Therefore, this can be considered a preferable combination for making GPC using FA and ground-granulated blast furnace slag. However, other results that are worth mentioning have revealed that equal proportions are not preferable. Chaliasou (2015) compared the equal proportions for the recycled FA-slag-based geopolymers and discovered that the compressive strength was lower than that for ordinary Portland cement. Exceptionally fast relative to the rate of gain, which decreased with age.

Studies by Rajan and Ramujee (2015), Kim and Kim (2012), Gopalakrishnan and Chinnaraju (2016), Gao *et al*. (2016), and Deb *et al*. (2015) yielded the same results as those reported by Rajini *et al*. (2014): The combination of FA0-GGBS100, irrespective of the curing period or method, achieves the optimum compressive strength, and any FA content increase causes a decrease in compressive strength.

In contrast, other researchers have discovered that when most of the binder mix is slag, the optimum compressive strength could be achieved, but without 100% fulfillment of slag content. For example, Wardhono *et al*. (2017) demonstrated that the optimum compressive strength of FA-slag geopolymers could be achieved at the ratio of 30/70 (FA/slag) and that any increase in the FA content after 30% causes a decrease in compressive strength; by this ratio of 30/70, the compressive strength of the FA-slag is comparable to ordinary Portland cement concrete. Liu *et al*. (2017) proved that the optimum compressive strength of FA-slag geopolymers could be achieved at the ratio of 40/60 (FA/slag). Additionally, Parthiban *et al*. (2013) illustrated that the 7-day strength was discovered to be 70% of the 28-day strength, and this percentage increased when the slag content was increased, but decreased for 100% slag content. The strength after 28 days was higher relative to OPC, which indicates that geopolymer concrete can be regarded as an excellent alternative for cement concrete.

In a comparison of the partial replacement and full replacement of cement with GGBS and FA, Sheral *et al*. (2016) compared the compressive strength of OPC to Slag-FA Geopolymer concrete at 3, 7, and 28 days. The test results exhibited no difference in the behavior of the partial replacement and full replacement of cement with GGBS and FA. Cost analysis was conducted, and it indicated that the costs for the production of conventional concrete (FA 60% and GGBS 40%) and geopolymer concrete (FA 30%, GGBS 30%, and cement 40%) are nearly the same. Dhavamani *et al*. (2018) observed a considerable increase in compressive strength with slag-FA geopolymer relative to OPC; this was determined to be a result of the longer curing duration of the concrete, which enhanced the geopolymerization process. Increasing the molarities of the concrete also improved the compressive strength. The GGBS-based GPC exhibited increased compressive strength substantially more than FA-based GPC.

Additionally, the source of the slag affects the compressive strength. For example, Hameed, Rawdhan, and Al-Mishhadani (2017) demonstrated that the compressive strength of geopolymer using commercial grade Na2SiO3 was considerably higher than that using industrial grade Na2SiO3, irrespective of the type of alkali hydroxide.

The curing temperature also exerted a significant effect on the compressive strength; for example, Raj and Ajay (2017) concluded that the FA-slag geopolymer compressive strength is influenced significantly by the curing temperature. It is increased when it is cured in a hot air oven as opposed to being cured in ambient temperature. Also, Jindal (2018) revealed that Ground granulated blast furnace slag as a partial replacement of fly ash in geopolymer concrete achieves better properties even at ambient temperature curing.

Flexural strength

Partha *et al*. (2013) revealed that the increase in the slag content in FA-slag geopolymer concrete is associated with increased flexural strength. Additionally, Kumar *et al*. (2013) discovered that the flexural strength increased by 1.37 times because of the addition of slag content to the FA based geopolymer. Ganapati *et al*. (2012), Apoorva *et al*. (2016), Pratap *et al*. (2016) also demonstrated that the increase in the slag content increases the flexural strength of the geopolymer concrete. Additionally, Pradip and Prabir (2017) concluded that flexural strength increased when GGBFS replaced 10% of the total binder in the FA-based geopolymer concrete; the flexural strength of geopolymer concretes was higher than the OPC concrete of similar compressive strength.

When comparing FA-slag geopolymer concrete and ordinary Portland cement concrete, Chen *et al*. (2015) concluded that for three different combinations of slag-FA geopolymer concrete (slag/FA ratios were 25/75, 50/50, and 75/25), test results illustrated that the flexural strength of the tested geopolymer concrete was lower than that of ordinary Portland cement concrete.

2.3 Split tensile strength

Rajini *et al*. (2014) concluded that split tensile strength of the slag-FA geopolymer concrete for the different tested proportions (FA to slag ratios were 0/100, 25/75, 50/50, and 100/0) increased with age. The results suggested that the maximum split tensile strength of geopolymer concrete is for the FA0-GGBS100, irrespective of the curing period. After a 7-day curing period, the rate of gain in split tensile strength of geopolymer concrete was exceptionally fast. The rate of gain then decreased with age.

Additionally, Partha *et al*. (2013) revealed that an increase in slag content in FA-slag geopolymer concrete increases the split tensile strength. In the same context, Kumar *et al*. (2013) illustrated that the split tensile strength could be enhanced by 1.26 times through the addition of slag content to the FA-based geopolymer. Jawahar and Mounika (2016) concluded that when the percentage of the slag content is increased in the FA-slag geopolymer concrete, the splitting tensile strength also increases, and the maximum splitting tensile strength achieved in GPC with 100% GGBS relative to other combinations (FA50-GGBS50 and FA25-GGBS75) after 28, 56, and 112 days of curing.

Qureshi and Tuvar (2017) concluded that a specific combination (FA 60% and GGBS 40%) of geopolymer concrete achieves the highest compressive and split tensile strength. Chi (2016) demonstrated that the compressive strength and splitting tensile strength of alkali-activated FA/slag (AAFS) concrete increases when the slag contents, Na2O concentrations, and activator modulus ratios increase; the tests results suggest that 100% slag-based AAFS concrete with a Na2O concentration of 8% and activator modulus ratio of 1.23 achieves superior performance.

3. Effects on durability

Hameed *et al*. (2017) demonstrated that geopolymers can offer an appropriate alternative to Portland cement (PC) binders, not only for the environmental benefits that result from the reduction of CO_2 emissions associated with PC production, but also in terms of performance and durability. Additionally, Jeyaseha *et al*. (2013) concluded that geopolymer binders have emerged as a possible alternative to OPC binders due to their proven high early strength and resistance against acid and sulfate attack, in addition to their environmental friendliness. Geopolymers also exhibit better corrosion resistance in corrosion tests. Lee *et al*. (2016) demonstrated that the addition of silica fume could improve reactivity and that a more polymerized aluminosilicate structure of FA-slag geopolymer enhances the durability of geopolymers in terms of chloride penetration and acid resistance.

3.1 Sulfate and acid resistance

Chi (2016) revealed that alkali-activated FA/slag (AAFS) concrete exhibited higher performance than OPC concrete when exposed to sulfate. According to scanning electron microscopy results, the main hydration yields of AAFS concrete were amorphous alkaline aluminosilicate and low-crystalline calcium silicate hydrate gel. As the slag content increased, the amount of C-S-H gel increased, while the volume of A-S-H gel decreased.

Mehta *et al*. (2016) demonstrated that FA-slag geopolymer concrete is highly acid-resistant, since even after 28 days of soaking in 2%, 4%, and 6% sulphuric acids, the specimen's persevered integral without any significant alteration in mass or shape. However, in the case of OPCCs, the specimens deteriorated severely, with highly observable externally damaged surfaces conveyed by visible bulging. Therefore, GPC could be regarded as superior to OPC concrete in terms of durability. Gopalakrishnan and Chinnaraju (2016) concluded that the geopolymer concrete combination (with 40%FA and 60% GBFS) exhibits a comparable performance in the acid environment, with a reduction rate of 53%; in comparison, geopolymer concrete prepared with GBFS (100%) has a reduction rate of 85%.

Srinivas and Rao (2016) concluded that when ordinary Portland cement concrete specimens are exposed to hydrochloric acid, there is a 3.61 to 8.93% loss in the compressive strength and a 5.86 to 18.20% loss in the compressive strength in sulphuric acid; it is 3.72 to 15.06% in the case of geopolymer concrete. Singh *et al*. (2018) also concluded that FA-GBFS-based geopolymers exhibited a comparable performance in terms of acid attacks resistance; as a result, they concluded that geopolymer concrete is more resistant than controlled concrete.

Jawahar *et al*. (2016) concluded that the increased slag content in the FA-slag geopolymer concrete enhanced acid resistance capability; therefore, the FA0-GGBS100 combination has the minimum loss of weight in the acid environment, and the reduction of the compressive strength is therefore limited.

3.2 Chloride

Gopalakrishnan and Chinnaraju (2016) concluded that the acid resistance, in terms of the rate of reduction of strength of GPC with GBFS is 85%, while for 40% replacement of FA to GBFS, it behaves well with a reduction rate of only 53%. Similar results are also produced in a chloride environment in which 40% replacement of FA to GBFS behaves well relative to GPC with GBFS. Therefore, geopolymer concrete with 40% replacement of FA for GBFS is the suitable level of replacement.

3.3 Water absorption and sorptivity

Mathew *et al*. (2015) demonstrated that geopolymer concrete's water absorption capacity is substantially lower than OPC-based concrete, which suggests that geopolymer concrete is more durable. Geopolymer concrete can decrease the sorptivity by almost 72.9%, therefore improving the durability of concrete; the density of geopolymer concrete is less than 3.8% than the control OPC concrete mix. Additionally, Marcin *et al*. (2016) illustrated that any increase in the amount of slag in the mixture exerts a positive effect on water absorption, as the higher slag content has lower water absorption.

3.4 Carbonation

Arbi *et al*. (2016) concluded that the carbonation depth is increased as the FA to slag ratio or the CO_2 exposure time is increased, but decreases when the curing age is increased. Slag rich-concrete exhibits better durability performance relative to a FA-rich combination either against CO_2 or under chloride ingress.

3.5 Corrosion resistance

Shaikh (2014) carried out that geopolymer concretes exhibited better corrosion resistance than ordinary concrete. Moreover, better corrosion resistance of geopolymer concrete is obtained due to the higher amount of Na_2SiO_3 and the concentration of NaOH solutions. Zaina *et al*. (2017) concluded that Fly ash-slag geopolymer (FSG) paste has good corrosion resistance and low corrosion rate compared to fly ash geopolymer.

4. Conclusions

Based on the literature review of the various research articles related to FA-slag geopolymer, the FA-slag geopolymer has significant potential as an attractive engineering material for future research. The following conclusions were found:

- The FA-slag geopolymer is not only environmentally friendly, but also exhibits high mechanical properties in terms of both strength and durability.
- The different mechanical properties of FA-slag geopolymer are influenced significantly by the curing period
- Researchers continue to disagree about the combination that achieves the highest mechanical properties of the FA-slag geopolymer concrete.

• The majority of the research outcomes indicate that the increase in slag content exerts significant positive effects on the mechanical properties, but the influence on compressive strength remains questionable.
• Most research has revealed that this type of geopolymer, irrespective of the amount of concrete, exhibits better mechanical properties than ordinary Portland cement concrete.
• Further research is required to understand the properties of other geopolymer types to offer excellent alternatives to OPC concrete, which are necessary for economic and sustainability purposes.

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