GEOPOLYMER TECHNOLOGY AND PROSPECTS

— LOW-CO2 CONCRETE THAT DOES NOT USE CEMENT —

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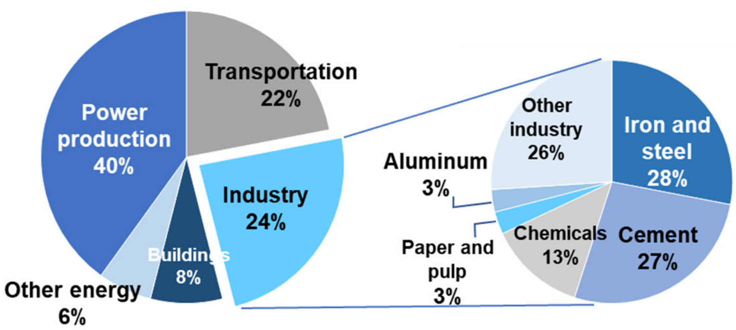
SUMMARY

- Geopolymers are an alternative to cement. Geopolymers, like cement, use the industrial waste materials of fly ash and blast furnace slag, but they can reduce CO_2 emissions by more than 70% compared to cement. For this reason, there are expectations for geopolymers to be widely used.
- Geopolymers are superior to cement in terms of heat resistance, acid resistance, and high viscosity. However, they also have issues such as high cost, lack of practical examples, and users' hesitation to switch from cement.
- Because of their superior characteristics, geopolymers may be introduced for applications in harsh environments in the short term. In the long term, the adoption of geopolymers in replacement of cement will likely advance through initiatives such as applications in general buildings and combination with architectural 3D printers.

Similar to the steel and chemical industries, the cement industry is an energy-intensive industry, accounting for 27% of CO_2 emissions in the industrial sector (second only to steel) and 6.5% of total global emissions (Figure 1). Therefore, while a key issue is how to reduce CO_2 emissions in the cement manufacturing process, the development of materials that can replace cement is also an urgent task. Research and development of geopolymers have proceeded in recent years, putting some of them into practical use as alternative materials to cement. This paper focuses on geopolymers from the viewpoint of decarbonization and discusses their technological development trends and prospects.

Figure 1 Global CO_2 emissions by sector and industry



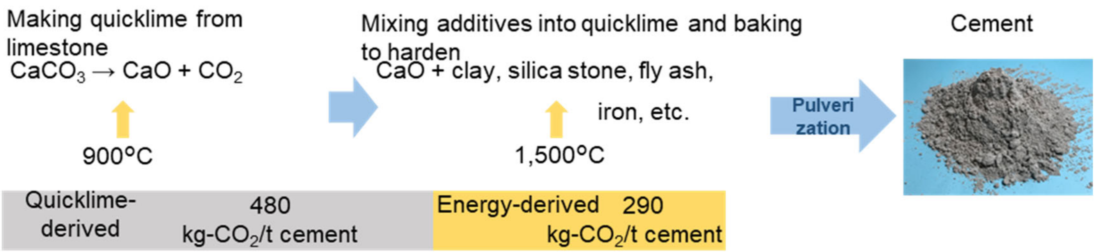
Source: Compiled by MGSSI based on Renewable and Sustainable Energy Reviews, Volume 144, July 2021, "Carbon capture and biomass in industry: A techno-economic analysis and comparison of negative emission options"

1. WHY GEOPOLYMERS ARE GAINING ATTENTION FOR DECARBONIZATION

1-1. CO_2 emissions in the cement manufacturing process

Cement is made by heating limestone ($CaCO_3$) at 900°C or higher to process it into quicklime (CaO), then adding clay, silica stone, fly ash[1], iron, etc. to the mixture. This is subsequently heated to around 1,500°C and hardened into a powder (Figure 2). CO_2 is generated by heating during the production of quicklime from limestone and by the energy input during baking with the additives. About 770 kg of CO_2 is emitted in the production of one ton of cement, of which 480 kg (about 60%) is derived from quicklime and 290 kg (about 40%) from the energy input. Energy-derived CO_2 emissions could be reduced by switching from the fossil fuels used as the heat source to renewable energy. On the other hand, since cement is produced by decomposing quicklime in a thermal reaction, the CO_2 derived from quicklime cannot be reduced as long as quicklime is used as a raw material. This makes decarbonizing cement production fundamentally difficult.

Figure 2 Cement production process and CO_2 emissions



Source: Compiled by MGSSI based on various available sources

1-2. Geopolymers as an alternative material to cement and comparison of CO_2 emissions

Just as concrete is made by mixing cement with sand and gravel, geopolymer concrete can be produced by mixing geopolymer with water, sand, and gravel (Figure 3). In this respect, geopolymers are an alternative material to cement, and geopolymer concrete can be considered cement-free concrete.

Figure 3 Cement concrete and geopolymer concrete

Cement + Water + Sand & gravel → Cement concrete

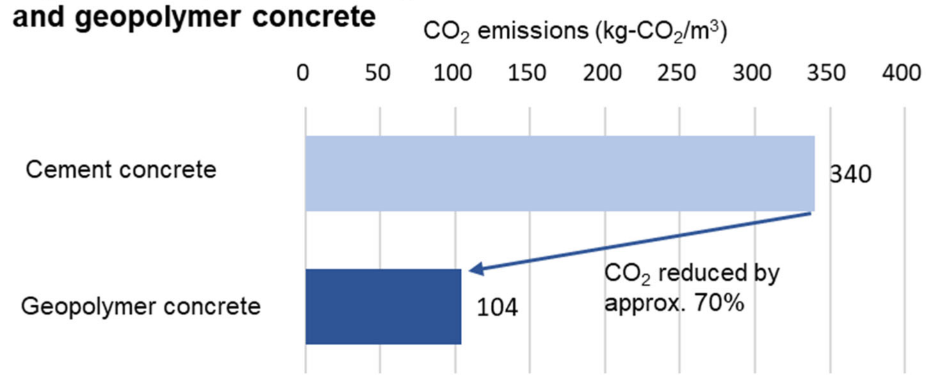
Geopolymer + Water + Sand & gravel → Geopolymer concrete

Source: Compiled by MGSSI

Geopolymers do not use quicklime, the main raw material of cement, nor do they have a manufacturing process that requires the high temperatures of 900 to 1,500°C. (The raw materials and manufacturing process of geopolymers are discussed later.) Therefore, CO_2 emissions during the production process of geopolymer concrete are significantly lower than those of cement concrete. Figure 4 shows an example[2] of a comparative study of CO_2 emissions from cement concrete and geopolymer concrete.

1 Fly ash is the ash produced when coal is burned. It comprises particles of ash collected when exhaust gases are treated in an electric precipitator, mainly at coal-fired power plants.
2 Nishimatsu Construction Technical Report VOL 39, "Properties and construction case of geopolymer" [in Japanese] https://www.nishimatsu.co.jp/solution/report/pdf/vol39/g039_14.pdf

Figure 4 Comparison of CO_2 emission estimates for cement concrete and geopolymer concrete



Source: Compiled by MGSSI based on Nishimatsu Construction Technical Report VOL 39, "Properties and construction case of geopolymer" [in Japanese]

The study shows that cement concrete emits 340 kg CO_2 per m^3 while geopolymer concrete emits 104 kg CO2, a reduction of about 70% in CO_2 emissions. Other studies and published values from geopolymer manufacturers also report 70-90% CO_2 reduction compared to cement concrete.

2. WHAT IS A GEOPOLYMER?

2.1 Geopolymer raw materials and production methods

The raw materials for geopolymer are an active filler[3] that includes silica and alumina components, and an alkali solution such as caustic soda or water glass, as shown in Figure 5.

Figure 5 Raw materials for geopolymers

Active filler		+	Alkali solution	
Example	Components		Example	Components
Fly ash	SiO_2 Silicon dioxide Al_2O_3 Aluminum oxide Fe_2O_3, FeO Iron oxide CaO Calcium oxide MgO Magnesium oxide		Sodium hydroxide NaOH	Na, (H_2O)
Blast furnace slag			Potassium hydroxide KOH	K, (H_2O)
Metakaolin			Water glass Na_2SiO_3	Na, Si, (H_2O)
Mineral tailings and others			Silica SiO_2	Si, (H_2O)

Source: Compiled by MGSSI based on various available sources

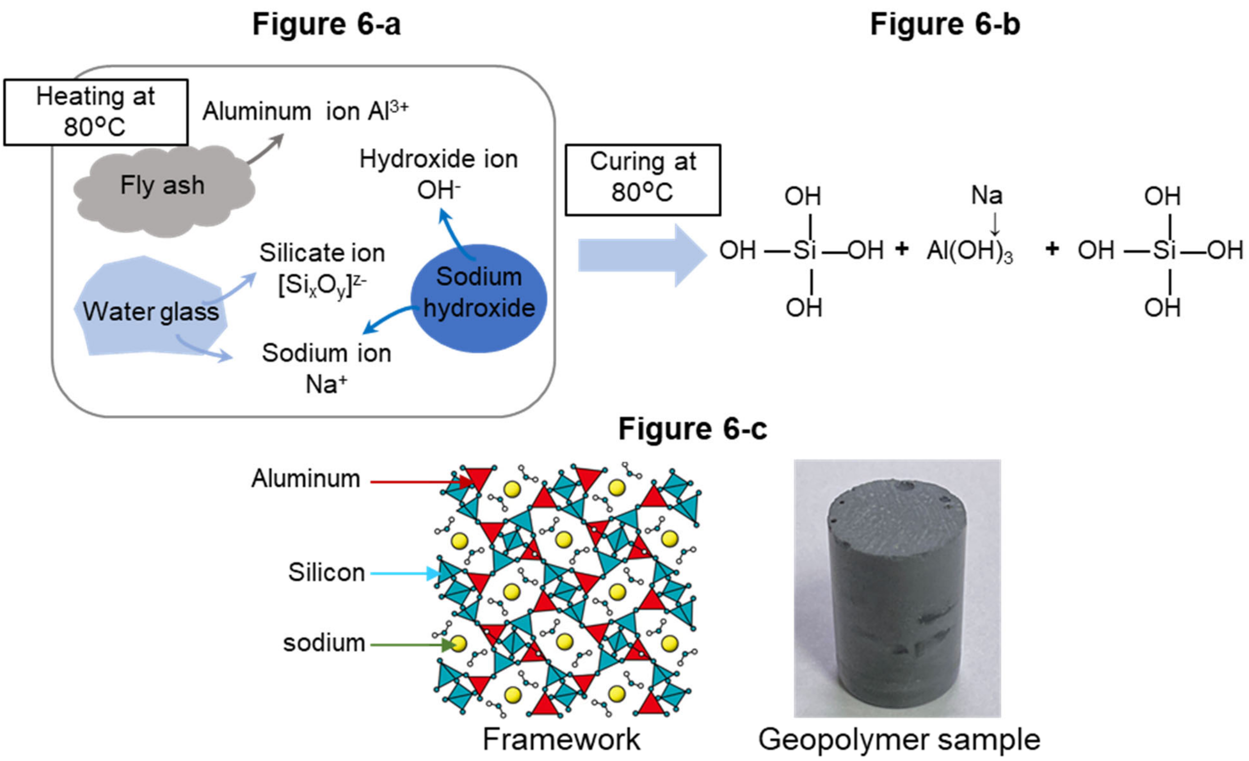
There are various combinations of geopolymers depending on the choice of active filler and alkali solution, and their reaction mechanisms are also diverse. Here in this report, a geopolymer made from fly ash, water glass, and sodium hydroxide is taken as a typical example, to describe the reaction mechanism.

When fly ash is added to an alkaline solution of water glass and sodium hydroxide to create a highly alkaline state and then heated to 80°C, aluminum ions (aluminum) and silicate ions (silicon) are released from the fly ash and water glass, respectively (Figure 6-a). Due to their ionic state, the released aluminum and silicon react with hydroxide ions (OH-) separated from sodium hydroxide. Curing it in that state advances the reaction, creating a bond between aluminum and silicon (Figure 6-b). This bond is a geopolymer, which is a strong

3 Materials with reaction activity.

framework of aluminum and silicon (Figure 6-c).

Figure 6 Geopolymer made from fly ash, water glass, and sodium hydroxide



Source: Compiled by MGSSI based on various available sources
(The illustration of the framework is created with reference to Nishimatsu Construction Technical Report VOL 56 “Geopolymer’s current status and future prospects” [in Japanese] (https://www.jstage.jst.go.jp/article/coj/56/5/56_409/_pdf)
(The sample photo provided by Mitsuaki Matsuoka, Associate Professor of Kansai University)

Thus, unlike cement, which emits CO_2 during the process of heating limestone, no CO_2 is emitted during the process of synthesizing geopolymer. The curing conditions that promote the reaction are also much lower than the high temperatures of cement (900-1,500°C) at around 80°C. These are the reasons why geopolymers can reduce CO_2 by about 70% or more compared to cement.

Geopolymers were so named by the French materials scientist Joseph Davidovits in 1991. The term is derived from “geo,” meaning earth, and “polymer,” suggesting condensation polymer. Geopolymer is a generic term for various condensation polymers formed by the reaction of active fillers such as fly ash with alkaline solutions. The name is probably based on the fact that the mechanism by which geopolymers form by bonding silica and aluminum is similar to that by which the sedimentary rocks covering the Earth’s surface are formed. Incidentally, the concrete that was utilized in ancient Roman architecture is thought to be a type of geopolymer.

2.2 Advantages and challenges of geopolymers

Figure 7 shows the advantages and challenges of geopolymers. Numerous research and development efforts have shown that geopolymers are superior to cement, primarily in heat resistance, acid resistance, and substance fixation.

Figure 7 Advantages/opportunities and challenges of geopolymers

Advantages/opportunities	Challenges
· Heat resistance · Acid resistance · Substance fixation · High viscosity (low fluidity) · CO_2 reduction · Large-scale use of industrial waste	· High cost · Lack of practical examples · High viscosity (poor filling) · Hesitation to switch from cement

Source: Compiled by MGSSI

Their high heat resistance makes geopolymers an excellent fire-resistant material, while their high acid resistance may make them useful in the construction of sewerage facilities and other buildings where acid corrosion is a concern. Substance fixation refers to the characteristic whereby geopolymers tend to adsorb substances when they are polymer-bound. This characteristic is expected to be used to confine harmful heavy metals and radioactive materials within the geopolymer and safely sequester them for long periods of time. The high viscosity of geopolymers can be widely used not only in architecture but also in the fabrication of modeling objects as a material for 3D printers, which require materials with low fluidity. Furthermore, the use of industrial wastes such as fly ash as a raw material allows for the effective utilization of resources.

On the other hand, at a cost several tens of percent higher than cement, geopolymers are considered to be expensive at present. They also have a limited track record because they are still in the process of development. As detailed above, some of the raw materials for geopolymers can be made from industrial waste, but the alkali solution and water glass are high-cost factors. It is expected that future research and development will reduce the amount of raw materials used, which is a high-cost factor, and investigate the substitution of inexpensive raw materials. High viscosity offers advantages, but it is also a challenge because it creates resistance during filling. In addition, there is public hesitation to adopt new geopolymers in replacement of the proven existing technology of cement. The keys to reducing this hesitation are to lower the cost of geopolymers and to make their advantages widely known to society.

3. EXAMPLES OF GEOPOLYMER DEVELOPMENT

As shown in Figure 8, geopolymers are being developed and commercialized by building material manufacturers, general contractors, and research institutions, including universities.

In Japan, groups such as EeTAFCON Research Group and Nishimatsu Construction are manufacturing manholes and blocks from geopolymers. Manholes and blocks are standardized concrete products known as "precast concrete," which are manufactured in advance at a factory, transported to the construction site, and assembled there. Precast concrete is considered a suitable application for geopolymer in the development stage because factory production allows for thorough quality and safety control, in contrast to on-site construction, which is affected by weather and other environmental factors. Meanwhile, Obayashi Corporation, Pozzolith Solutions, and other companies have developed geopolymers that can be pumped by concrete pumps to improve applicability to on-site construction. This geopolymer concrete has been used for repair work on retaining walls (walls that support heavy loads) at steel mills, where heat resistance is required.

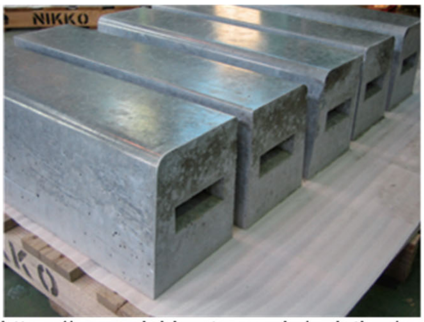
Figure 8 Examples of geopolymer development

Research institutions & companies	Overview
(Japan) EeTAFCON Research Group (Nakagawa Humepipe, Central Research Institute of Electric Power Industry, Showa Concrete Industry, etc.)	Development of geopolymer made from fly ash and blast furnace slag, which can be manufactured using only alkaline solution without water glass. Commercialization of precast products such as sewer manholes and road gutter covers.
(Japan) Nishimatsu Construction, Kyowa Concrete, JFE Steel, Tohoku University, Nihon University	Development of geopolymer that can be installed even in cold regions and is resistant to frost damage, based on more than 10 years of research and development experience, including the development of geopolymer blocks.
(Japan) Obayashi Corporation, Pozzolith Solutions, Nippon Steel	Development of geopolymer that can be pumped by concrete pump truck, using fly ash and blast furnace slag as raw materials. The geopolymer was applied to repair work on retaining walls at Nippon Steel Works.
(Finland) Betolar	Manufacture and sales of geopolymer paving blocks and conduit materials (trade name: Geoprime®). Raw materials are 95% industrial by-products such as fly ash, reducing CO_2 by 80% compared to cement.
(Australia) Wagners, Hassel Architect, University of Queensland	Development of geopolymer (trade name: Earth Friendly Concrete®) made from fly ash and blast furnace slag. The geopolymer was adopted as a structural material for buildings for the first time in the world.
(Russia) RENCA	Application of geopolymer to architectural 3D printing and development of a technology that enables on-site geopolymer construction by portable 3D printer.

EeTAFCON Research Group
Sewer manholes

https://www.eetafcon.com/

Nishimatsu Construction and others
Exterior blocks



https://www.nishimatsu.co.jp/solution/report/pdf/vol35/g035_23.pdf

Obayashi Corporation and others
Retaining wall repair work

https://www.obayashi.co.jp/news/detail/news20210330_1.html

Wagners and others
Floor materials for University of Queensland facilities

http://www.geopolymer.org/news/worlds-first-public-building-with-structural-geopolymer-concrete/

RENCA
On-site construction using a portable 3D printer

https://www.youtube.com/watch?v=EXoslZaYWgI

Source: Compiled by MGSSI based on various available sources

Overseas, Betolar of Finland has commercialized and is selling geopolymer paving blocks, while Wagners and others in Australia have adopted geopolymer floor panels in a four-story building on the campus of the University of Queensland, marking the first use of geopolymer as a structural material in a building. Taking advantage of the high viscosity characteristic of geopolymer, RENCA of Russia has adopted geopolymer as a material for its architectural 3D printers. The company has developed a portable 3D printer and is focusing on geopolymers for construction, with an emphasis on on-site working. The combination of geopolymers and 3D printers may attract more attention in the future, as 3D printers can improve work efficiency and decarbonize the cement concrete construction process compared to conventional formwork.

4. PROSPECTS FOR GEOPOLYMERS

Like cement, geopolymers use the industrial wastes fly ash and blast furnace slag as raw materials, but they can reduce CO_2 emissions by more than 70% compared to cement. Against the backdrop of decarbonization, in the short term, factory-manufactured precast products that take advantage of geopolymers' superior acid resistance and heat resistance will probably be used, for example, in sewage facilities where durability under acidic conditions is an issue, and in firewalls where heat resistance is required. In the long term, new initiatives are likely to continue to replace cement concrete, such as the application of precast panels and other materials for general buildings, combined with geopolymer and 3D printers that allow for easy on-site construction like conventional cement concrete.