Committee Report : JCI- TC155A

Technical Committee on Application of Geopolymer Technology to Construction Field

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Abstract:

Geopolymers have small CO_2 emissions at the time of production, can be effectively used in various industrial byproducts, and are excellent in resistance to alkali silica reactions, strong acids and high temperatures. However, before its practical use, many issues remain to be resolved, such as the solidification mechanism not being clear, and little information being available on its long-term properties.

This technical committee was established for the purpose of compiling the existing domestic and international knowledge on geopolymer technology and clarifying the geopolymer system and expected quality, exploring the manufacturing method for geopolymers in the construction fields in Japan, and making proposals for the application of geopolymers to the construction fields in Japan. This paper is an outline of the results of the technical committee's activities over a two-year period.

Keywords: geopolymer, reaction mechanism, mechanical properties, durability, manufacturing and construction, round robin test, e-learning

1. Introduction

Geopolymer is defined as "Geopolymer is not use cement clinker, and a solidified body is obtained from a mixture of raw materials mainly composed of amorphous aluminum silicates and at least one kind of an aqueous solution which is used alkali metals such as silicate, carbonate, hydroxide." and generally based on fly ash and sodium silicate, are often supplemented with ground granulated blast-furnace slag(GGBS) or sodium hydroxide in order to promote solidification. Its major characteristics are low carbon emission because no use of clinker, and does not always require calcium for solidification, so it is excellent in acid and high temperature resistance, and can consume large amounts of industrial byproducts such as fly ash. On the other hand, many issues remain to be resolved for practical application, such as the solidification mechanism has not been sufficiently clarified, the mixture where the characteristics of geopolymers can be shown is extremely specific, geopolymers are higher cost than conventional concrete, and there is not much data on the long-term characteristics.

Within the circumstances described above, this technical committee, for a period of two years from 2015 to 2016, was active for the purposes of compiling the existing domestic and international knowledge on geopolymer technology: clarifying the geopolymer system and expected quality, exploring the manufacturing method of geopolymers suitable for the domestic situation, and making proposals for the application of geopolymers to the domestic construction fields.

The committee members are shown in **Table 1**. The committee is composed of researchers and engineers with deep knowledge of concrete in various fields such as civil engineering, architecture, and chemistry, and the existing knowledge was arranged among three workgroups – the Reaction Mechanism Working Group (WG1: Chair Dr. Atarashi), the Mechanical

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Properties, Durability, and Structure Working Group (WG2: Chair Dr. Kunieda), and the Manufacture and Construction Working Group (WG3: Chair Dr. Harada). Additionally, we conducted a round robin test on geopolymer mortar with specified materials and mixtures.

Table 1 – Technical Committee Members

Committee Chair : Kazuo ICHIMIYA(National Institute of Technology, Oita College) Vice Chair : Shigemitsu HATANAKA(Mie University) Secretary General : Daiki ATARASHI(Shimane University) Secretary : Minoru KUNIEDA(Gifu University) Hiroki GODA(Kyushu Institute of Technology) Koji HARADA(Nishimatsu Construction Co.,LTD)	
WG1: Reaction Mechanism	
◎Daiki ATARASHI (Shimane University) ○Shinobu HASHIMOTO(Nagoya Institute of Technology) ・Motoki UEHARA (Railway Technical Research Institute) ・Junichi OOYA (Nippon University) ・Kazuyuki TORII (Kanazawa University) ・Takeshi YAMAMOTO (Central Research Institute of Electric Power Industry)	・Taku OOTSUKA(Central Research Institute of Electric Power Industry) ・Takahiro SAGAWA(Maebashi Institute of Technology) ・Ippei MARUYAMA(Nagoya University) ・Zhuguo Li (Yamaguchi University)
WG2: Mechanical Properties and Durability	
◎Minoru KUNIEDA(Gifu University) ○Yasutaka SAGAWA(Kyushu University) ・Kazuo ICHIMIYA((National Institute of Technology, Oita College)	・Shigeyoshi MIYAHARA(TAISEI CORPORATION) ・Shigemitsu HATANAKA(Mie University) ・Toshinobu YAMAGUCHI(Kagoshima University)
WG3: Manufacture and Construction	
◎Koji HARADA(Nishimatsu Construction) ○Hiroki GODA(Kyushu Institute of Technology) ・Kozo ONOUE(Kumamoto University)	・Takumi SUGAMATA(BASF JAPAN) ・Shinsuke KUMAGAI(KONISHI) ・Akihiro MAEGAWA(Mie Prefecture Industrial Research Institute) ◎ WG Chief ○ WG Deputy Chief

The task addressed by each WG are as follows.

<u>WG1: Reaction Mechanism</u> – 1) explanation of reaction mechanisms that are understandable to people with knowledge of concrete, 2) differences in composition for hardened cement with geopolymer combined with GGBS, 3) evaluation method for various chemical analysis regarding geopolymers, and 4) geopolymer definition.

<u>WG2: Mechanical Properties and Durability</u> – 1) organization of knowledge on the physical properties of geopolymers, 2) implementation of round robin tests, and 3) preparation of e-learning to explain the outline of geopolymer to engineers and students with basic knowledge of concrete.

<u>WG3: Manufacture and Construction</u> – 1) collecting domestic and international case studies regarding practical use of geopolymer (factory products, on-site construction, etc.).

In this paper, Section 1 is introduction, Section 2 is the reaction mechanisms and materials, Section 3 is the potential of geopolymers, Section 4 is the basic knowledge on application to construction field, Section 5 is construction examples, Section 6 is round robin tests, Section 7 is the outline of e-learning, and Section 8 is future prospect.

2. Reaction Mechanism and Materials

2.1 Outline

The reaction mechanism of geopolymers was discussed in WG1. Within the discussion, the definition of geopolymers particularly required a lot of discussion time. The materials used for the geopolymer vary, and the reaction products which constitute the matrix vary greatly depending on the materials used. Additionally, not all of the reaction mechanisms are clear. In this section, it was shown that the definition of geopolymers and the outline of reaction mechanism and materials used of geopolymers.

2.2 Geopolymer Definition

Geopolymer is a term coined by Joseph Davidovits, showing a state in which inorganic silicic acid is polymerized by polycondensation. This is due to its use as the powder metakaolin (heat-treated so that the kaolin mineral is in an amorphous state) as a starting material in the early 1970s when geopolymer was developed, then it undergoes alkali stimulation action to produce condensation polymer of aluminosilicate (called geopolymer), similar to the structure of natural zeolite as shown in **Figure 1**. Afterwards, fly ash discharged from coal-fired power plants has been widely used from the viewpoint of increasing waste usage and reducing carbon dioxide emissions, but when fly ash is cured under the high temperature alkali stimulation conditions of 60 °C or above, as expected a polymer of aluminosilicate is formed. For this reason, things that use only fly ash can be referred to as geopolymers from the viewpoint of reaction products.

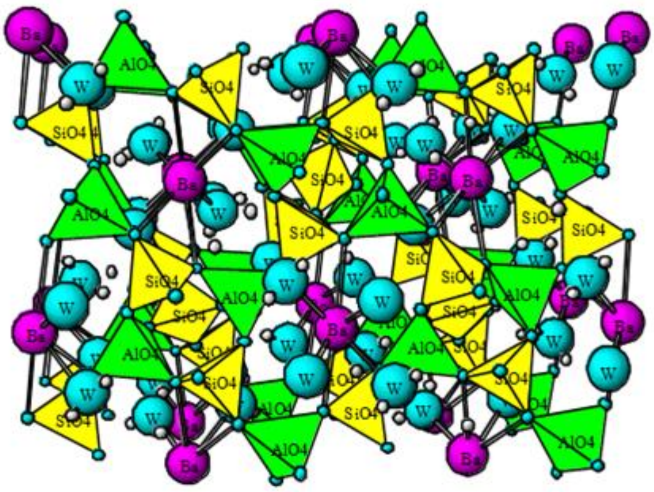


Figure 1 – Example of a Crystal Structure of Natural Zeolite (Edingtonite)

In recent years, GGBS has also seen usage, in order to improve the initial strength, which is a weak point of geopolymer using solely fly ash. When using GGBS, due to the influence of the calcium oxide component, the structure of the reaction product becomes more complicated as compared to ones produced with only the aluminum silicate based active filler such as metakaolin or fly ash. Generally, due to the presence of calcium ions, it becomes difficult for silicate ions to form a three-dimensional structure like zeolite, and will have a structure that is different from what is referred to as a geopolymer. For this reason, when using GGBS, from the viewpoint of the structure of the reaction product it would not be correct to call the reaction product of a geopolymer.

However, in order to better represent the actual substance of geopolymer research, this committee does not especially consider the short-range order structure of the reaction product that forms the solidified body. We classify in accordance with the difference in the starting materials, and define the geopolymer as “Geopolymer is not use cement clinker, and a solidified body is obtained from a mixture of raw materials mainly composed of amorphous aluminum silicates and at least one kind of an aqueous solution which is used alkali metals such as silicate, carbonate, hydroxide.". Here, representative examples of amorphous aluminum silicate (active filler) include not only fly ash and GGBS, but also metakaolin, sewage sludge, and certain volcanic ash. The alkali metal silicate is a water glass, or a mixture of sodium hydroxide (NaOH) solution and potassium hydroxide (KOH) solution, and Na_2CO_3 solution and K_2CO_3 solution are representative of the alkali metal solution, and NaOH solution and KOH solution are representative of the aqueous hydroxide solution. Therefore, we decided that geopolymer excludes a system that uses a small amount of cement mixed with large amounts of fly ash or GGBS as an admixture and also excludes a system cured mainly using a Ca-type solution as an alkali stimulant.

2.3 Geopolymer Reaction Mechanism

(1) Using Fly Ash or Metakaolin as an Active Filler

Currently, as described above there are various differences between geopolymers and starting powders, and the mix proportions to be used as largely different as well. Therefore, the reaction of the geopolymer and the properties of the product are greatly different depending on the difference in the starting powder and the chemical composition of the aqueous solution to be used, and many researchers are conducting research regarding the details of products and reaction mechanisms for each mix proportion.

Although there are many things about the geopolymer reaction that are unknown, we can make an outline-like explanation, as follows. Silicate ions originally exist in the sodium silicate solution called water glass, and additionally, silicate ions are also eluted from active fillers such as fly ash due to strong alkali components, and a high temperature curing environment. Likewise, aluminosilicate framework is generated by elution of the aluminate ions from the active filler, and the polycondensation reaction with this and the silicate ions. At this time, since the framework is negatively charged as a whole by the substitution of Al_3^+ to Si_4^+, hydrated ions of Na^+ and K^+ are incorporated into the framework. This is the product of hardened geopolymer originating from metakaolin or fly ash. Here, although it is shown lumped together with the geopolymer product, similar to how there are various structures and types of the mineral zeolite, there are large differences in the types, mix proportions, and curing temperature of the aluminum silicate based active filler. Also, since the produced geopolymer is primarily composed of an amorphous structure, it has no clear peak of the product obtained even when analyzed by X-ray diffraction due to low crystallinity.

(2) Using Fly Ash and GGBS Together as Active Filler

As described above, the product can be organized with the active filler is an aluminum silicate-based material, such as metakaolin or fly ash. However, in recent years, from the viewpoint of controlling strength promotion and a resistance to a migration of goods, etc., something called a hybrid-type geopolymer, to which a material that includes a calcium (Ca) source such as GGBS is added. As a result, there are cases where the solution used is only water glass and does not use sodium hydroxide, etc., and is carried out in a relatively low alkali region, realizing a situation where room temperature curing – not high temperature curing, is carried out. For this reason, the structure of the geopolymer product varies greatly depending on the starting material, the mix proportions of the solution used, and the curing temperature, resulting a situation where the product is not necessarily primarily composed of an aluminosilicate amorphous substance with a three-dimensional network structure as described in (1). Generally, due to the presence of calcium ions, it is presumed that it is difficult for silicate ions to form a three-dimensional structure like zeolite, and take a structure similar to C-S-H produced by cement hydration. However, it has also been pointed out that this structure is different from the C-S-H in cement, so it is necessary to wait for future research developments in clarifying this structure.

2.4 Materials

Fly ash, which is largely handled in Japan, is primarily characterized by Si and Al. On the other hand, GGBS is primarily characterized by large amounts of Ca in addition to the Si and Al components. Also, metakaolin, etc., whose primary ingredients are Si and Al, like fly ash, are also used, but as they are relatively expensive when compared to fly ash, there are not many research examples as substitutes for cement concrete. Regarding the reactivity of fly ash, various research, such as amorphous contents and the various properties of its composition, and the relationship with strength, is being conducted, and since we do not have an evaluation technique with complete consistency, we have expectations for future research such as the application of an API method, which is a method for evaluating the pozzolanic reaction of fly ash in cement. Additionally, at present there are many research cases involving a mixed system of fly ash and GGBS, however compared to fly ash alone, the relationship between powder and the various properties is more complicated. In the future, it would be preferable to include something like the reactive factor of the mixed powder into the mix proportions description.

Generally, a sodium hydroxide (NaOH) solution or a potassium hydroxide (KOH) solution and water glass are used as a component of the alkali solution for preparing the geopolymer. Within that, for example, and NaOH solution is divided into NaOH and H_2O. Similarly, the KOH solution is divided into KOH and H_2O, and the water glass is divided into NaOH, SiO_2, and H_2O components.

3. Potential of Geopolymers

3.1 Outline

As the reaction product is different compared to ordinary Portland cement, and the amount of industrial waste used is large for geopolymers, we can expect excellent properties such as a refractory material, acid resistant material, heavy metal/radioactive nuclide fixation and reduction of CO_2 emission.

3.2 Refractory Material

In refractory materials such as bricks, firing is generally required, and from the viewpoint of improving productivity and reducing CO_2 emissions, an interest in using concrete materials is also rising. However, in conventional concrete that uses ordinary Portland cement, dehydration and the decomposition of cement hydrate are caused when the temperature becomes high, so the structure of the gaps changes, resulting in a considerable reduction in strength. On the other hand, in concrete that uses geopolymer, cement hydrate is not generated as a reaction product as described in 2.3, or it can be considered that dehydration and decomposition rarely occur even at high temperatures, so it is possible that geopolymer concrete can be used as an excellent refractory material. However, as mentioned above, it is important to note that not all geopolymers have excellent fire resistance, because the reaction products change greatly depending on the curing conditions and the starting materials.

3.3 Acid Resistant Material

Many studies have reported that geopolymers using metakaolin or fly ash show an extremely high resistance to acid, as compared with ordinary Portland cement[1)]. For cement, since the matrix composition is CH and C-S-H, the reaction product easily dissolves with acid, but for geopolymers, since the product is an aluminosilicate condensation polymer, dissolution in acid rarely occurs. Even with a hybrid-type geopolymer, in which GGBS has been added, with a substitution rate of around 20% to fly ash the acid resistance is not considerably lowered. Therefore, geopolymer can be used in places where ordinary cement cannot be used is an advantage.

3.4 Immobilization of Heavy Metals and Radioactive Materials

Studies on the immobilization of heavy metals such as Cd, Pb, and radioactive nuclides such as Sr, Cs, etc., have also been conducted. In general, substances with higher numbers and larger atomic numbers, due to cation selectivity, are easier to adsorb as they have smaller hydrated ion radii. A method of improving the cation exchange capacity to about 200 cmol/kg has been discovered, and it is possible to develop a performance comparable to that of various zeolites. On the other hand, appropriate consideration should be given to the elution of some heavy metals such as As, Se, etc., for cases of heavy inclusion in raw materials, and including the materials manufacturing method as well as the usage environment.

3.5 Construction Materials for Establishing a Low Carbon and Resource-Recycling Society

A particular expectation for the use of geopolymers in the construction field are significant reduction in CO_2 emissions at the manufacturing and using large amounts of industrial byproducts such as fly ash and blast furnace slag. According to certain trial calculations, there is a report stating that carbon dioxide emissions were reduced by about 80% compared to Portland cement in the construction of the same structure[2), 3)]. In this way, it is possible for geopolymers to become a next-generation concrete binder in the realization of a low carbon and resource-recycling society.

4. Basic Knowledge for Application to the Construction Field

4.1 Outline

We conducted a literature survey, including international journals, however here we will outline the characteristics of geopolymer concrete and mortar referencing the information from domestic literature.

4.2 Manufacture

(1) Materials

In a construction field, fly ash and GGBS are most frequently used as active fillers. Examples of other materials can be used as silica fume, municipal waste molten slag, etc.

As an alkaline solution, sodium-based and potassium-based water glass, sodium hydroxide, and potassium hydroxide are frequently used. At the research level, they are manufactured mixed in a laboratory. A commercially available GP solution for geopolymers are occasionally used in Japan.

(2) Mix proportions

The geopolymer formulation and design method have not yet been established and many compounding proposals are presented. An example of formulation is shown in **Table 2**. The table shows the formulation using fly ash and GGBS as the active filler and sodium-based commercially available GP solution as the alkaline solution. Since the specifications of the alkaline solution also greatly differ in specifications of fly ash and GGBS, it is necessary to consider the formulation for each material.

Table 2 - Mix proportions

Unit Content (kg/m^3)				
Alkali Solution*1	Fly Ash*2	GGBS *3	Fine Aggregate	Coarse Aggregate
235	457	65	618	927

*1: Sodium-Based Solution
*2: Fly Ash Type I Product
*3: No Gypsum, 4,000 Brain Class

(3) Mixing

Geopolymer mixing is the same procedure as for cement base materials. Mortar mixers, pan-type mixers, and forced biaxial mixers (**Image 1**) are also used. Since geopolymers has a high viscosity, it is necessary to sufficiently grasp its performance and to determine the mixing equipment and mixing time.

Image 1 - Mixing Geopolymer in a Forced Biaxial Mixer

(4) Workability

Regarding the workability of geopolymer, the fluidity, segregation resistance, setting time, etc., are particularly important. For geopolymers, the workability is generally considered by the slump flow ratio. This is because geopolymers are highly viscous, and have the same fresh characteristics as cement concrete high-flowing concrete. An example of slump flow over time is shown in **Figure 2** [4]. As shown in the figure, the slump flow of the geopolymer often decreases rapidly with the flow of time. Though there have been a number of studies on the setting time, there is no definition for geopolymer setting, and no test method has been established as well, so although a uniform evaluation cannot be made, the tendency is that the setting time is shorter than that of concrete.

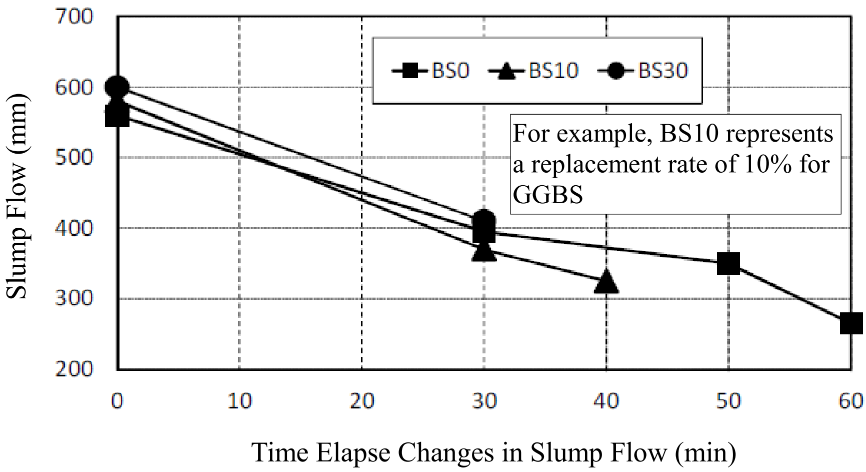


Figure 2 - Time Elapse Changes in Slump Flow[4]

(5) Curing

Geopolymer curing is based on heated curing. Steam curing, added heat curing, and autoclave curing are being studied as types of heat curing. The strength of the geopolymer tends to increase as the higher temperature and the longer curing time. Additionally, there are considerations for geopolymers cured at room temperature.

4.3 Mechanical Properties

Ichimiya et al.[5] produced a geopolymer mortar using water glass and sodium hydroxide as an alkaline solution, and fly ash and GGBS as active filler, and conducted strength tests. The results, as shown in **Figure 3**, are that a high degree of strength can be obtained by substituting 30% of the GGBS in the active filler, that the geopolymer mortar already shows 75% of 28-day strength at material age of 1-day after steam curing, and that the compressive strength increases linearly with time up to 24 hours for steam curing.

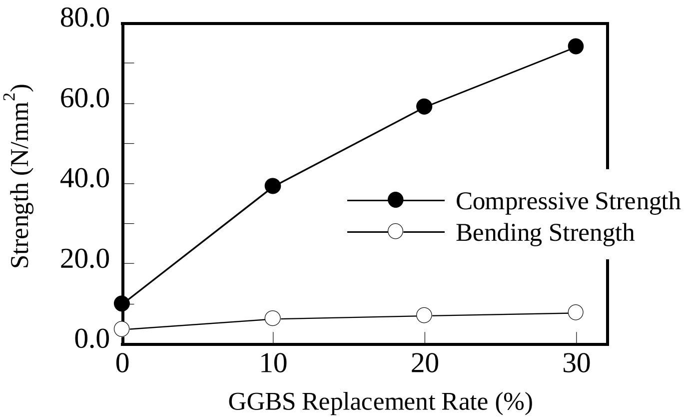


Figure 3 - Relationship Between GGBS Replacement Rate and Strength[5)]

Uehara et al.[6)] created a geopolymer-hardened material primarily composed of fly ash with differing alkali/H_2O ratios, Si/alkali ratios, and GGBS substitution rates, using water glass as the Si component in the “general method,” and mixing silica fume at the time of kneading in the “silica fume addition method”. Although there were no big differences in the product by the preparation method, compared to the general method, the silica fume addition method had a lower strength due to the low alkali and in the areas where the GGBS substitution rate was small. For the mix proportions, when the replacement rate of the GGBS is large and the alkali concentration is high, pores are densified and the strength is increased. Furthermore, from the investigation of the correlation between the properties of fly ash and the compressive strength of cured geopolymer, Uehara et al.[7)] reported that when there are many amorphous components and many components of Al, Fe, and Ca, and when the surface area is large, the compressive strength increases. Minami et al.[8)] measured the compressive strength, the static elastic modulus and the tensile strength in a wide range of strengths (10 to 70 N/mm^2) in order to ascertain the physical properties of the hardened geopolymer. As a result, as shown in **Figure 4**, the relationship between the compressive strength and the static elastic modulus of the hardened geopolymer can be represented by an exponential function using the compressive strength as an index similar to general concrete, and the static elastic modulus is about 50 to 80% of the cement based material, and the ratio of the tensile strength to the compressive strength is about 1/17 to 1/9, as shown in **Figure 5**.

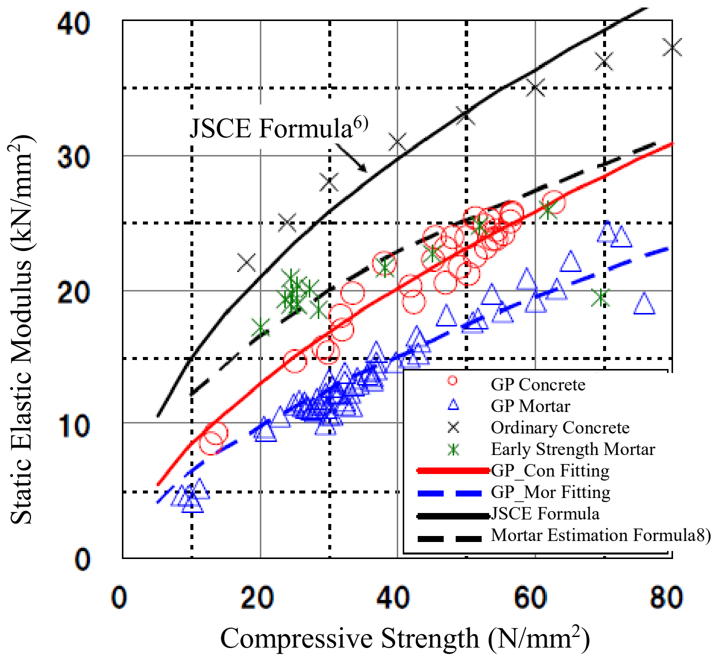


Figure 4 – Relationship Between Compressive Strength and Static Elastic Modulus of Hardened Geopolymer[8)]

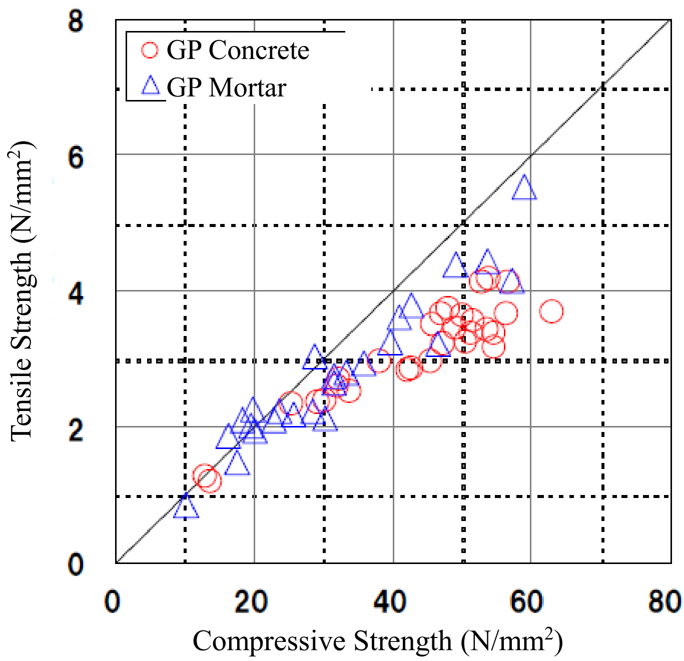


Figure 5 - Relationship Between Compressive Strength and Tensile Strength of Hardend Geopolymer[8)]

Regarding creep behavior, Minami et al.[9)] implemented a compressive creep test on geopolymer concrete of class 70 N/mm^2 compressive strength. The basic creep strain at 410 days after loading is about 320 x10^{-6} and a creep coefficient of 0.39. Then, a creep curve equation by logarithmic function is obtained.

Regarding bond properties with reinforcement, Ota et al.[10)] sought the bond strength with the reinforcement by a pull-out test. For deformed reinforcement, is has been shown that geopolymer mortar has the better bond properties compared to ordinary cement mortar.

Regarding usage in structures, Kawajiri et al.[11] is investigating the basic mechanical properties of RC components. The result is that it is a similar to the destruction process of general cement concrete, and that the calculated value and the experimental value have a favorable consistency. Tsukahara et al.[12] performed a bending test, for the practical application of PVA short fiber reinforced geopolymer sleeper by making a rectangular test sample with various amounts of fiber and reinforcement in order to investigate the mechanical properties and reinforcement effect. In the bending test of the rectangular test sample, since the loads and displacement curves of different test samples largely agree with each other, and based on the results such as dry shrinkage strain, it is noted that Si/Al should be selected as a measure, and the result of the reinforcing effect of PVA short fiber with a tensile reinforcement ratio of 1% was corresponding to about 0.5% in terms of the tensile reinforcement ratio.

4.4 Durability

Regarding carbonation, Harada et al.[13] reports that even if it is colorless immediately after spraying with phenolphthalein, there is the property of discoloration after time has passed, and regarding research into the cause as well as the evaluation method of carbonation, further considerations are necessary in the future.

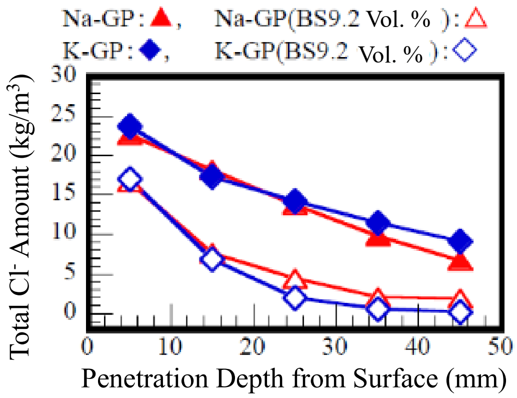
Regarding efflorescence, Ichimiya et al.[14] applied geopolymer to the sidewalk boundary block in a road, and from the fact that deformation such as efflorescence and scaling was observed in the surface layer within one year of installation. Then, a partial water absorption test was carried out on geopolymer mortar test based on fly ash, using a combination of GGBS in order to enhance strength. From this test, it was clarified that deterioration is promoted in lower temperatures and humidity. The substitution of the GGBS has the effect of suppressing surface layer deterioration and the scaling is suppressed by adjusting the solution concentration.

Regarding resistance to chemical erosion, Ichimiya[14] conducted an acid resistance test (indoors sulfuric acid immersion test, in situ hot spring water immersion experiment in acidic hot spring area) for fly ash-based geopolymers, using a test sample in which a part of the active filler was replaced with GGBS. As shown in **Figure 6**, it was reported that while the geopolymer has low acid resistance as the GGBS replacement rate increases, the property change is very slight when compared to ordinary cement concrete. Goda et al.[16] conducted immersion tests on the resistance to chemical attacks on fly ash-based geopolymer, which is considered to have a high sulfuric acid resistance. As a result, it was reported that the resistance of the geopolymer to the sulfate environment is higher than that of the acidic environment, and that the sulfuric acid resistance of the geopolymer tends to be improved by incorporating silica fume.

BS0 BS10 BS20 BS30 OPC

Figure 6 - Sulfuric Acid Immersion Results[15]

Regarding the chloride ion penetration resistance, Uehara et al.[6] has created a hardened geopolymer primarily composed of fly ash, with different alkali/H_2O ratios, Si/Alkali ratios, and differing GGBS substitution rates, using the "general method" of water glass as the Si component, and the "silica fume addition method" in which silicafume is mixed at the time of kneading, and investigated the penetration status of chloride ion (see **Figure 7**).



Alkali/H_2O ratio = 0.25, Si/Alkali ratio = 0.33,
Unit Water Amount = 170 kg/m^3, BS Replacement Rate 9.2 Volume %

Figure 7 - Chloride Ion Penetration Characteristics of Geopolymer Mortar[6)]

Regarding the alkali silica reaction, Harada et al.[13)] reported that geopolymer mortar does not undergo alkali silica reaction, and is resistance to high alkali silica reactions.

Regarding the high-temperature properties, Ichimiya et al.[17)] conducted a high-temperature heating experiment to investigate the influence of GGBS replacement rate on the high temperature resistance of geopolymer, as shown in **Figure 8**. As a result, by replacing a part of the active filler with the GGBS, the strength of the geopolymer under high temperature conditions is higher at 500 °C compared to normal temperature strength, and it is lower at temperatures that exceed 800 °C, and so on.

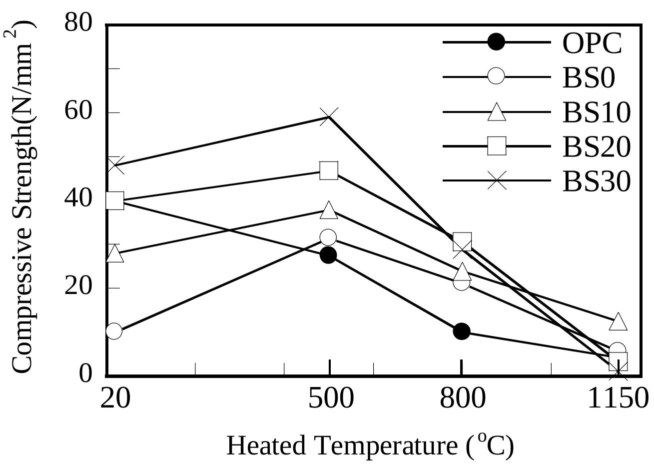


Figure 8 - Heating Temperature and Compressive Strength

Regarding the freeze-thaw resistance, Minami et al.[9)] has been experimentally investigating the effect of the silicon/alkali ratio (mortar ratio) in alkali silicate solution on freeze-thaw resistance.

Regarding the change in length, Ichimiya et al.[18)] reported that the shrinkage strains of the four types of fly ash at the 4th week of the test material age are about 5 times that of the same type, about 1.7 times that of regular cement, and for changes in length that are larger than other mixtures. Honma[19)] examined the change in length of geopolymer mortal during heat curing, and the dry shrinkage of geopolymer mortar with different heat curing times. Geopolymer mortar is reported to exhibit expansion at room temperature curing and shrinkage at heat curing, and the shrinkage characteristics will vary in accordance to the curing time as well as the alkali type.

5. Construction Examples

5.1 Outline

For case examples of geopolymer construction, there are 4 cases domestically (including trial construction) and several cases overseas. Here, two of the domestic cases and one of the overseas cases are introduced.

5.2 Creek Retaining Wall in Farmland

Regarding the maintenance of creeks in the agricultural rural development project, a fly ash-based geopolymer paste was used for establishing a highly durance creek slope protection method as a substitute way of the wooden fence construction method.

(1) Materials and Mixture

The materials used are fly ash, sodium metasilicate powder, and water.

(2) Condition After Construction

Image 2 shows the condition 7 years after construction. While some slight signs of deterioration are visible on the outer surface, currently it is fully satisfying its functionality as a retaining wall.

Image 2 － On site condition after 7 years from construction.

5.3 Boundary Block of Walkway in a Strongly Acid Hot Spring Area

At the construction site concrete made of ordinary Portland cement deterioration by acid was intense, so geopolymer concrete with its excellent acid resistance was adopted.

(1) Construction Outline

The construction result is an order from Oita Prefecture Office for sidewalk improvement construction. The constructed geopolymer concrete-type block is a JIS A 5371 boundary block, shown in **Image 3**.

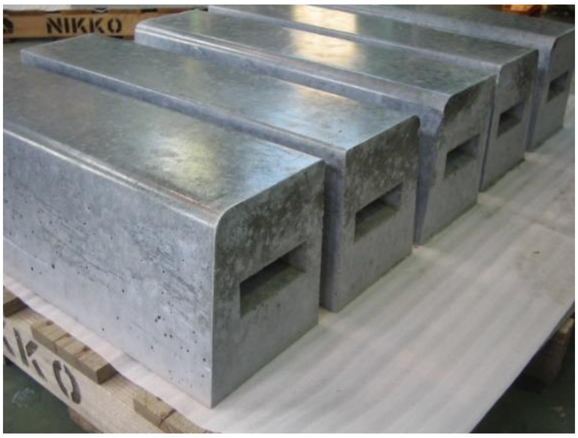


Image 3 － Boundary Block

(2) Condition After Construction

Image 4 shows the condition after construction. The number of geopolymer concrete block is 128 pieces, and the total construction extension is about 80 m.

Image 4 － On site condition after construction.

5.4 Aircraft pavements in Australia

Approximately 40,000 m^3 of geopolymer concrete was applied to the new airport Toowoomba Wellcamp Airport (formerly Brisbane West Wellcamp Airport) in Darling Downs, Queensland, Australia.

(1) Geopolymer Concrete Specifications

The geopolymer concrete specifications are an average bending strength 4.8 MPa of material age 28-day, and a maximum dry shrinkage strain of 450×10^{-6} at 28-day material age.

(2) Production Facilities and Condition after Construction

Image 5 shows facilities for manufacturing geopolymer concrete. The geopolymer concrete was produced in a two-batch plant with a forced biaxial mixer with capacity of $3m^3$. Also, the condition after construction is shown in **Image 6**.

Image 5 － Concrete Plant

Image 6 － On site condition after construction.

6. Round Robin Tests

6.1 Outline

The material properties of geopolymer being considered for application as construction materials are listed in 4.3 and 4.4. Much knowledge, both domestically and internationally, is being reported. However, even with similar research contents, the research institute tends to show different trends in knowledge and results. As a factor of this, there are great differences in the materials and mix proportions, the manufacturing method, etc. Additionally, we can also consider the influence of the experiment environment of each research institute's facilities on the manufactured geopolymer. With the exception of the Japan Concrete Institute, Kyushu Branch's results[20)], there are basically no reports for domestic Round Robin Tests regarding geopolymers.

Therefore, this committee conducted to do round robin tests on fresh properties and compressive strength under conditions that unify material, mix proportions, manufacturing method, and investigated the effect of the difference of the research agencies on the material properties of geopolymer. Based on the following experimental conditions, it was simultaneously conducted with the participation of 10 research agencies.

- The target is geopolymer mortar.
- The alkaline solution is Na-based water glass and sodium hydroxide system, and the active filler is fly ash and GGBS.
- The curing conditions are two standards - normal temperature curing (20 °C: 28 days), and heat curing (60 °C: 24 hours, then 20 °C: 27 days).

6.2 Materials and Mix proportions

As an alkaline solution, a mixed solution of Na-based water glass of No.1 of JIS standard, sodium hydroxide aqueous solution, and tap water was used. For water glass, a 1.5-fold diluted solution was used in consideration of workability. For the active filler, JIS II type fly ash of the same lot and solely GGBS containing no gypsum having a specific surface area of 4000 mm^2/g

were used. JIS standard sand was used for the fine aggregate.

Table 3 shows the mix proportions of the geopolymer mortar used in the round robin test.

Table 3 - Mix proportions (g/L)

Mix proportions Name	Material	FA	BS	1.5x WG	35% NaOH	Water W	Standard Sand	A/W Mortar Ratio	Si/A Mortar Ratio
	Density	2.26	2.91	1.30			2.64		
BS10	BS Replacement Rate 10%	489	70	232	52	64	1297	0.102	0.707
BS20	BS Replacement Rate 20%	434	140	232	52	64	1297	0.102	0.707

FA: Fly Ash, BS: GGBS, WG: Water Glass, NaOH: Sodium Hydroxide
A/W＝Na/H_2O, Si/A＝Si/Na

6.3 Mixing and Curing

For mixing, the JIS mortar mixer was used as a standard at 20 °C. First, after the active filler and the fine aggregate were mixed for one minute, then an alkaline solution was added and mixed for an additional five minutes. All of the curing was done in a sealed state, and as described above, at two curing standards of normal temperature curing and heat curing.

6.4 Test Results

As an example of the results, **Figure 9** shows the flow value, and **Figure 10** shows the result of the compressive strength which was of heat curing. From the results of this experiment, it became clear that it is a relatively reproducible material if the material quality can be secured. Additionally, examples of manufacturing procedures that can be referred to by many engineers, were shown, including the tabulating recipe of mixing and preparation.

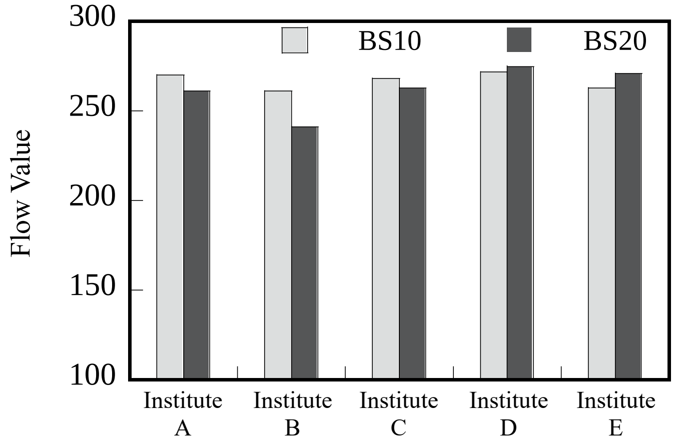


Figure 9 - Flow Test Results (with 15 beats)

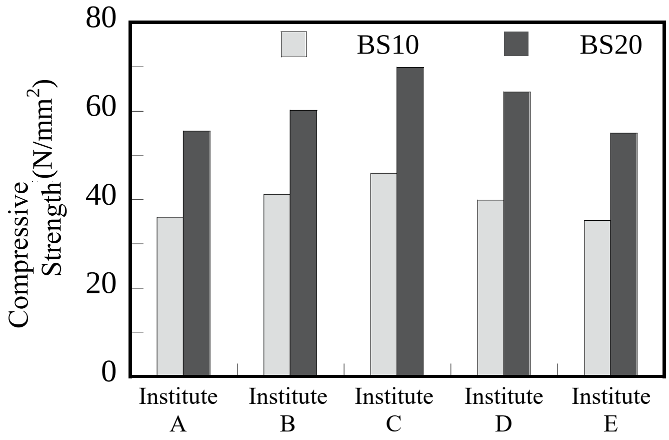


Figure 10 – Compressive Strength Test Results (60 °C)

7. e-learning

A prototype of e-learning of geopolymer for engineers and students with basic knowledge of concrete engineering was created. This system used the web learning plaza (currently the JREC-IN Portal "Available as e-learning for Research Human Resources (https://jrecin.jst.go.jp/)") created by the Japan Science and Technology Agency (JST) as a reference. **Figure 11** shows an example of the content. The screen consists of images, commentaries (narration sentences), and related knowledge icons (gray square button at the bottom of the figure), with consideration given for efficient learning. There are plans to eventually include images, commentary, and icons of related knowledge in the geopolymer e-learning.

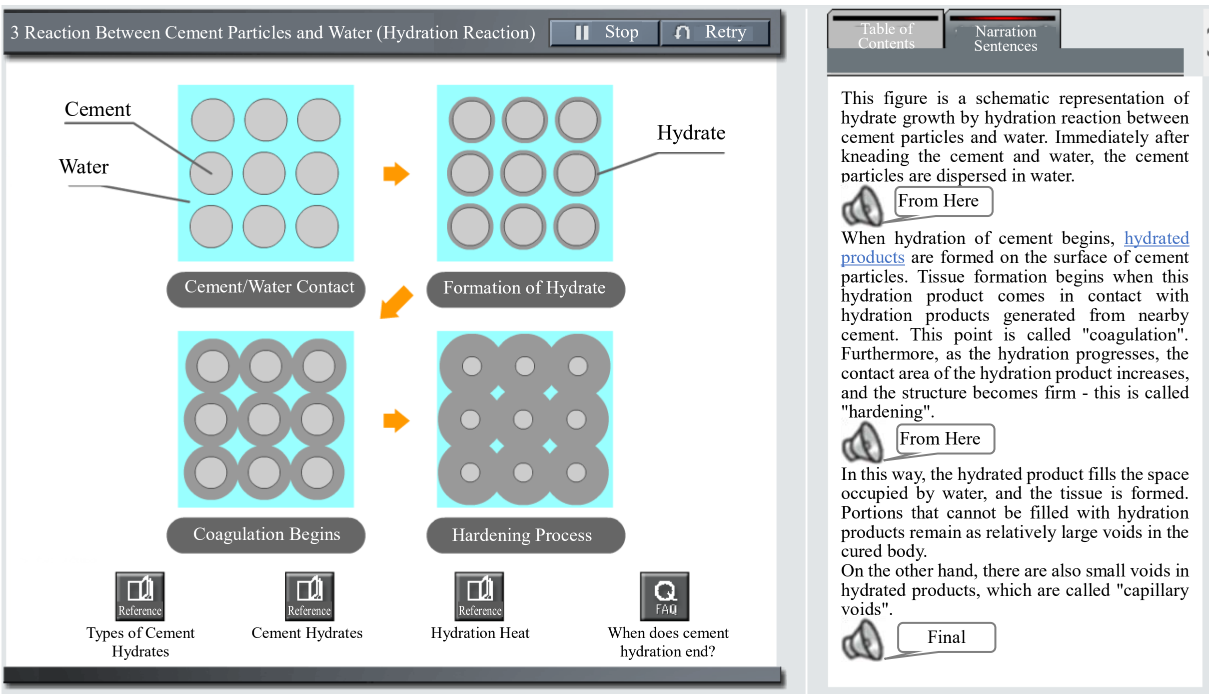


Figure 11 – Example of the JST Web Learning Screen (Reaction Between Cement Particles and Water (Hydration Reaction))

The e-learning content types of geopolymer are displayed as follows.

1. Definition and Characteristics

2. Materials Used and Manufacturing Method
3. Solidification Method
4. History
5. Strength
6. Volume Change
7. Durability
8. Adhesion Between Reinforcement and Geopolymer
9. Future Developments

Figures 12 and **13** show an example of mixing and preparation exemplified from “2. Materials Used and Manufacturing Method” and an example of carbonation from “7. Durability.”

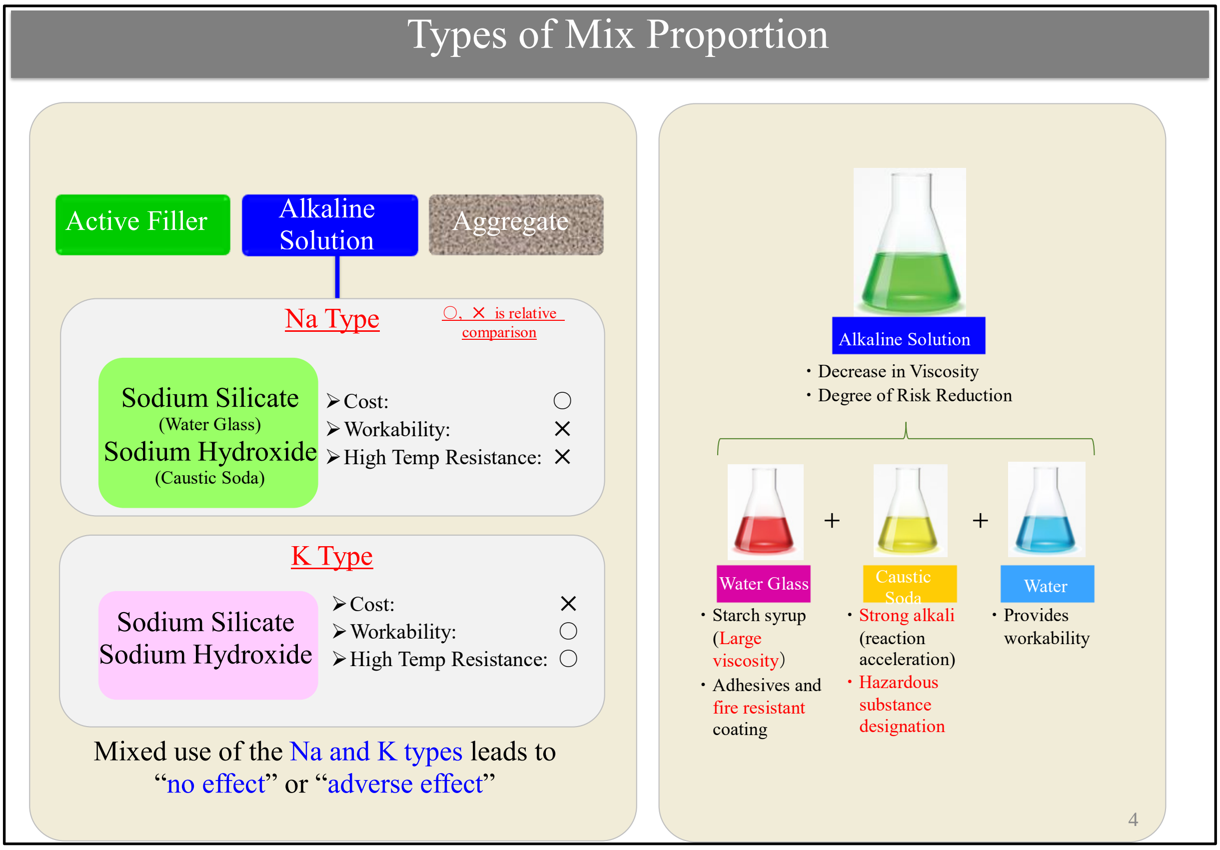


Figure 12 – Example of e-learning Screen
Example of Types of Mix Proportion from “2. Materials Used and Manufacturing Method”

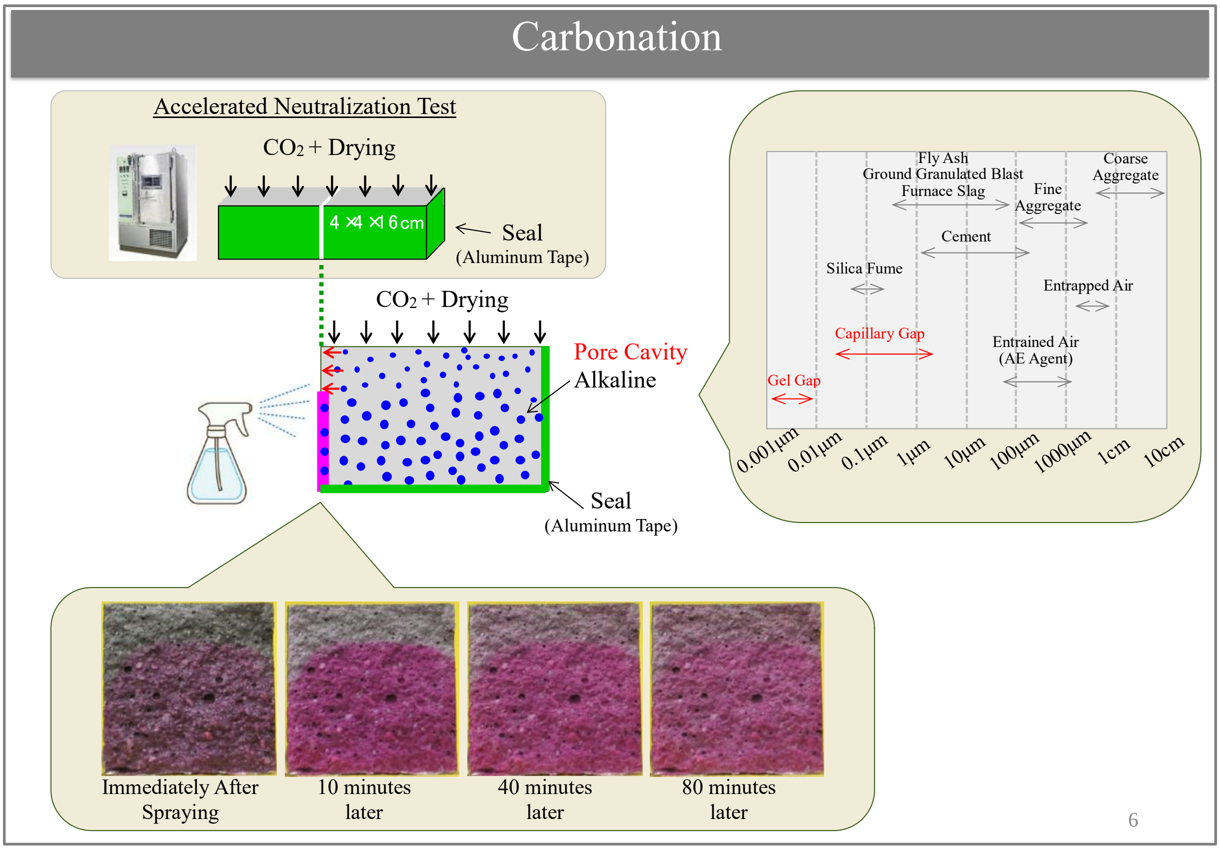


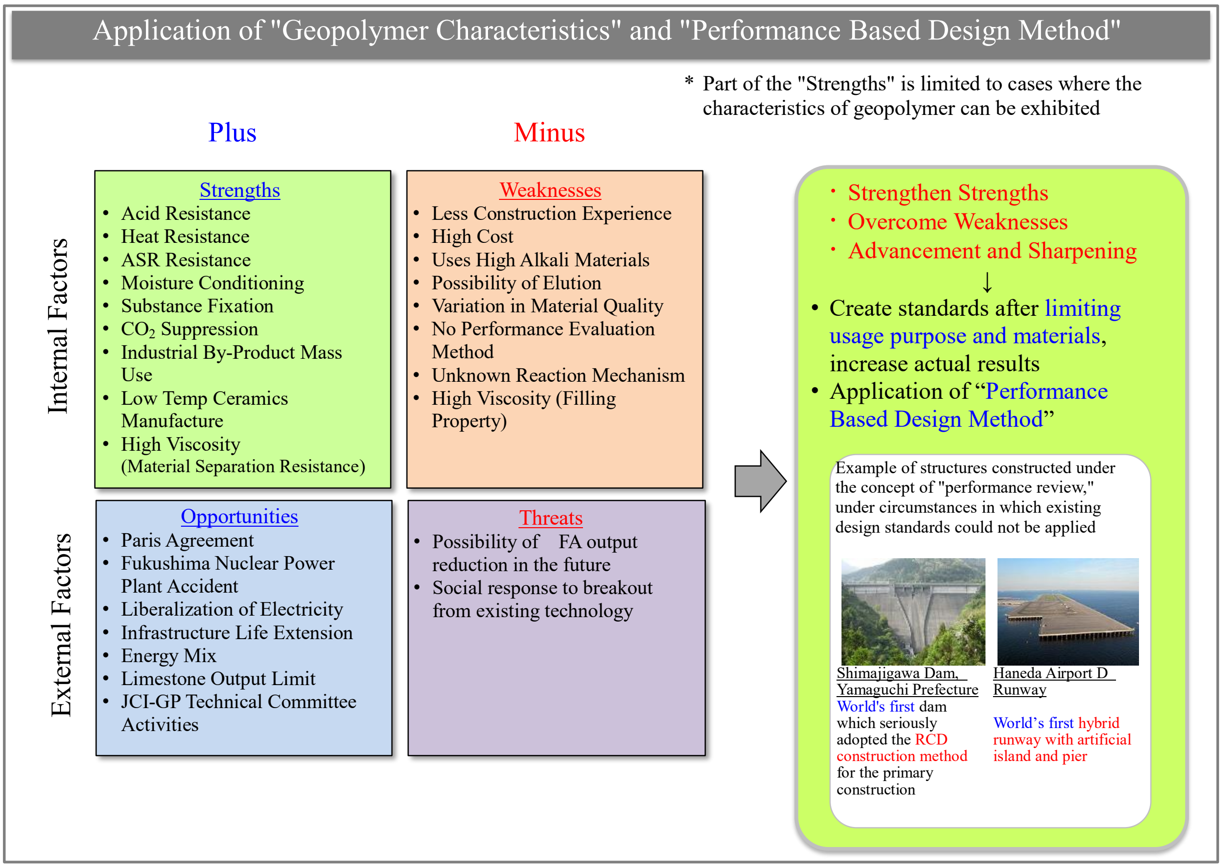
Figure 13 – Example of e-learning Screen
Example of Carbonation from "7. Durability"

8. Summary

As mentioned above, geopolymer can be evaluated with the same index as conventional concrete, but in order to derive the characteristics of geopolymer, consideration from a different viewpoint is required.

The current issues considered for the practical use of geopolymers are – (1) reduction of material cost, (2) manufacturing technology for obtaining a stable quality, (3) establishment of accelerated test methods for estimating long-term characteristics and evaluation methods of the data, (4) establishing standards, and (5) PR activities for promotion. At the same time, in order to promote practical application, it is also necessary to conduct large-scale on-site experiments for non-structural components, and applied test construction for structural materials.

Figure 14 is a diagram showing the SWOT analysis in which the plus and minus aspects of geopolymers are divided into internal and external factors, and the result in which application of the performance based design method is effective. Subsequently, together with measures to clarify the solidification mechanism and physical properties in the laboratory level, creating standards and increasing actual results through the limitation of usage purpose and materials, are considered to be realistic directions for the spread of geopolymer technology.



SWOT analysis (or SWOT matrix) is an acronym for strengths, weaknesses, opportunities, and threats and is a structured planning method that evaluates those four elements of an organization, project or business venture. A SWOT analysis can be carried out for a company, product, place, industry, or person. Wikipedia

Figure 14 - Characteristics of Geopolymer and its Application to the Performance Based Design Method

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