Committee Report: JCI- TC193A

Technical Committee on Advanced Utilization of Volcanic Sediments as Mineral Admixture for Concrete

Takafumi NOGUCHI[*1], Tatsuhiko SAEKI[*2], Hiroshi JINNAI[*3], Atsushi TOMOYOSE[*4], Satoshi WATANABE[*5]

Abstract

Japan has several volcanoes, and therefore, an abundant reserve of volcanic sediments with pozzolanic reactivity. In this committee, we focused on various volcanic sediments that can be utilized as mineral admixture for concrete. We conducted surveys on volcanic sediment distribution and reserves in Japan and overseas as well as their physical and chemical composition characteristics. In addition, we conducted surveys on the actual usage and characteristics of the concrete that utilizes these materials and test methods for using volcanic sediments as mineral admixture for concrete using a simple manufacturing method. We proposed an optimal manufacturing and usage method.

Keywords: Volcanic sediments, mineral admixture, aggregates, pozzolan, effective utilization

1. Introduction

Japan has many volcanoes, and therefore, it has abundant reserves of volcanic sediments with pozzolanic reactivity. The advanced utilization of such volcanic sediments as mineral admixture for concrete can help improve concrete durability and carbon reduction. The effective utilization of volcanic sediments in Japan has been conducted since the Meiji era, and thus far, many examples of utilization have accumulated throughout history regardless of the fields of civil engineering and architecture. Various research institutions have started reconsidering its effective utilization owing to the enactment of the JIS A 6209 “Volcanic glass powder for use in concrete” in March 2020.

In this committee, we focused on various volcanic sediments that can be used as mineral admixture for concrete. We conducted surveys on information such as volcanic sediment distribution and reserves in Japan and overseas and their physical and chemical composition characteristics. In addition, we conducted surveys on the actual usage and characteristics of the concrete that utilizes those materials (from the aspects of fluidity, strength development, durability, etc.) and the test methods required for using volcanic sediments as concrete materials with a simple manufacturing method. We proposed an optimal manufacturing method and usage method.

Table 1: Committee composition

Chair	Takafumi Noguchi	University of Tokyo
Secretary	Tatsuhiko Saeki	Niigata University
Secretary	Hiroshi Jinnai	Tokyo Polytechnic University
Secretary	Atsushi Tomoyose	University of Tokyo
Secretary	Satoshi Watanabe	Taisei Corporation
[WG1: Raw Materials WG]		
Chief	Hiroshi Jinnai	Tokyo Polytechnic University
Vice Chief	Satoshi Watanabe	Taisei Corporation
	Yoshikazu Akira	Kagoshima University
	Daiki Atarashi	Shimane University
	Atsushi Ueno	Tokyo Metropolitan University
	Yasuyuki Kakihara	Hokkaido Research Organization
	Gaochuang Cai	Kumamoto University
	Masami Sato	Nihon University
	Kenichi Sodeyama	Kagoshima Prefectural Institute of Industrial Technology
	Madoka Taniguchi	Hokkaido Research Organization
	Hironobu Nishi	Flowric
	Hiroaki Mori	Taiheiyo Cement
	Yuya Yoda	Shimizu Corporation
[WG2: Utilization WG]		
Chief	Tatsuhiko Saeki	Niigata University
Vice Chief	Atsushi Tomoyose	University of Tokyo
	Yoshikazu Akira	Kagoshima University
	Daiki Atarashi	Shimane University
	Atsushi Ueno	Tokyo Metropolitan University
	Yoshimori Kubo	Kanazawa University
	Gaochuang Cai	Kumamoto University
	Kuniaki Sakurai	Obayashi Corporation
	Kenichi Sodeyama	Kagoshima Prefectural Institute of Industrial Technology
	Madoka Taniguchi	Hokkaido Research Organization
	Takeshi Torichigai	Kajima Corporation
	Hironobu Nishi	Flowric
	Tetsuro Matsushita	Takenaka Corporation

The committee members are listed in **Table 1**. In the Raw Materials WG (WG1: Hiroshi Jinnai, Chief), we survey information such as volcanic sediment distribution and reserves in Japan and overseas and their physical and chemical composition characteristics. Further, we conducted surveys on the actual usage as materials for utilization in concrete and test methods required for using them. In the Utilization WG (WG2: Tatsuhiko Saeki, Chief), we used experimental data on concrete that utilized volcanic sediments from around the world as mineral admixture or aggregates,

*1 University of Tokyo Graduate School of Engineering Department of Architecture Professor, D.Eng. (Fellow member)

*2 Niigata University Faculty of Engineering Department of Civil Engineering and Architecture Professor, D.Eng. (Regular member)

*3 Tokyo Polytechnic University Faculty of Engineering Department of Engineering Architecture Course Professor, D.Eng. (Regular member)

*4 University of Tokyo Graduate School of Engineering Department of Architecture Assistant Professor, D.Eng. (Regular member)

*5 Taisei Corporation Technology Center Urban Infrastructure Technology Research Department Structural Laboratory Material Team, D.Eng. (Regular member)

and we focused on the freshness, hardening process characteristics, and post-hardening characteristics of the materials. We surveyed the effects of physical characteristics such as chemical composition, mineral composition, and fineness of volcanic sediments on concrete regardless of its place of origin. In addition, we conducted various tests on volcanic glass powder conforming to JIS A 6209, which has not been investigated to date, to the best of our knowledge. Finally, we investigated the condensation and adiabatic temperature elevation characteristics.

2. Distribution, properties, actual usage, and test methods of volcanic sediments

2.1 Volcanic eruption and sedimentation

This technical committee included members who specialize in concrete engineering and geology. We defined the term "volcanic deposit" as handled by this technical committee. We summarized the process from the volcanic eruption to the accumulation of ejecta, and the classification of accumulated volcanic sediments from the perspective of geology.

The term "volcanic deposit" as handled by this technical committee was defined as "material released by the eruptive activity of a volcano that has moved and subsequently accumulated." From the perspective of mineral admixture for concrete, it may seem that "volcanic glass," which is made by quenching high-temperature magma and is expected to have pozzolanic reactivity, is desirable. However, "volcanic sediments" defined by this technical committee then include not only lava that is cooled and solidified by hot molten magma, which is famous for the Kilauea volcano on the Big Island of Hawaii, but it can also include deposits that do not contain magma-derived substances such as from phreatic eruption strongly recognized during the eruption of Mt. Ontake (September 27, 2014). Indeed, even the latter may exhibit sufficient performance if used as an aggregate for concrete.

The descriptions of its content are provided in Section 2.1. The reasons for understanding the style of volcanic eruption, overview of volcanic eruption, alteration actions, era of eruption, acceptable conditions, and the classification of volcanic sediments, in Sections 2.1.2–2.1.6. This section was written by a committee member who is conducting research on volcanic sediments as illustrated in Photograph 1; this section was drafted to allow others to utilize volcanic sediments for deepening their basic understanding.

2.2 Distribution of volcanic sediments in Japan

The Japanese archipelago is a region with active volcanic activity even on a global scale, and there are a large number of volcanic sediments distributed and buried from the Paleogene period to the present day. The distribution of volcanic sediments in Japan can be determined to some extent when searching for and using volcanic sediments with potential pozzolanic reactivity as mineral admixture for concrete. In Section 2.2, we summarize the distribution of major volcanoes and volcanic sediments as indicated in **Fig. 1**. We summarize the findings of volcanic sediments in Hokkaido, Tohoku, Kanto Koshinetsu, Izu Islands, Chugoku, Shikoku, and Kyushu regions.

Photograph 1: Welded tuff (bottom: soft; top: hard)

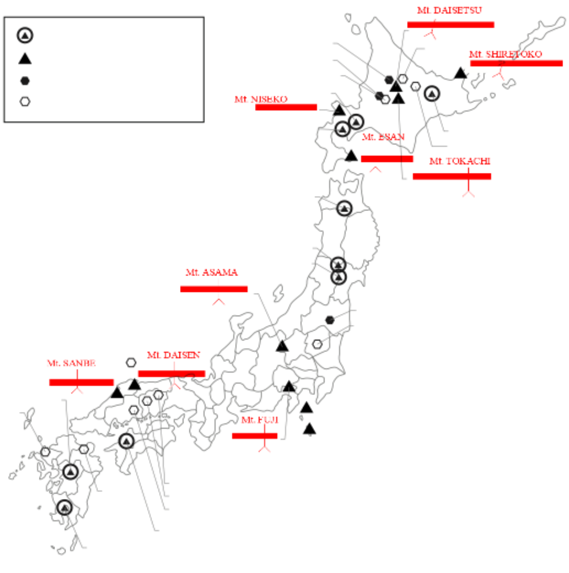


Fig. 1: Distribution of major volcanoes and volcanic sediments

In the field of geology, there is a massive amount of information on volcanic sediments that cannot be investigated using only the present survey. Therefore, it is important to continue surveys on such information in the future for promoting the effective use of volcanic sediments in the field of concrete.

2.3 Properties of volcanic sediments

In this section, we review literature that deals with volcanic sediments and summarize the properties of volcanic sediments in Japan and overseas.

In Section 2.3.1 (volcanic sediments in Japan), we classify its contents between (1) composition and pozzolanic reactivity of volcanic sediments and (2) survey results on indices of the pozzolanic reactivity of volcanic sediments. Further, we collect and analyze information related to volcanic sediments in Japan.

The specific surface area of the material used as the reactive powder is important, and it needs to be composed of an amorphous phase (glass phase). Such materials show broad peaks, as observed using the powder X-ray diffraction (XRD) images. Volcanic ash that has undergone quenching does not easily experience crystallization during cooling, and therefore, volcanic ash with such broad peaks is likely to occur; its cooling rate is a crucial factor. Even if the chemical composition is rich in Si and Al, the reactivity is extremely low in cases of volcanic ash composed of highly crystalline quartz or mullite.

Table 2 summarizes the examples of the chemical composition and volcanic glass content of volcanic sediments in Japan; the chemical composition, basicity ($(CaO+MgO+Al_2O_3)/SiO_2$), and M value ($(CaO+MgO+Na_2O+K_2O)/SiO_2$) of volcanic glass is provided. This table reorganizes data that is published as a database online[2)] based on Reference 1). Data on 20 types in Hokkaido, 9 types in Honshu, and 25 types in Kyushu are published in this database. We extract and summarize the chemical composition, X-ray diffraction pattern, and thermal analysis results. The symbols of extracted samples are Hokkaido (HS-3, HT-1, HK-1, HV-7), Honshu (MT-3, MV-1, MM-1, MS-1), and Kyushu (KA-1, KA-6, KP-3, KO-5). As summarized in Table 2, the volcanic glass phase content in volcanic ash in Japan exceeds 60%, and many deposits have relatively high values. As summarized in Table 3, the average CaO and MgO contents of the volcanic glass phase are low at 1.10% and 0.38%, respectively. Furthermore, the mean and standard deviation were 0.21 and 0.02, for the basicity of the volcanic glass phase and 0.12 and 0.01 for its M value, respectively. These results show that most of the volcanic glass contained in Japanese volcanic ash is composed of glass with low basicity and a low M value. In Section 2.3.2, we show the range of volcanic sediments that can be surveyed. There are too many volcanic sediments to fully survey overseas;

however, the survey results of this research are believed to serve as a reference when using volcanic sediments overseas.

2.4 Actual usage of volcanic sediments

In this section, we summarize the results of surveys conducted on the actual usage of volcanic sediments in Japan and overseas.

In Section 2.4.1 (actual usage in Japan), we classify the contents based on use into (1) early days (Meiji–early Showa), (2) addition, and (3) fine aggregate; we collected and analyzed information on the actual usage of volcanic sediments in Japan.

In (1), we summarize the actual usage of volcanic sediments for concrete from history. Here, we summarize the usage methods and regulations of volcanic sediments in early days based on photographs at the time such as Photograph 2 and descriptions in old literature.

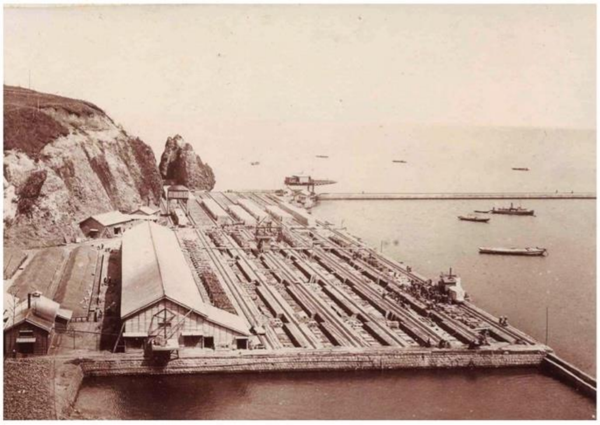
In (2), we summarize the results of surveys on the actual usage of volcanic ash used as mineral admixture for concrete from the Meiji era to Showa era; we explain the processing method of volcanic glass powder has been put to practical use in recent years.

Table 2: Example of the chemical composition of volcanic sediments in Japan[Modified from 2)]

No.	Name	化学組成と火山ガラス含有率（mass%）											塩基度 Basicity	M 値
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	Ig. loss	Total	ガラス含有率		
3	HS-3	67.98	15.63	3.46	0.39	2.69	1.06	3.27	1.89	3.56	99.93	57.59	0.29	0.13
6	HT-1	72.1	13.36	2.82	0.26	0.81	0.94	4.00	2.29	3.66	100.24	55.16	0.21	0.11
9	HK-1	66.48	15.44	4.11	0.69	3.75	1.31	4.26	1.3	2.31	99.65	58.43	0.31	0.16
20	HV-7	73.28	12.96	1.36	0.14	1.16	0.31	3.46	3.18	4.22	100.07	78.37	0.20	0.11
23	MT-3	67.72	15.23	3.55	0.52	3.72	1.19	3.87	1.08	3.07	99.95	63.83	0.30	0.15
26	MV-1	73.37	13.27	1.08	0.05	0.56	0.08	2.79	4.72	3.98	99.90	68.92	0.19	0.11
27	MM-1	73.37	13.27	1.08	0.05	0.56	0.08	2.79	4.72	3.98	99.90	68.92	0.19	0.11
29	MS-1	71.74	14.13	1.93	0.18	0.9	0.48	3.34	3.55	3.45	99.7	60.16	0.22	0.12
30	KA-1	64.24	17.21	3.16	0.57	1.86	0.95	3.76	3.51	4.61	99.87	75.33	0.31	0.16
35	KA-6	62.36	16.87	4.76	0.72	3.42	1.72	3.99	2.96	2.87	99.67	50.25	0.35	0.19
39	KP-3	71.42	14.16	2.38	0.26	2.24	0.58	3.72	2.77	2.55	100.08	70.27	0.24	0.13
48	KO-5	70.36	13.16	2.48	0.12	2.58	0.62	3.2	2.95	3.49	98.96	66.39	0.23	0.13
平均	—	69.54	14.56	2.68	0.33	2.02	0.78	3.54	2.91	3.48	99.83	64.47	0.25	0.13
標準偏差	—	3.58	1.42	1.14	0.23	1.17	0.48	0.45	1.11	0.65	0.31	8.06	0.05	0.02

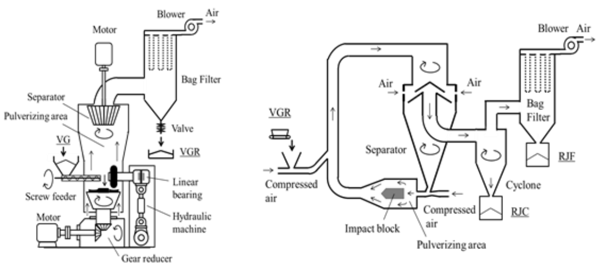
Table 3: Example of the chemical composition of volcanic glass in volcanic sediments in Japan[Modified from 2)]

No.	Name	分離した火山ガラスの化学組成（mass%）										塩基度	M
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	Ig. loss	Total	Basicity	値
3	HS-3	74.02	13.27	1.15	0.17	1.35	0.40	3.77	2.47	3.45	100.05	0.20	0.11
6	HT-1	74.14	12.89	1.56	0.08	0.34	0.36	4.37	2.92	3.55	100.21	0.18	0.11
9	HK-1	73.88	12.45	2.11	0.38	1.60	0.50	3.99	1.73	3.15	99.79	0.20	0.11
20	HV-7	73.11	12.48	1.43	0.11	0.93	0.15	3.21	3.45	4.65	99.52	0.19	0.11
23	MT-3	72.45	13.10	2.24	0.35	2.20	0.66	3.81	1.19	3.60	99.60	0.22	0.11
26	MV-1	73.75	13.22	1.06	0.04	0.53	0.06	2.77	4.73	3.87	100.03	0.19	0.11
27	MM-1	73.75	13.22	1.06	0.04	0.53	0.06	2.77	4.73	3.87	100.03	0.19	0.11
29	MS-1	72.42	13.85	1.06	0.08	0.56	0.35	3.51	4.15	4.05	100.03	0.20	0.12
30	KA-1	67.73	15.94	1.94	0.45	1.13	0.58	3.85	4.00	4.21	99.83	0.26	0.14
35	KA-6	68.54	15.17	1.79	0.44	1.38	0.77	3.99	4.12	3.59	99.79	0.25	0.15
39	KP-3	74.60	12.39	1.57	0.15	1.14	0.32	3.42	3.45	2.95	99.99	0.19	0.11
48	KO-5	74.68	12.38	1.96	0.16	1.47	0.33	2.96	2.72	3.03	99.69	0.19	0.10
平均	-	72.76	13.36	1.58	0.20	1.10	0.38	3.54	3.31	3.66	99.88	0.21	0.12
標準偏差	—	2.18	1.08	0.41	0.15	0.52	0.21	0.50	1.08	0.48	0.20	0.02	0.01



Photograph 2: Construction of north breakwater (from Otaru Museum collection)

Historically, techniques have been developed to separate crystalline minerals and volcanic glass from volcanic deposits using heavy liquids. Currently, dry specific gravity separation using an air table has enabled the sorting of volcanic sediments into volcanic glass, crystalline, pumice, and weathered materials at a low cost[3)]. It is possible to produce finely powdered volcanic glass that can be used for high strength concrete by crushing the volcanic glass sorted in this manner with a mill as shown in **Fig. 2**[4)].



(Roller mill) **(Jet mill)**

Fig. 2: Improved roller mill and jet mill[3)]

In (3), we focus on the actual usage in Kagoshima Prefecture, islands off Tokyo, and Hokkaido by describing the historical background and spread of the material. As shown in Photograph 3, in Kagoshima Prefecture, volcanic sediments are used for the construction of various concrete structures; its applications are diverse, and they range from secondary products, high-fluidity concrete for bridge foundation work, and sprayed concrete for tunnels. Furthermore, there are factories in Kagoshima certified by the Ministry of Land, Infrastructure, Transport and Tourism for the architecture field that can ship concrete. There are the house built with exposed concrete walls.

In Section 2.4.2, the contents are classified into (1) use for concrete in Roman times, (2) use as mineral admixture for concrete in modern times, and (3) volcanic sediment products in practical use overseas. We collected and analyzed information on the actual usage of volcanic sediments overseas.

The long history of using volcanic sediments in concrete can be easily understood by considering its use in concrete in ancient Rome. Reviews of recent literature show many examples in places such as Pakistan, Saudi Arabia, Cameroon, Indonesia, Turkey, Algeria, Italy, Papua New Guinea, and the United States; this is a technology used in many countries. In addition, examples of applications to cements, geopolymer mixtures, and lightweight aggregates can be collected when surveying the websites of international companies, and therefore, it is thought that there are various uses of volcanic sediments overseas.

2.5 Investigation of the test methods of volcanic sediments for concrete

In this section, we summarize the results of surveys on the test methods of volcanic sediments in Japan and overseas. The performance of volcanic sediments can be evaluated on other mineral admixture for concrete and aggregates for concrete. However, further research is required for the evaluation methods of activity indices for mineral admixture and evaluation methods of surface dryness required for measuring the density and water absorption for aggregates; research is still underway even today. Thus, we summarized the status of these studies.

In Section 2.5.1, we summarized research cases of the activity index test of volcanic sediments as mineral admixture. The activity index of volcanic glass powder whose specific surface area is close to that of fine powders such as silica fumes can be obtained by activity index tests specified in JIS A 6209 (Volcanic glass powder for use in concrete).


(Secondary product) **(High-fluidity concrete)**

(Sprayed concrete) **(Concrete for architecture)**

Photograph 3: Actual usage in Kagoshima

However, it may not be possible to determine the essential properties of the target volcanic sediments with evaluations that use Blaine's specific surface area and activity index in JIS A 6201 ("Fly ash for use in concrete") as shown in **Fig. 3** for volcanic sediments whose specific surface area has been adjusted to the size of fly ash. In Reference 5), the relationship between the specific surface area and activity index is obtained by the BET method as shown in **Fig. 4** obtained for the same volcanic sediment as in Fig. 3; however, it is confirmed that the specific surface area is considerably larger than the Blaine's specific surface area and increase in the specific surface area tended to decrease the activity index.

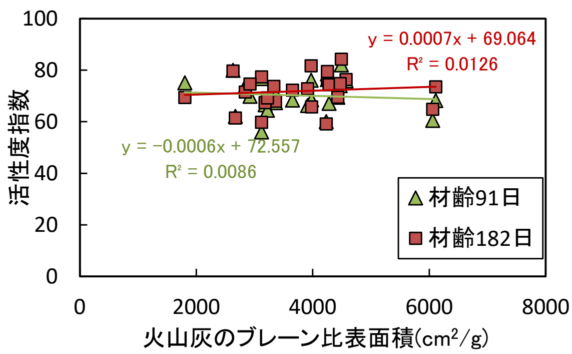


Fig. 3: Blaine's specific surface area and activity index in JIS A 6201 (W/B = 50%)[5)]

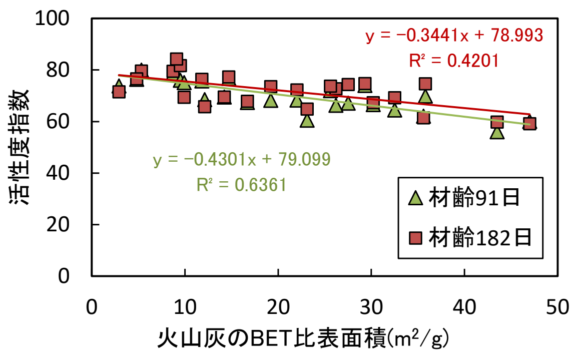


Fig. 4: BET specific surface area and activity index in JIS A 6201 (W/B = 50%)[5)]

Fig. 5: Water absorption test by electrical resistance method The BET specific surface area not only includes the surface layer of the volcanic sediment but also the surface area of the internal voids. The activity index test results of the volcanic sediments in Figs. 3 and 4 showed that the voids in volcanic sediments led to a decrease in the physical strength of mortar and concrete instead of explaining chemical strength contribution rates such as the pozzolanic reaction. This area is a topic for future research when using volcanic sediments with large specific surface area for mineral admixture in concrete.

In Section 2.5.2, we summarize the method for evaluating the surface dryness of volcanic sediments as fine aggregates. The surface dryness of fine aggregates is determined by the collapse of a sample packed in a flow cone with an inclined surface angle exceeding 70°, as specified in JIS A 1109 ("Methods of test for density and water absorption of fine aggregates"). However, the applications are difficult because of measurement principles in cases where the particle shape of the fine aggregate used as a sample is significantly angular, density is significantly large or small, particle size distribution is significantly biased, fine particle amount is large, or when hydrophilicity is significantly low. Thus, Kagoshima University and Tokyo Metropolitan University proposed an evaluation method unlike from JIS A 1109. Kagoshima University examined a method for judging surface dryness using an upright cone with a flow cone angle changed to 90°[6] and adopted this in the "Construction Manual for Design of Concrete that Uses Shirasu as Fine Aggregate (Draft)," which was "established in Kagoshima Prefecture in 2006. Furthermore, Tokyo Metropolitan University is conducting research on a method for judging the surface dryness by an electrical resistance method that does not use a flow cone[7], and it examines the application of the electrical resistance method to fine aggregates that originates from volcanic sediments. It may be difficult to evaluate the surface dryness of volcanic sediments as fine aggregates with methods that use a normal flow cone; therefore, an upright cone method or electrical resistance method should be used for such cases.

2.6 Conclusions

In Section 2.6, we briefly summarize the contents of Section 2.

3. Characteristics of concrete that uses volcanic sediments

In this section, we summarize the characteristics of concrete that uses volcanic sediments as obtained from the literature review. The main contents are presented below.

3.1 Freshness characteristics

3.1.1 Slump, slump flow, and mortar flow

(1) When using volcanic sediments as mineral admixture for concrete

Pastes that use volcanic glass powder have decreased fluidity when high-performance AE water reducing agents are not used. Discussions indicated that this was attributed to the agglomeration of the volcanic glass powder. Meanwhile, it was shown that this agglomeration could be eliminated using a high-performance AE water reducing agent.

Further, the adsorbed chemical addition adsorption amount is high when clayey content is included in volcanic sediments, and the fluidity decreases as a result (**Fig. 6**) and therefore, it has been indicated that removing the clay components before crushing is desirable in the volcanic glass powder production process.

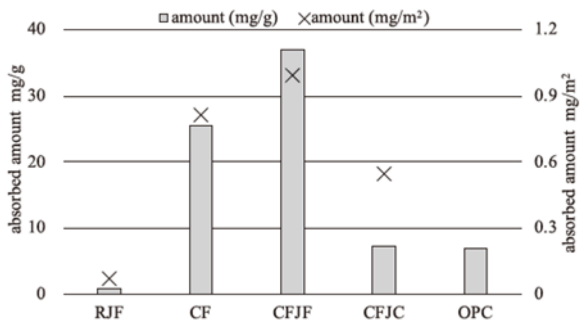


Fig. 6: Absorption amount of high-performance AE water-reducing agent

(2) When using volcanic sediments as part of the aggregate

Concrete where Shirasu is used as a fine aggregate requires about 10% more of the unit water volume for securing the same slump as concrete where Shirasu is not used (**Fig. 7**). In concrete that uses Shirasu, the unit water volume required for securing the same slump as in concrete that does not use Shirasu decreases by setting an optimal fine aggregate ratio that can minimize the unit water volume required to secure the target slump level; this increases the air amount using an AE agent.

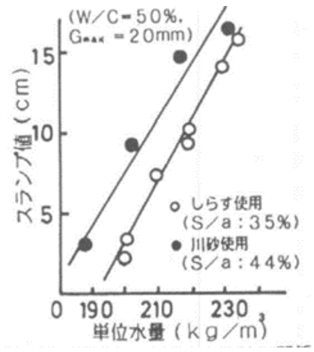


Fig. 7: Relationship between unit water volume and slump

3.1.2 Chemical admixture and air entrainment

The target fluidity and air volume can be met sufficiently with commercially available chemical admixture in both cases where volcanic glass powder is used as an addition and where volcanic ash is used as a substitute for fine aggregate. The addition rate changes based on the characteristics of the volcanic sediment; however, it is believed that the fluidity is equivalent to that of an unused one can be obtained by adjusting the addition rate of a dispersant in a realistic range (**Fig. 8**).

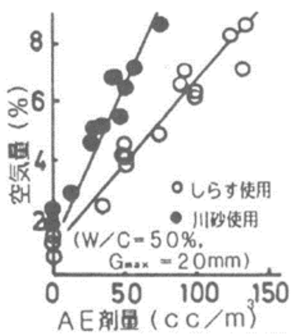


Fig. 8: Relationship between the AE agent amount and the entrained air amount

3.2 Characteristics of hardening process

3.2.1 Bleeding and condensation

Condensation time when volcanic sediments are used as an addition is affected by the replacement rate (or cement amount). Mortars with a constant water-bonding material ratio have accelerated start and end times with the use of volcanic sediments. The experimental results show that the bleeding rate is smaller because of fly ash mixing (**Fig. 9**).

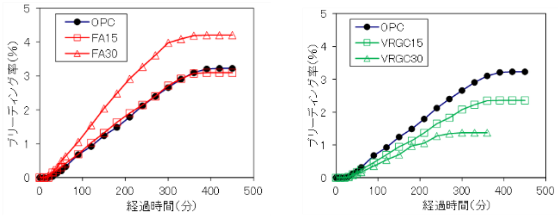


Fig. 9: Bleeding test results

3.2.2 Shrinkage (self-shrinkage and dry shrinkage)

There are few studies that focus on self-shrinkage in concrete that uses volcanic sediments as an addition; however, there are reported cases where volcanic sediments are used as fine aggregates. A study focuses on aggregates with an internal curing effect reported that self-shrinkage decreases to a certain replacement rate.

There is a tendency for the unit water volume to increase when volcanic sediments are used as fine aggregate; there have been reported cases wherein studies were conducted to confirm its impacts. The shrinkage increases slightly when compared to that of Portland concrete; however, it has been indicated that this is attributed to the unit water volume. The pozzolanic reaction progresses with wet curing at long-term material ages, water evaporation decreases, and dry shrinkage strain can be suppressed.

3.2.3 Adiabatic temperature increase / thermal characteristics

The addition of volcanic glass powder in cement as an addition has been reported for reducing the adiabatic temperature increase while ensuring the same compressive strength as that of concrete mixed with fly ash (**Fig. 10**). However, further research is required because there are little data on adiabatic temperature increases and thermal characteristics of concrete using volcanic sediments.

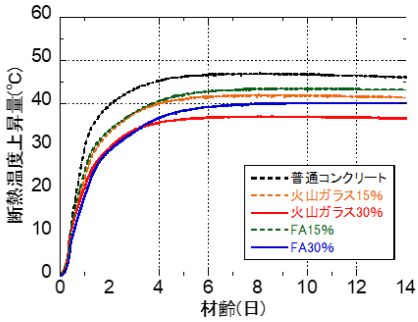


Fig. 10: Adiabatic temperature increase test results

3.3 Characteristics after hardening

3.3.1 Phase composition, void structure, and transition zone

The type of hydrate produced is the same as that of Portland cement even when volcanic sediments are used as an addition; however, it has been confirmed that the amount of calcium hydroxide produced is reduced by the pozzolanic reaction.

The void amount in hardened cement that uses volcanic sediments as an addition decreases with longer material ages; there is a tendency for the average void diameter to shift to a smaller value. Further, reports have indicated that the transition zone thickness decreases and the microhardness of the transition zone increases.

3.3.2 Strength

(1) When volcanic sediments are used as an addition

The specific effects of volcanic sediments differ depending on their chemical composition and physical properties (particle size, etc.).

The compressive strength tends to be higher than that of OPC when the replacement rate is 0–20 (~30)%; however, the compressive strength tends to be lower than that of OPC when the replacement rate is over 30% (**Fig. 11**).

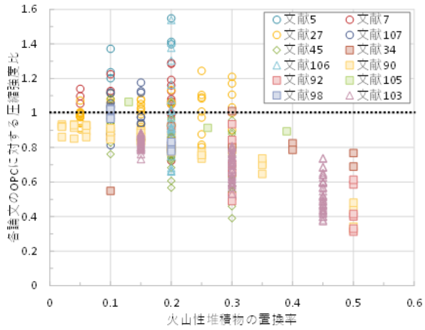


Fig. 11: Replacement rate of volcanic sediments and compressive strength ratio with respect to OPC (comparison by paper)

Furthermore, there are many volcanic sediments with lower strength than that of OPC in the early material age period; however, in the long-term material age period, there tend to be an increasing number of volcanic sediments with higher strength than OPC. Cases where the volcanic sediment particle size is small have a high compressive strength from the early stage; cases where the particle size is large have a good strength expression in the long-term material age period.

(2) When volcanic sediments are used as fine aggregate

Cases where volcanic sediments are used as a fine aggregate tend to have a compressive strength equal to or higher than that of comparative concrete. However, higher average water absorption rates of fine aggregate linearly decrease the compressive strength of mortar; further, the densification of the fine aggregate particles has a significant impact on the compressive strength (**Fig. 12**). The particle size of volcanic sediments impacts the compressive strength even when using the fine aggregate; the compressive strength tended to be higher when using volcanic sediments with a smaller particle size. In addition, the volcanic sediments exhibited better strength than OPC and had higher compressive strength when curing at high temperatures.

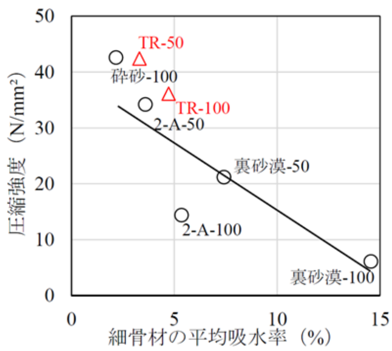


Fig. 12: Average water absorption and compressive strength of fine aggregate

3.3.3 Elastic modulus

(1) When using volcanic sediments as an addition

There are few studies on the elastic modulus of concrete when volcanic sediments are used as an addition. The decrease in the elastic modulus of concrete was less than 5% at a volcanic ash mixing ratio of 20%; there was hardly any effect.

(2) When using volcanic sediments as a fine aggregate

The elastic modulus of concrete using Shirasu as a fine aggregate was approximately 10–15% smaller than that of river sand concrete at the same strength level. This is because Shirasu is porous when used as a fine aggregate, and the elastic modulus of Shirasu is low.

(3) When using volcanic sediments as a coarse aggregate

The elastic modulus of concrete decreases when using volcanic sediments as a coarse aggregate. Replacing 50% of normal coarse aggregate with volcanic sediments results in a decrease of the elastic modulus of concrete by approximately 12%; the elastic modulus was reported to become approximately 45% of that of normal concrete when replacing 100% of the coarse aggregate.

3.3.4 Chloride ion permeability

(1) When using volcanic sediments as an addition

Mixing volcanic glass powder or Shirasu suppressed the penetration of chloride ions into concrete (**Fig. 13**). The apparent diffusion coefficient decreased with an increase in the replacement rate; however, the effect tended to become smaller with the specific surface area decreased.

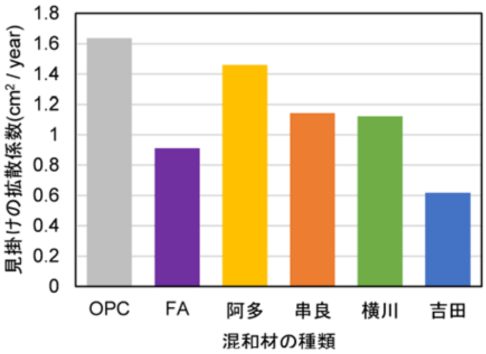


Fig. 13: Apparent diffusion coefficient of chloride ion

(2) When using volcanic sediments as a coarse aggregate

The apparent diffusion coefficient of Shirasu concrete was clearly smaller than concrete that used normal sand, and it was equal to or less than the JSCE standard specification formula; therefore, it was confirmed that the material had high salt-shielding properties.

Cases where the chloride ion permeability was investigated in concrete in which four types of volcanic ash were replaced with a part of fine aggregate showed that the extent of improvement in mass transfer resistance because of the reaction of volcanic ash can be explained by the reaction rate of the volcanic ash used and the amount of fine particles contained.

3.3.5 Neutralization

(1) When using volcanic sediments as an addition

All volcanic glass powder replacement materials had a higher neutralization rate than that of the OPC when the replacement rate was 20% (**Fig. 14**). This was attributed to the decrease in the alkali amount caused by the decrease in cement. The neutralization rate of the volcanic glass powder with a large specific surface area was suppressed when compared to that in volcanic glass powder with a small specific surface area.

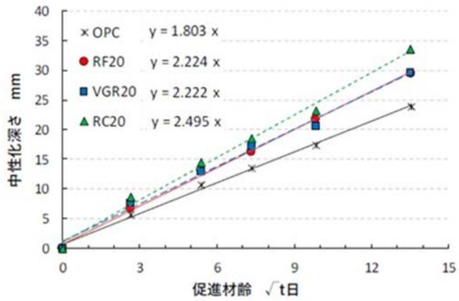


Fig. 14: Results of accelerated neutralization test of OPC and concrete with an addition replacement rate of 20%

A neutralization rate similar to that of OPC was achieved at 5% replacement; however, a neutralization rate similar to that of OPC was achieved even at 10% replacement with eight weeks of underwater curing. These results indicate that resistance to neutralization can be secured to a similar level as that in OPC by ensuring an appropriate replacement rate or number of curing days.

(2) When using volcanic sediments as an aggregate

Cases where the volcanic sediment replaces the part of the aggregate are conducted; the concrete structure becomes denser and the resistance to neutralization improves when the pozzolanic reaction is sufficiently exerted. Further, it is believed that the amount of amorphous material contained in volcanic sediments and its fineness (particle size, specific surface area) are related to the densification of the structure by the pozzolanic reaction of volcanic sediments.

3.3.6 Sulfate resistance and acid resistance

(1) Acid resistance

The results of preparing concrete by replacing the absolute volume of the fine aggregate with four types of volcanic sediment, and the investigated mass loss rate and neutralization depth associated with immersion in sulfuric acid solution showed that the values were equivalent to those in comparative terrestrial sand concrete that did not use volcanic sediments. The differences attributed to volcanic sediments were also unclear.

(2) Sulfate resistance

The dynamic elastic modulus of river sand concrete was higher than that of concrete using Shirasu as a fine aggregate at the initial stage of immersion in an aqueous solution of sodium sulfate. However, the dynamic elastic modulus of river sand concrete significantly decreases with an increase in the age of the immersion material when the W/C is high. Meanwhile, in Shirasu concrete, changes in the dynamic elastic modulus caused by immersion are suppressed regardless of W/C (**Fig. 15**). Further, the use of Shirasu with a small particle size tends to increase the sulfate erosion resistance.

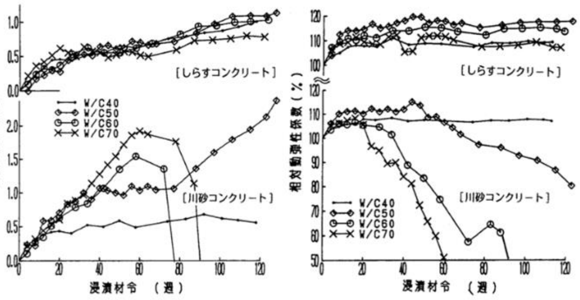


Fig. 15: Changes in mass and kinematic modulus in 10% Na_2SO_4 solution

3.3.7 Freeze–thaw resistance

(1) When using volcanic sediments as a fine aggregate

Concrete in which volcanic ash replacements of 30% of the fine aggregate volume showed an equivalent or higher freeze–thaw resistance to that of base concrete (**Fig. 16**). The fine powder part can result in the densification of the pore structure caused by the filler effect and the pozzolanic reaction at long-term material ages; thus, it contributes to improvements in the freeze–thaw resistance. Further, volcanic sediments that did not undergo classification processing and those that are close to their original sediment state reduce the freeze–thaw resistance to the same extent as that with inferior fine aggregates with high water absorption.

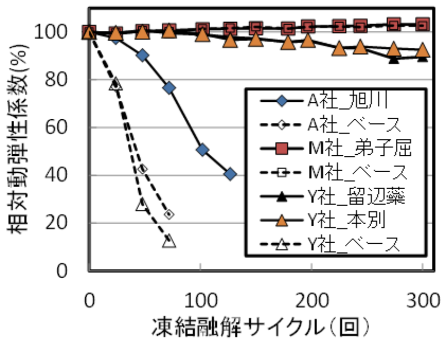


Fig. 16: Results of water freeze–thaw test

(2) When using volcanic sediments as an addition

The results of conducting freeze–thaw tests on concrete with varying replacement rates of natural pozzolan or shale ash for cement indicate that concrete with replacement rates up to 20% had a durability index of 80 or higher; concrete with replacement rates higher than this value had a durability index that was less than 60.

3.3.8 ASR suppression

(1) When using volcanic sediments as an addition

Experiments that used volcanic glass powder with three different fineness levels showed that a 20% replacement of volcanic glass powder in Portland cement was effective for suppressing alkali-silica reactivity regardless of the specific surface area (**Fig. 17**).

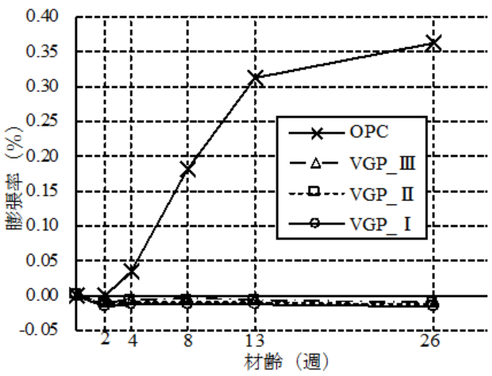


Fig. 17: Test results by mortar bar method

(2) When using volcanic sediments as a fine aggregate

A suppressive effect is observed when using Shirasu as a fine aggregate if the number of fine particles is large. However, the expansion amount may increase in some cases when a generic fine aggregate is mixed.

3.4 Geopolymer

Volcanic ash contains an aluminosilicate glass phase as a constituent substance, and therefore, glass phase can react (dissolve) in a high-temperature, high-alkali environment, which can cause a reaction collectively known as a geopolymer reaction, in addition to hardening.

Several global studies on geopolymers that employ volcanic ash have been conducted; other studies have focused on aspects such as curing temperature, combined use with other mineral admixture, and treatment for increasing the reactivity of volcanic ash.

Many volcanic sediments in Japan are composed of glass with low CaO and MgO content (i.e., low basicity). Therefore, although a geopolymer reaction occurs, its rate is slow, and it progresses at a very slow rate.

4. Conclusions

We summarized the results of the activities of the committee over a three-year period. ”Slow reactivity” and “decreased fluidity” are cited as issues when using volcanic sediments in concrete. However, the specific impacts of these issues are dependent on individual physical and chemical properties, and it is difficult to quantitatively summarize volcanic sediments as a whole. This is because of the limited number of studies that compare multiple types of volcanic sediments. This limited number of studies can be attributed to the use of volcanic sediments being premised on local production for local consumption, variations in the objective of utilizing volcanic sediments depending from the effective utilization of resources to improvements in concrete quality, and diverse materials being used together.

In March 2020, JIS A 6209 ("Volcanic glass powder for use in concrete") was published to achieve the effective utilization of natural resources and higher performance of concrete via local production for local consumption. Even with just Ito Shirasu in southern Kyushu, the production was approximately 75 billion m^3, which is approximately 9,000 times the annual by-product of the blast furnace slag. Therefore, the effective utilization of volcanic sediments in concrete is worth considering when aiming to realize a resource-recycling and carbon-free society. We hope that this report will help towards realizing such efforts.

References

1) Kimura, K.: Study on the production of heated foam from volcanic vitreous deposits, Tokyo Institute of Technology Thesis, 1984

2) Database on properties and uses of volcanic glass http://www.kumin.ne.jp/vsi/vglass/ (last viewed: April 2, 2022)

3) Sodeyama, K.: Total utilization of Shirasu as construction materials through dry gravity classification and pulverization, Journal of the Society of Materials Science, Japan, Vol. 66, No. 8, pp. 574-581, 2017

4) Tomoyose, A., Noguchi, T., Sodeyama, K., and Higashi, K.: Basic characteristics of concrete that uses fine volcanic glass powder for use in concrete, Proceedings of the Japan Concrete Institute, Vol. 40, No. 1, pp. 255-260, 2018

5) Yoshida, S., Taguchi, F., Taniguchi, M., Kakihara, Y., Takahashi, T., and Akiyama, M.: Reactivity of volcanic ash and characteristics of concrete using volcanic ash, Monthly Report, Civil Engineering Research Institute for Cold Region, No. 729, pp. 10-24, 2014

6) Takewaka, K.: State-of-the-art-report on characteristics of SHIRASU concrete and its practical use, Proceedings of the Japan Concrete Institute, Vol. 12, No. 3, pp. 38-47, 2004

7) Ueno, A.: Influence of fine aggregate properties on judgment of saturated surface dry conditions, Concrete Journal, Vol. 51, No. 12, pp. 967-974, 2013