Technical Report

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Explanation about the Development Process, Several Unique Characteristics and Application Examples on Steel Slag Hydrated Matrix (SSHM)

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Abstract

Steel slag hydrated matrix (SSHM) is a new technology that has been developed to enable the use of steelmaking slag as a substitute for non-reinforced concrete and artificial stone. Formerly, in the field of concrete and other hydrated matrixes, the use of steelmaking slag as an aggregate for the hydrated matrix was prohibited because its expansion can hardly be evaluated accurately. In order to avoid the influence of inaccuracies in expansion measurements and to enable the use of steelmaking slag for the steel slag hydrated matrix, a technical manual that clarifies quality standards for steelmaking slag and provides a manufacturing procedure and relevant instructions has been recently approved by a public organization. In this paper, we shall explain the technical points and quality characteristics that have led to the official approval mentioned above and present examples of application of steel slag hydrated matrix to actual structures and facilities by evaluating various types of applications.

1. Introduction

Usage of steel slag, one of iron and steel slag, has been limited on the account of its variation in quality caused by differences in various steel making processes, expansion due to hydration of free lime (f-CaO) and free magnesium (f-MgO), elution of water of high alkalinity and so on. Therefore, it has been primarily used for relatively low-grade materials such as road bed of temporal, refilling material. Particularly in recent years, as needs of observance of compliance is socially growing stronger, use of steel slag in land civil engineering works without covering has become increasingly difficult, and therefore, the development of the usage of steel slag in new areas has been sought.

The steel slag hydrated solidified body (hereafter called as steel slag hydrated matrix or SSHM) has been developed as a new technology for using steel slag under such situation and was officially approved by the Coastal Development Institute of Technology in the form of “Technical Manual for Steel Slag Hydrated Matrix Technology” in 2003. Later in 2008, revised issue incorporating improved technologies was published. Furthermore, in 2007, “Artificial stone material of Flontier Stone and Flontier Rock made of iron and steel slag hydrated matrix” obtained technical certification as a result of confirmation examination and assessment of the technology from a private sector related to ports and harbors. Actual performance of construction work wherein the material was used was assessed and, in 2009, the technology received “Award of Excellence for National Land Development Technology” cited by the Minister of Land, Infrastructure and Transport.

In this paper, the outline of hydrated solidified body (hereafter called as hydrated matrix) technology and technical points for the acquisition of official approval, and latest example in the respective field of application are introduced.

2. Outline of Hydrated Matrix

2.1 Outline of technology

Hydrated matrix is an alternate technology for conventional concrete and is a recycled material utilization technology using blast

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Table 1 Type of Hydrated Matrix

Type		Aggregate	Main binder	Alkaline activator	
				Material	Range of mixing ratio
Type I	A	Steel slag 100 wt%	Fine-powdered blast furnace slag	Slaked lime or lime dust and so on	Not specified (However, effect of slaked lime as alkaline activator ceases to increase above the mixing ratio of 20 wt% with respect to total weight of slaked lime and fine-powdered blast furnace slag.)
	B	Steel slag 50 wt% to less than 100 wt%			
Type II	A	Steel slag 100 wt%	Fine-powdered blast furnace slag	Conventional Portland cement or other kinds of cement	Mixing ratio of Portland cement with respect to total weight of fine-powdered blast furnace slag and Portland cement should be less than 70 wt%.

furnace fine powder slag, steel slag, and water as indispensable materials. Amorphous materials having high vitrification rate represented by blast furnace water-granulated slag (hereafter referred to as water-granulated slag) are known for having latent hydraulicity. This is the characteristic of hydration of water-granulated slag developed by proper alkaline activation and added water, and when finely crushed water-granulated slag is used, the material exhibits self-solidifying characteristics like cement.

Hydrated matrix is made to have the function of the aggregate of concrete (coarse aggregate, fine aggregate), while ground water-granulated blast furnace fine powdered slag is made to function as cement, and steel slag is made to function as alkaline activator. In case of weak alkalinity of steel slag, cement or slaked lime and so on is added as necessary as an alkaline activator. Furthermore, in case the particle size distribution of steel slag is inappropriate and undesirable workability at the completion of kneading is developed, the properties are improved by adding water-granulated slag and/or fly ash (hereafter called as FA).

As **Table 1** shows; hydrated matrix is classified to Type I and Type II mainly depending on the kind of alkaline activator and further classified to A and B under Type I and Type II depending on the ratio of steel slag in aggregate, wherein Type I-A has the highest usage ratio of recycled material. Furthermore, sometime Type II is further classified to Type II-2 and Type II-2 depending on the ratio of Portland cement as one of the activators.

2.2 Subjects and solution measures in acquiring official approval

In the field of concrete, triggered by the problem of expansion cracks that appeared in structures caused by the use of aggregate having reactivity like alkaline aggregate reaction, use of a material having expansibility for aggregate has been strictly prohibited. Therefore, the method of using steel slag that contains in itself hydration-expansion-causing ingredients, such as f-CaO and f-MgO, could hardly find its way to the stage of official approval. However, owing to thorough implementation of classification control on the part of manufacturers, slag came to be partly recognized as aggregate and electric furnace oxidized slag, and the like have acquired JIS certification. Furthermore, as a solidified body (hereafter called as matrix) using recycled materials, other technologies of FS concrete[1)] and NA Crete,[2)] which utilize steel slag in part, have been disclosed.

Since the selection of steel slag appropriate for hydrated matrix completely free of expansion-causing ingredients is practically impossible, determining the quality standard of the applicable steel slag was crucial. The expansion characteristics of steel slag are in general assessed with the expansion rate after water-immersion as specified in Appendix 2 of JIS A 5015. This is widely used as the method of assessing the average expansion rate that steel slag has.

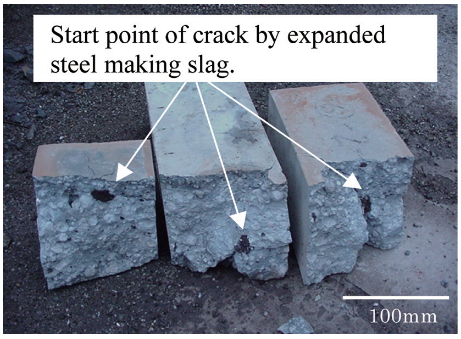

Photo 1 Typical expansion clack by steel making slag

However, in a hydrated matrix, a hydrated matrix exists on the surface of a steel slag particle and since it has high strength and is constrained to a great degree. There is a possibility that expansion of a particle may induce a crack that develops to a fracture. **Photo 1** shows the fracture surface of a section of a test sample of a hydrated matrix wherein it is observed that the expansion crack caused by a particle of steel slag initiated the entire crack.

From this, to acquire the official approval of hydrated matrix, it has become absolutely essential to establish a method that enables the detection of expansion characteristics of steel slag particles. The following were listed as requirements that the method should comply with:

(1) In order for the entire slag be appropriately assessed, a certain amount of sample sufficient enough for the assessment can be secured.
(2) In order for the employed test method be used widely, the test method should be practiced without using any special apparatus for assessment process.

An assessment method was worked out by compiling the analytical result of expansion fracture of a steel slag particle. Based on the findings as shown below, a steel slag quality standard defined by indices of "Powdering rate" and "MgO content" was settled.

(a) Steel slag particles suspected of expansion develop self-cracking during the expansion process, resulting in change in the particle size distribution. This means that by quantifying the amount of fine particles produced under an accelerating condition (powdering rate), the rate of slag particles that imply the possibility of causing expansion crack can be assessed (**Fig. 1**).
(b) Powdering rate depending on f-CaO can be assessed by continuously immersing test samples in water at 80°C for 10 days. This condition is considered to be an accelerating condition that signifies the servicing for 50 years or longer, and considered to be practically applicable.
(c) Crack rate depending on f-MgO that requires long expansion

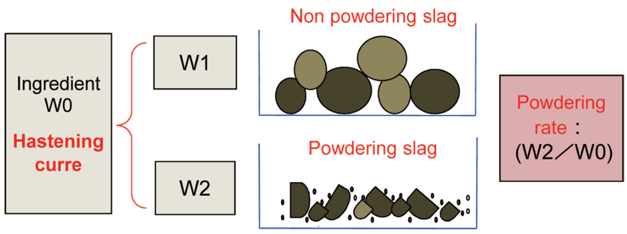

Fig. 1 Concept of powdering rate

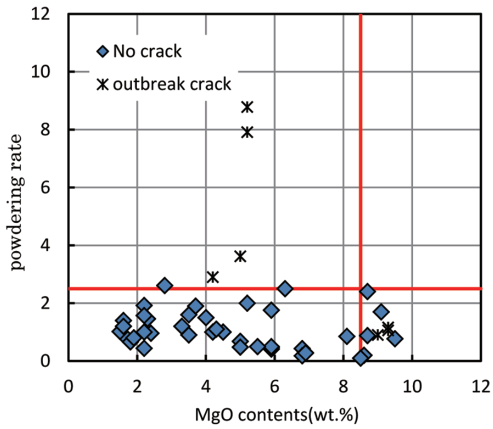

Fig. 2 Quality reference of steel making slag for steel slag hydrated matrix (SSHM)

time do not converge readily under the condition of being immerged in water at 80°C for 10 days, and therefore, assessment with an autoclave becomes necessary. However, in case of steel slag that contains MgO at above certain content level, assessment with hot water method is possible.

Based on these findings, the expansion stability of steel slag hydrated matrixes having varied powdering rates and MgO contents was assessed using the hot-water-immersion method, and as **Fig. 2** shows, it was found that use of steel slag with "powdering rate of 2.5% or less" and "MgO content of 8.5% or less" can save the problem of expansion crack. This condition was employed as the quality standard.

2.3 Method of designing mixing ratio

Designing of mixing ratios of a hydrated matrix is started at defining required strength index based on the relation between strength index and compressive strength, as shown in **Fig. 3**, after determining the aimed strength required for the usage. Strength index is expressed by an experimentally deprived equation of the first order with respect to the compressive strength, as expressed by equation (1). It has been deprived from the test results conducted for hydrated matrixes having varied materials and mixing ratios.

$$\text{Strength index} = \frac{BP + CH + 2NP + 0.35FA}{W} \qquad (1)$$

where;

BP: Mixed amount of fine powdered blast furnace slag (kg/m^3)

CH: Mixed amount of alkaline activator (kg/m^3)

NP: Mixed amount of conventional Portland cement (kg/m^3)

FA: Mixed amount of fly ash (kg/m^3)

W: Unit quantity of water (kg/m^3)

After setting the strength index, like the case of concrete, mixing ratios are determined after confirming by mixing test the unit quantity of water required for obtaining aimed slump and the amount of chemical admixture required for obtaining aimed workability.

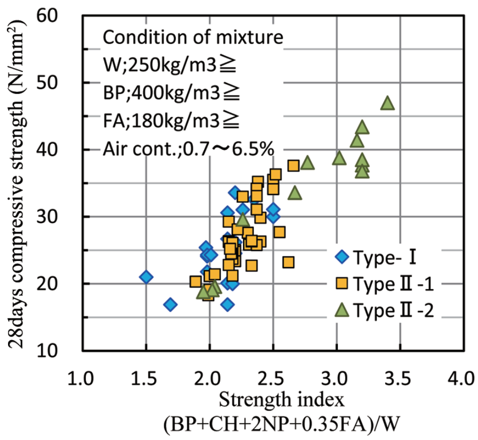

Fig. 3 Relationship between strength index and compressive strength

2.4 Various characteristics

2.4.1 Dynamics characteristics

Emergence of strength of a hydrated matrix tends to be slower than conventional concrete, and attention is needed when the strength of a young material age of within 3 days is sought. Past studies show that Type I is superior in emergence of strength under low temperature [3] and that the bending strength and the tensile strength are higher than those of conventional concrete having equivalent compressive strength. Furthermore, Young's modulus is slightly lower than that of conventional concrete having equivalent strength.[4]

2.4.2 Durability

(1) Adiabatic temperature rise characteristics

The adiabatic temperature rise characteristics that develop hydration heat cracking are expressed, for example, by the equation (2) of Concrete Standard Specifications published by the Japan Society of Civil Engineers.

$$Q(t) = Q_\infty (1 - e^{-rt}) \qquad (2)$$

where,

$Q(t)$: adiabatic temperature rise (°C) at material age of tth (day)

Q_∞: adiabatic temperature rise (°C) at the termination of temperature rise

r: a constant related to the rate of temperature rise

Among them, as for Q_∞ and r, results as shown in **Fig. 4** and **Fig. 5** have been obtained as to hydrated matrixes. It is found that the temperature rise of hydrated matrixes is lower and the rate of temperature rise using the current method is lower than that of concrete using blast furnace cement.

(2) Characteristics of drying shrinkage

It is shown that the amount of drying contraction of hydrated matrixes is 150–350 μm at the approximate material age of 100 days, which is about half of that of conventional concrete mixed with equivalent unit amount of water,[5] and the hydrated matrix is excellent in characteristics of drying contraction. However, there are cases wherein drying exerts big influence to strength and a report says that the bending strength of a hydrated matrix affected by drying will drop to about 56% when dried to the absolute dry state.[5]

(3) Freezing and thawing characteristics

Freezing and thawing characteristics of a hydrated matrix is secured like conventional concrete if it contains entrained air of above certain level. **Figure 6** shows the result of the freezing and thawing

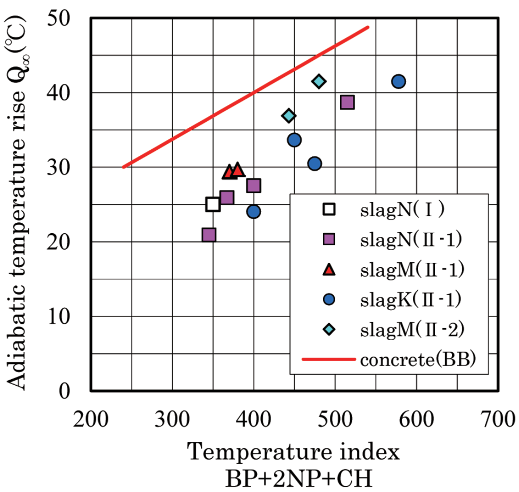

Fig. 4 Adiabatic temperature rise on SSHM

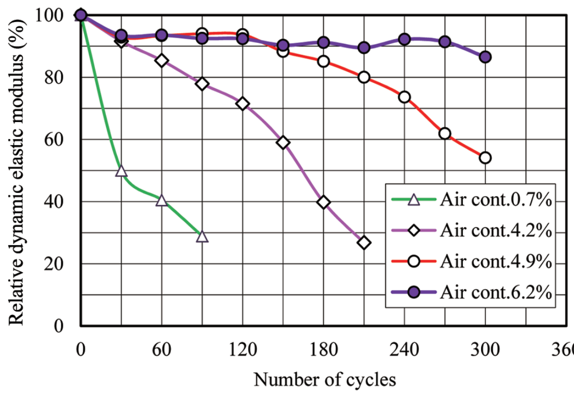

Fig. 6 Performance of freezing and thawing test on vary air volume condition

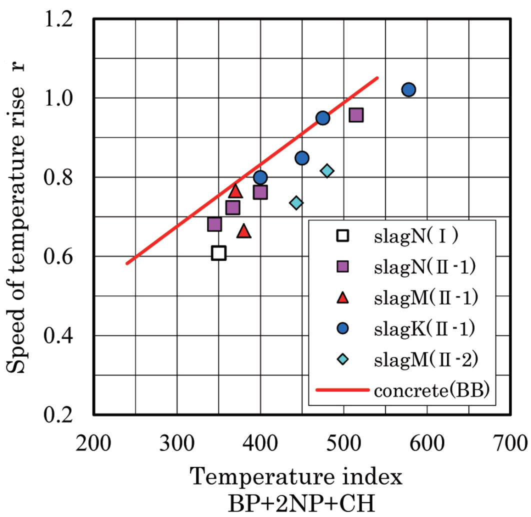

Fig. 5 Speed of temperature rise on SSHM

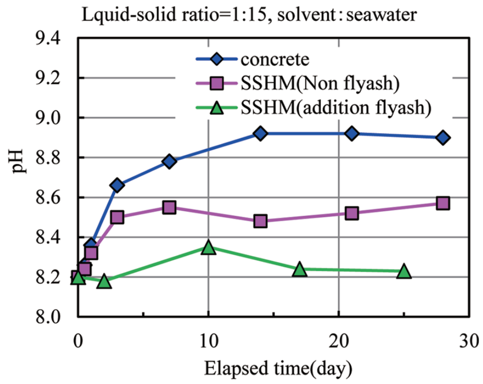

Fig. 7 Alkalinity of SSHM in seawater [6]

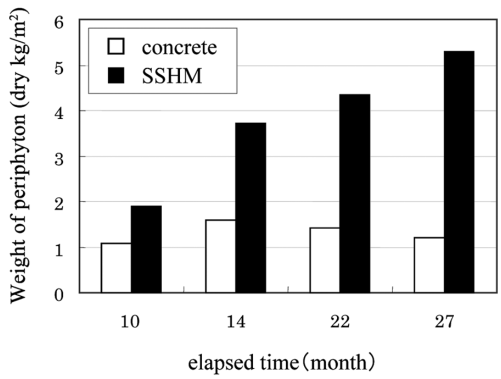

Fig. 8 Performance of biofouling to SSHM [6]

test conducted for hydrated matrixes having different air contents. It is known that the larger the air content is, the larger the relative dynamic elastic module becomes. Therefore, the larger the resistance to freezing and thawing becomes. Yet, in many cases, the surface layer of steel slag is porous with high rate of water absorption and the required air content must be secured after air content corresponding to the aggregate correction factor is subtracted from the entire air content. Since strength gradually decreases as air content increases, higher standard design strength is required.

2.4.3 Environmental characteristics

(1) Alkali elution characteristics

As an example of alkali elution characteristics of a hydrated matrix, the result of an investigation conducted on the change in the seawater pH having a volume of 15 times that of test sample volume is shown in **Fig. 7** [6]. From this, it is found that the pH dependent on elution of hydrated matrices is smaller than that of concrete, and furthermore, it is made smaller by adding fly ash. From this, it is assessed that the extent of alkali elution of hydrated matrixes is smaller than that of concrete.

(2) Biofouling performance

Since a material rich in mineral ingredients such as silicone and iron is used for a hydrated matrix, it exhibits higher amount of periphyton of seaweeds. **Figure 8** [6] shows a result of an investigation on the amount of periphyton of seaweeds on blocks made from a hydrated matrix and conventional concrete installed in the range of tidal ebb and flow, and observed after the elapse of certain time. The amount of periphyton increases as time elapses.

(3) Amount of emission of CO_2

A hydrated matrix scarcely uses cement as material. In the production process of cement, a great amount of CO_2 is emitted when quicklime (CaO) is made of lime ($CaCO_3$). Accordingly, a hydrated matrix which scarcely uses cement is a material that emits small amount of CO_2. **Figure 9** shows a result of model calculation of amount of emission of CO_2. It is possible to reduce the amount of emission of CO_2 by 76% and by 60% as compared with concrete using conventional Portland cement and concrete using blast furnace cement, respectively.

3. Examples of Application of Hydrated Matrixes

3.1 Application to non-reinforced concrete block as alternate material

For example, hydrated matrixes are used as alternate material to non-reinforced concrete blocks, such as wave-dissipating blocks, covering blocks, and fish reef blocks. Here, an example of application to large wave dissipating blocks is introduced.

The subject block is a wave-dissipating block of 80-t type, which is the largest one in Japan. In practice, it was a massive concrete structure and, as construction was conducted in winter, attention was paid to thermal cracking caused by hydration heat. Actual mixing ratios are shown in **Table 2**. By lessening the unit water quantity to the extent possible using high performance water reducing agent as admixture and by reducing the amounts of the entire binders and the cement as an alkaline activator, mixing ratios to suppress hydration heat was arranged. In the construction process, as shown in **Fig. 10**, a thermocouple was inserted inside and the temperature change was measured since the beginning of construction. Furthermore, emergence of strength, including the one of a young age material, was confirmed and was based on the aforementioned adiabatic temperature rise characteristics of hydrated matrixes; the measured temperature rise was reproduced using thermal conduction analysis.

The result of temperature analysis is shown in **Fig. 11**. Analytic values show relatively good agreement with measured values. Furthermore, based on the result of thermal conduction analysis and strength emergence data, thermal stress analysis was conducted, and the stress distribution (**Fig. 12**) and the chronological change of thermal cracking index were sought (**Fig. 13**). The material with mixing ratios of N-1 exhibits thermal cracking index of higher than 1.5, although it is dependent on strength emergence model. Cracking was not observed in the actual block.

3.2 Application to artificial stone

3.2.1 Usage as reclamation material (Flontier Stone)

The construction work schedule of Runway D of the Haneda Airport was tight, and as the schedule for ground improvement after reclamation was not made available, following performances were required to be achieved by simply throwing them into construction sea waters.

(a) To be not liquefied by earthquake (water permeability index ≥3 cm/s)
(b) Design strength to be secured (shearing resistance angle ≥35°)
(c) No subsidence to be developed (secondary compression index ≤0.02%)

As the method to satisfy the requirements, the idea of controlling

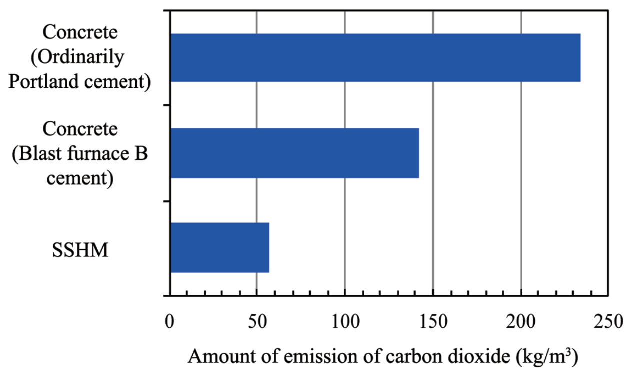

Fig. 9 Amount of emission of carbon dioxide on concrete and SSHM

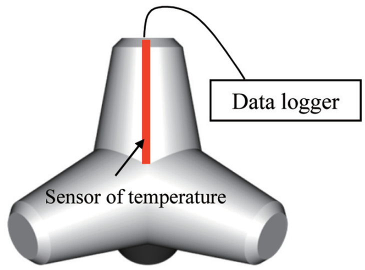

Fig. 10 Measurement position of internal temperature

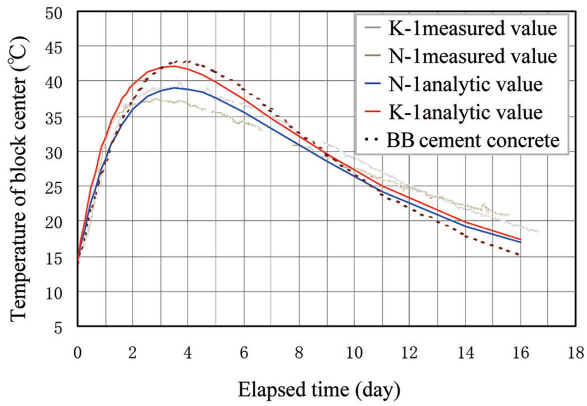

Fig. 11 Comparison of internal temperature by analytic value and measured value

Table 2 Combination example of SSHM on large wave extinguish block

Mark of combination	Classification	Maximum size of steel-making slag (mm)	Strength index (BP + 2NP + CH + 0.35FA) / W	Slump (cm)	Air content (%)	Unit weight (kg/m³) Service water W	Ground granulated blastfurnace powder BP	Alkaline activator (Portland cement) NP	Fly ash FA	Steel making slag (1) SS1	Steel making slag (2) SS2	Water deducing admixture AD1
K-1	II-A	20	2.59	12 ± 2.5	2.0 ± 1.5	174	297	53	134	1999		2.94
N-1	II-A	25	2.18	10 ± 2.5	2.0 ± 1.5	186	259	48	144		1852	2.18

particle size distribution to a certain range was taken up, and particle size distribution range, as shown in **Table 3**, was set up as standard.

Flontier Stone was produced based on the above particle size distribution control standard and approximately one million tons are used mainly for the temporary partition weir in actual construction work, as shown in **Fig. 14**.

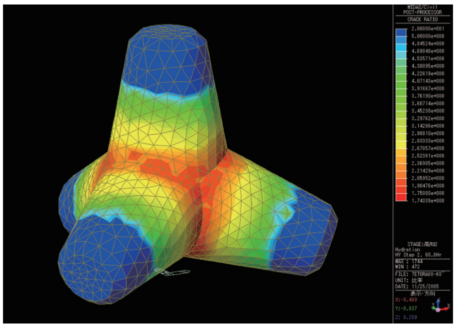

Fig. 12 Result of temperature stress analysis

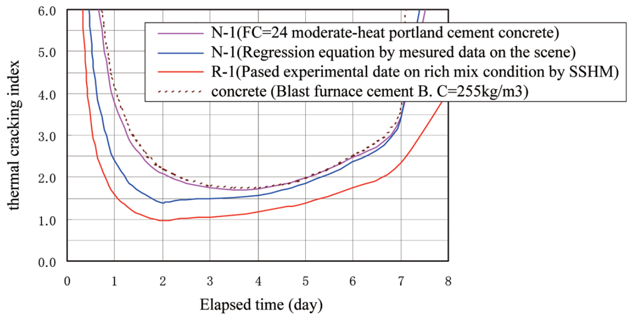

Fig. 13 Change of the time of thermal cracking index

Table 3 Quality target of Flontier Stone for Runway D of Haneda Airport

Quality requirements	Background of quality control item and concept of control value	Control value
Liquefaction not to be caused	Liquefaction depends on the permeability coefficient. Susceptible to fine particles. Assessed with D10 (a particle size which provides under size of 10%).	D10 ≥ 1 mm
Strength to be secured	Strength depends on the extent of self-meshing properties of particles. Strength increases as particle size distribution range becomes lager. Assessed with U_c (coefficient of uniformity) that defines particle distribution range.	Uc ≥ 5
Subsidence to be prevented	Wider range of particle size distribution is more advantageous than the distribution of particles of a single size as subsidence increases when inter-particle cavity becomes larger. Minimum allowable value of U_C denoting particle size distribution is worked out.	Uc ≥ 5

3.2.2 Utilization for river bank protection and as blanket stone of breakwater (Flontier Rock)

Flontier Rock was used for river bank protection, as examples, in Nakagawa and Sumidagawa in Tokyo. In both cases, Flontier Rock was used for the consolidation of the foundation of bank protection, and about 1 600 m³ was used in Nakagawa and 4 200 m³ was used in Sumidagawa (**Photo 2**). **Figure 15** and **Fig. 16** show the sections where it is used. Quality standard of strength and density of the material was 24 N/mm² or above and 2.5 t/m³ or above, respectively, and all satisfied the quality standard. In **Photo 3**, view of shipping of Flontier Rock is shown, and in **Photo 4**, the view of throwing of Flontier Rock is shown. Change in pH before and after throwing was confirmed, and it was found that pH increased by about 0.3 right after throwing but regained previous value several minutes after throwing and no change was observed afterwards.

On the other hand, as an example of application to breakwaters, following case is introduced: the material is used for the breakwater at the bay-mouth of Kamaishi Harbor, the work being under way as a reconstruction project for the Earthquake. The material is used at the foundation stone section, as shown in **Fig. 17**, and Flontier Rock

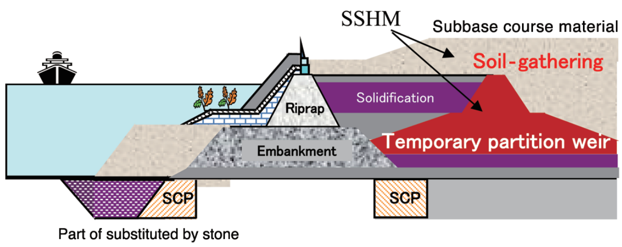

Fig. 14 Application of "Flontier Stone" to "D Runway" of Haneda Airport

Photo 2 View of reclamation work by "Flontier Stone"

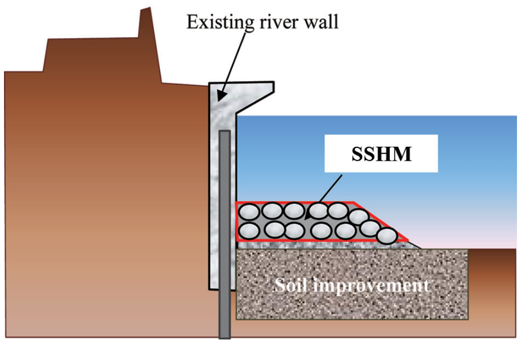

Fig. 15 Application of "Flontier Stone" in river Nakagawa

of about 70 thousand tons has already been used in the form of covering stone of 800 kg–1 t, a piece in the section where construction work has already been completed.

3.3 Application to material with underwater anti-washout performance [7)]

For the utilization of a hydrated matrix, in almost all construction works, products were produced on land and then installed underwater; however, in the reclamation works on the Nagoya public waters, a hydrated matrix that is poured to underwater on site is used as an alternate material for concrete with underwater anti-washout performance. In **Fig. 18** [7)], the section drawing of the construction work is shown. The material is used as leveling material for a pre-cast box culvert and as gap-filling material for the gap between the existing bank protection wall and the box culvert. To prevent separation underwater, thickener is added, and together with the high performance water reducing agent, self-filling properties and resistance to separation are secured (**Photo 5** [7)]). Mixing ratios are shown in **Table 4**. It was confirmed that the mixing-ratio-designing concept almost same with that of concrete with underwater anti-washout performance is applicable. Views of construction work are shown in **Photos 6** [7)], **7** [7)]. Muddy water scarcely occurred when pouring. Furthermore, rise in pH in its periphery during the implementation of the work was slight and the work was completed without any problems.

4. Conclusion

In the above, history of authorization, properties, and examples of recent applications of hydrated matrixes were stated. Since it is a material not widely circulated, it is true that there are still a number

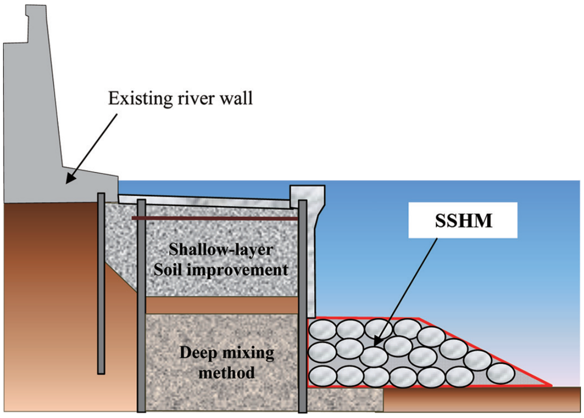

Fig. 16 Part of used of "Flontier Rock" for river wall of Sumidagawa

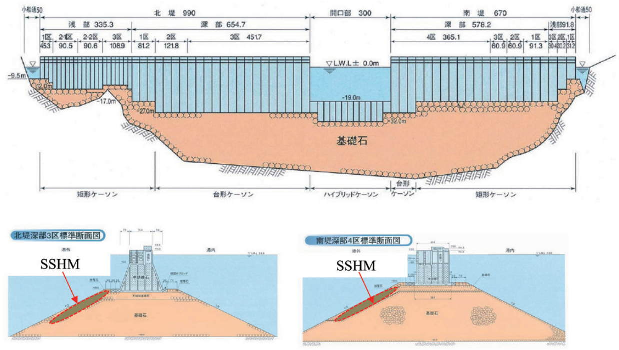

Fig. 17 Part of used of "Flontier Rock" for breakwater of Kamaishi Port

Photo 3 View of shipping "Flontier Rock"

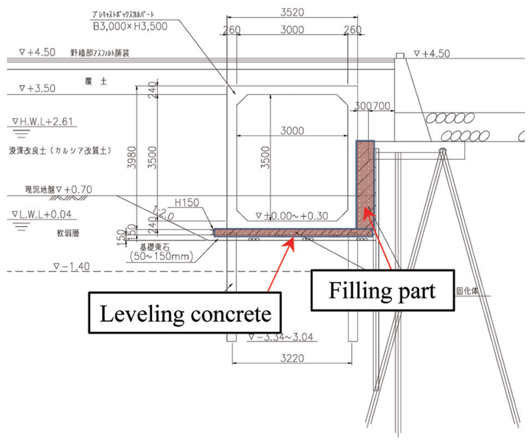

Fig. 18 Execusion part of anti-washout under water by SSHM [7)]

Photo 4 View of throwing "Flontier Rock"

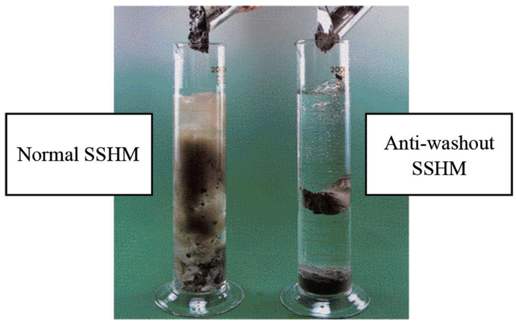

Photo 5 View of anti-washout under water [7)]

Table 4 Combination of SSHM with anti-washout performance

Case	Strength index	Alkaline activator ratio (%)	Sand-coarse aggregate ratio (%)	Unit weight (kg/m^3): Service water W	Unit weight (kg/m^3): Ground granulated blast-furnace powder BP	Unit weight (kg/m^3): Portland blast-furnace cement B BB	Unit weight (kg/m^3): Steel making slag coarse aggregate SS	Unit weight (kg/m^3): Steel making slag fine aggregate SG	Anti-wash-out admixture (W×%)	Air-entraning and highrange water reducing admixture (C×%)
1.8–15	1.8	15	45	45	275	109	812	1031	1.125	2.0

Photo 6 View of leveling concrete by anti-washout SSHM [7]

Photo 7 View of filling part by anti-washout SSHM [7]

of issues that need to be addressed in order for hydrated matrixes to be comprehensively used. However, since it has high density and is excellent in stability to waves and the reinforcing bar not readily becoming rusty owing to the anode sacrifice action of iron existing in the slag and owing to small drying contraction and cracking due to contraction hardly occurring, it is expected that the application will be expanded hereafter particularly in the area of harbor facilities. It is considered that it will be an effective technology for exploiting hard-to-sell slag like powdered slag.

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