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Development of "KATAMA™ SP (special)", An Environmentally Friendly and Instant Available Road Bed Materials

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Abstract

Having latent hydraulic property, blast furnace and steel making slags have been used as road bed materials. However, their strength is not enough for paving without asphalt cover. We blended blast furnace and steel making slags with or without other additives to prepare a series of new pavement materials that develops sufficient strength for paving simply by compaction with water. We also explored the mechanism of hardening. The products were successfully put on the market under the trade name of "KATAMA™ SP (special)" and they are gaining popularity. Several test constructions showed that the pavement is no risk to the environments with regard to spewing highly alkaline water.

1. Introduction

Steelmaking slag is a composite material composed mainly of calcium oxide, calcium silicate, iron oxide (II), and alumina. Owing to its high density and strength, steelmaking slag is widely used as a substitute for crushed stone and as a subbase course material. In addition, granulated blast furnace slag (hereafter called "granulated slag") and steelmaking slag have latent hydraulic properties and can be used in combination to form a strong subbase course.

Steelmaking slag alone has a modest hydraulic property to develop strength. It is well-known that when steelmaking slag, a strong alkali, is mixed with granulated slag, it stimulates the granulated slag having higher hydraulic property and produces a hydrate. This hydrate imparts considerably high strength to the mixture as a 'simple pavement material.' However, this mixture has not been used widely as a pavement material because of the unstable development of desired strength. Moreover, the complete mechanisms of solidification and strength development are not known. Furthermore, uncovered steelmaking slag as a pavement material can cause serious damage to the environment, especially, if there is groundwater flow close to the pavement because the surface and seepage rainwater react to form a strong alkali.

Under these conditions, Nippon Steel & Sumitomo Metal Corporation started the development of a new product in 2008, the mixture of steelmaking slag and granulated slag that only requires compaction with water to develop the desired strength and stability. The company has successfully developed and launched a new pavement material under the trade name of KATAMA™ [*1] SP (special). The new product has made it possible to significantly reduce the risk of seepage of highly alkaline water.

In the following sections, we will describe the salient characteristics and hardening mechanism of this new product and discuss its effects on the environment.

2. Development of KATAMA™ SP

2.1 Aim of development

The materials that have been most commonly used for road pavements are high-grade concrete, asphalt, etc. which are manufactured using large amounts of energy. For roads with little traffic, sidewalks, and administrative roads, which do not require very high strength materials, simple pavement materials that are inexpensive and can be easily handled are required.

On vacant grounds of expressways and railways, relatively costly pavement materials, such as concrete, asphalt, and soil-based ma-

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terial,[1] are used for weed prevention or plastic sheets are used for mulching. On parking lots, where such costly materials are not used, crushed stone is spread over the ground to prevent it from becoming muddy during rains. In this case, however, the ground surface is naturally made unsmooth. Moreover, if weeds grow thick there, they cannot easily be eradicated. Therefore, inexpensive pavement materials that can easily be handled are required (**Fig. 1**).

Under these conditions, the authors developed a new product, a mixture of steelmaking slag, a highly alkaline and granulated slag, which tends to solidify when stimulated by an alkali (latent hydraulic property).

2.2 Optimum blending design

Let us first blend steelmaking slag and granulated slag, which have been subjected to a certain process and then evaluate the strength of the mixture as a subbase course material following JIS A 1211. Then, it can be seen from **Fig. 2** that there is an optimum blinding ratio. The proportion of granulated slag having a strong hydraulic property must be neither too large nor too small. In addition to the development of strength by hydraulic property, an optimum particle size distribution that allows the close packing of particles to develop strength is required. When the proportion of fine granulated slag with uniform particle size is large, it does not develop sufficient strength. In the latter case, a certain proportion of aggregate of steelmaking slag with large particles is considered necessary.

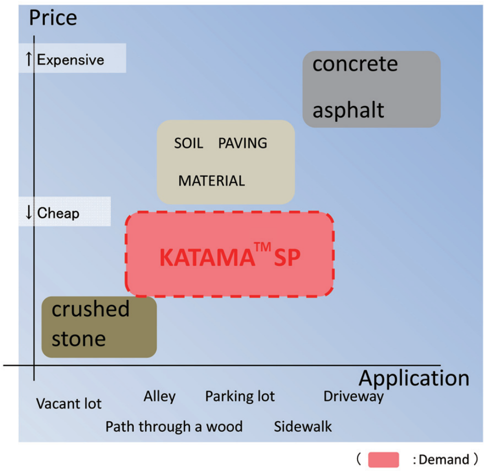


Fig. 1 Concept of the new material

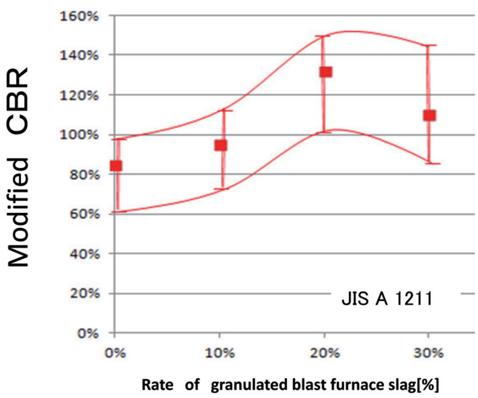


Fig. 2 Typical relationship between modified CBR and the rate of granulated blast furnace slag

On the other hand, it can be reasonably said that the steelmaking slag and granulated slag produced at Nippon Steel & Sumitomo Metal differ in particle size, composition, basicity, alkalinity, etc. from one steelworks to another, and that the strength developed by them also differs accordingly. Therefore, with the aim of securing a certain level of quality, the authors set a strength target (quality standards) and conducted an optimum blending design for each of the steelworks.

First, the authors examined the dynamic stability of a pavement by a wheel tracking test and the dynamic elastic coefficient of a pavement by a twist aggregate dispersion test (**Photos 1** and **2**). It was found that they have a strong correlation with the unconfined compression strength, as shown in **Figs. 3** and **4**. Therefore, it was decided to adopt the unconfined compression strength as an index of strength for simple pavement materials.

In addition, as shown in **Table 1**, we specified the value of modified California bearing ratio (CBR) required in subbase course design and the value of soil hardness index (obtained with the Yama-

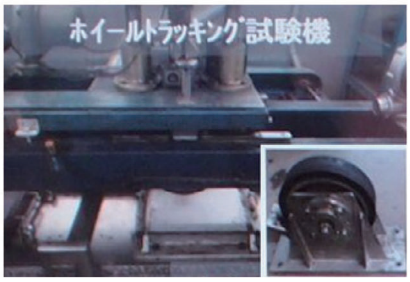


Photo 1 Schematic overview of tracking test

Photo 2 Schematic overview of twist aggregate test

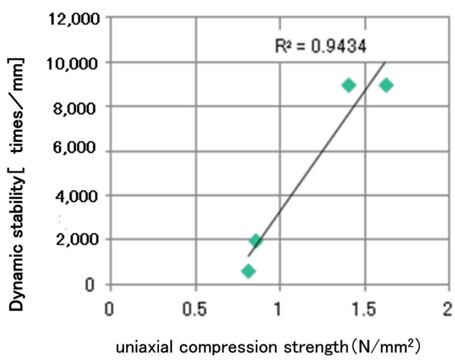


Fig. 3 Relationship between dynamic stability and uniaxial compression strength (twist aggregate test)

naka hardness tester)[2] used as an index of weed preventive performance of soil-based pavement. Then, for the company to be able to sell our new product that develops the desired strength, the individual steelworks carried out optimum blending design and established their own manufacturing setup. Consequently, it has become possible for many of the company's steelworks to prepare the new product as shown in **Fig. 5**.

To establish the abovementioned quality standards, we performed a series of simple pavement tests on the parking lots and vacant grounds of the company's steelworks using different blending designs and different types of heavy machinery with varying degree of soil compaction and the method of water sprinkling, as described in 2.3. The condition of ruts made by vehicles and the growth of weeds at the test sites was confirmed by these tests. The quality standards include manufacturing indexes of KATAMA™ SP.

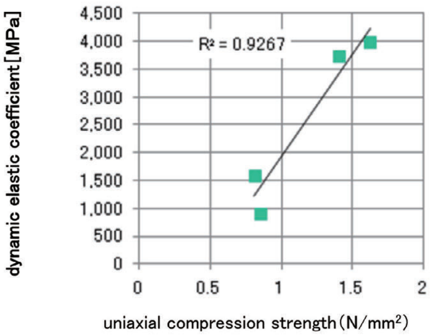


Fig. 4 Relationship between dynamic elastic coefficient and uniaxial compression strength (twist aggregate test)

Table 1 Quality standards of the strength of KATAMA™ SP

		KATAMA™ SP
Unconfined compression strength	N/mm²	>1. 2 (age on the 14th)
Modified CBR	%	>80
Hardness Index (with Yamanaka method)	mm	>30

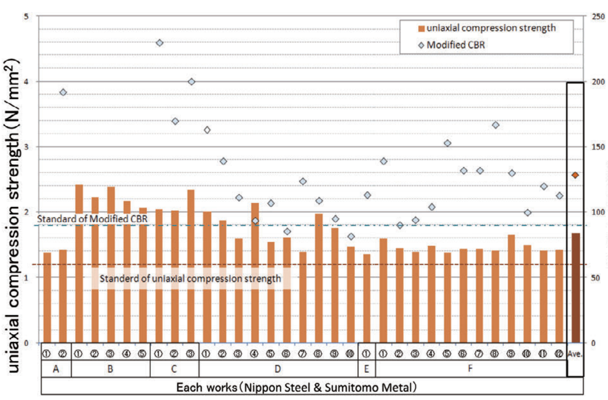


Fig. 5 Strength in each iron mill

2.3 Development of technology for work execution

The strength of a simple pavement obtained differs depending on how the pavement material is prepared and processed or how the pavement work is executed. In general, it is necessary that the pavement material should be inexpensive and the execution of pavement work should be easy. As can be seen from **Fig. 6**, the strength of KATAMA™ SP manufactured using a certain blending ratio correlates with its dry density. Thus, as in the case of subbase course materials, it is possible to secure desired material strength by rolling the material for compaction with a heavy machine.

Therefore, to ensure stable compaction of the material by rolling with a heavy machine, the material design was implemented assuming a minimum degree of compaction (93%) that can easily be achieved by civil engineering work. Needless to say, water is indispensable for enhancing the hydraulic property of the material. In addition, sufficient compaction of the material requires that the water content of the material be in the optimum range. For the water sprinkling work shown in **Table 2**, we determined a suitable water content of the material by season and weather. In addition, we prepared a manual for work execution by type of heavy construction equipment, as shown in Table 2, to allow optimum design and pavement work for obtaining the required quality.

2.4 Evaluation of performance of completed subbase course

The major performance requirements of simple pavements are: (1) ground strength that eases the movement of people and vehicles and (2) weed prevention that helps in maintaining and improving the landscape. The measurement results of these performances of KATAMA™ SP are described below.

(1) Ground strength

Figure 7 shows the time-serial change in ground strength at the site where test pavement work using KATAMA™ SP was executed in accordance with the execution manual mentioned in 2.3. The ground strength was measured using a Caspol, which is a simple device for measuring ground bearing capacity developed by the Kinki Regional Development Bureau. Even the steelmaking slag slightly increases the ground strength because it has some hydraulic property. On the other hand, the ground strength for KATAMA™ SP is about twice as strong as that for the steelmaking slag.

Simple pavements of parking lots where vehicles come in and out at all times are required not only to have sufficient strength but

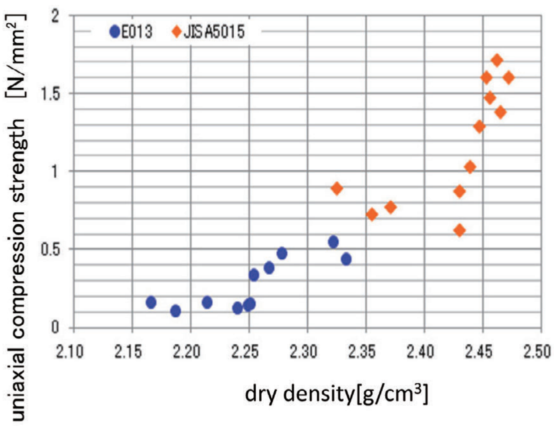
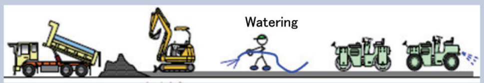
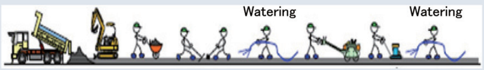


Fig. 6 Relationship between drydensity and uniaxial compression strength

Table 2 Paving process of KATAMA™ SP

Type	Constraction method
Finisher	Acceptance of material, spreading: Finisher; rolling compaction: vibrating roller, tire roller 
Grader	Acceptance of material, spreading: grader; rolling compaction: vibrating roller, tire roller 
Backhoe	Acceptance of material, spreading: backhoe; rolling compaction: vibrating roller, tire roller 
Without heavy industrial machine	Acceptance of material, spreading: backhoe; rolling compaction: Hand guide roller, Vibration plate 

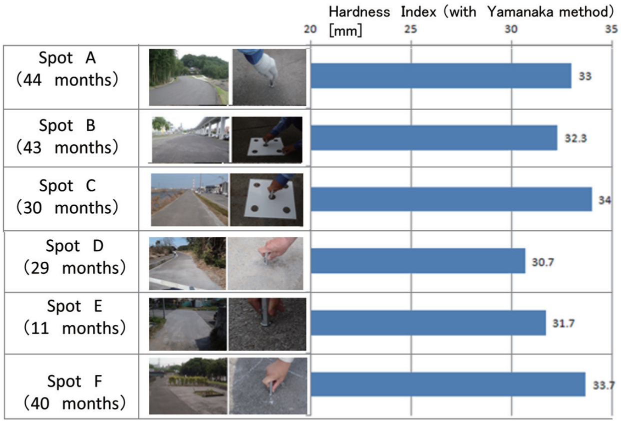


Fig. 8 Hardness index with Yamanaka method & weed-proof effects

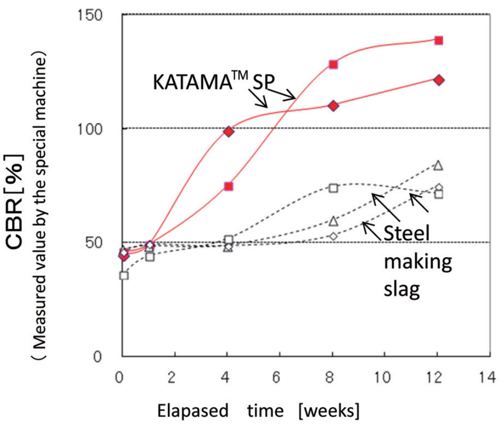


Fig. 7 Characteristic of strength of KATAMA™ SP

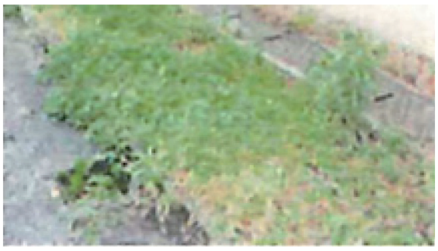


Photo 3 Before paving

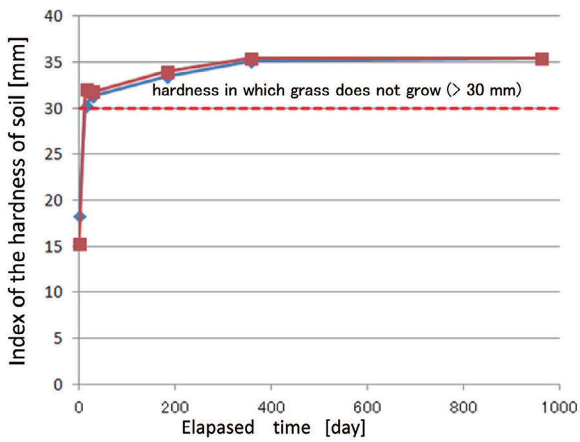


Fig. 9 Relation between index of the hardness of soil with yamanaka method and elapsed time

also to be free from surface loosening, scattering of aggregates, etc. In view of these requirements, we have also developed surface protection technology utilizing asphalt emulsion and supplied it to the customers and constructors.

(2) Weed prevention

As mentioned earlier, the index of weed protection capacity of soil-based pavement is measured by the Yamanaka soil hardness tester. When the soil hardness index is 30 mm or more, the growth of plant root systems in the soil is almost impossible. At the sites of work execution using KATAMA™ SP, it was confirmed that weeds did not grow markedly, with the exception of sites where the thickness of pavement was too small (less than 100 mm) or there was a clearance left between the pavement and the boundary block wall because of poor execution work. At other sites where the pavement work was executed properly, all the pavements developed the required strength and prevented weed growth, as shown in **Fig. 8**.

As an example, we shall present the results of execution of pavement work using KATAMA™ SP on the weed-covered grounds (**Photo 3**) of Oita National College of Technology (ONCT).[3] As shown in **Fig. 9**, the soil hardness index of 30 mm or more has been maintained for about three years. Since the completion of the pavement work on October 2010, weeds have not grown noticeably, although moss has partially convered the surface (**Photos 4** and **5**).

3. Clarification of Solidification Mechanism

3.1 Analysis of phenomenon of solidification by formation of binding material

Figure 10 shows the results of an EPMA mapping elemental analysis of the solidified portion of the upper layer (50 mm in thick-

Photo 4 Mensuration

Photo 5 After paving with KATAMA™ SP

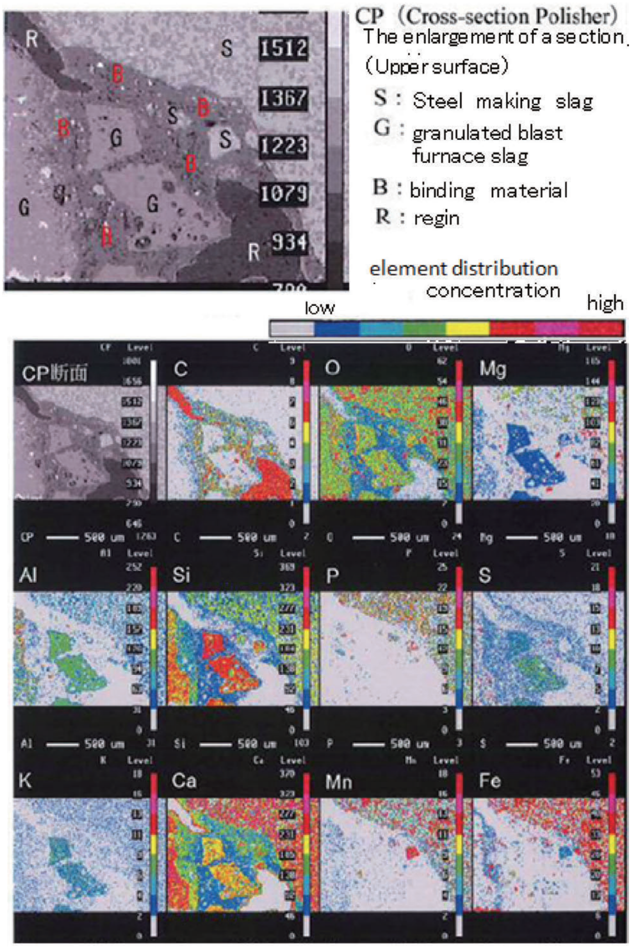


Fig. 10 EPMA result of the upper layer of KATAMA™

ness from the surface) of the pavement that was completed using KATAMA™ SP three years ago.[4)] The particles labeled S shown in Fig. 10 up contain P and Fe, indicating that they are aggregates of steelmaking slag. On the other hand, particles labeled G contain Al, Si, and S, indicating that they are granulated slag particles. The binding material (B) that binds these slag particles together has high concentrations of C, O, Al, Si, Ca, and S. Thus, calcium carbonate ($CaCO_3$), hydrates of calcium silicate, and hydrates of calcium aluminate (C-S-H, C-A-S-H) were confirmed to have formed.

3.2 Evaluation of hydrates and calcium carbonate formed and solidification mechanism

As shown in **Fig. 11**, KATAMA™ SP was first placed in a cardboard tube of 200 mm in diameter and packed till its unit bulk weight became 20 kN/m^3. Then, to simulate rainfall, 416 ml of water that was equivalent to the average annual rainfall of 1612 mm was sprinkled over the pavement material every three days. The change in composition of the material after execution of pavement work was analyzed by the thermogravimetric method.[4)] Its should be noted that H_2O is lost from C-S-H and C-A-S-H and CO_2 in a temperature range of 100°C to 150°C and CO_2 is lost from $CaCO_3$ in a range from 600°C to 700°C (Saikia et al.; 2002). **Figures 12** and **13** show the results of thermogravimetry using 10 mg samples. It can be seen that the hydrates and calcium carbonate were formed and that the concentration of calcium carbonate in the top and bottom layers increased gradually. As shown in **Fig. 14**, hydrates are considered to have been formed by reactions of silicic acid and aluminate ions eluted from the granulated slag by the steelmaking slag that functioned, as an alkali whereas $CaCO_3$ is formed by the reaction between Ca^{2+} and carbon dioxide supplied from the atmosphere and soil air.

In addition to the abovementioned experiment, the 100 mm-thick pavement of a forestry road in Oita prefecture, that was completed one year and two months ago using KATAMA™ SP, was analyzed by the thermogravimetric method and the gas detection tube method.[5, 6)] As shown in **Fig. 15**, it was found that the concentration of calcium carbonate in KATAMA™ SP was about three times

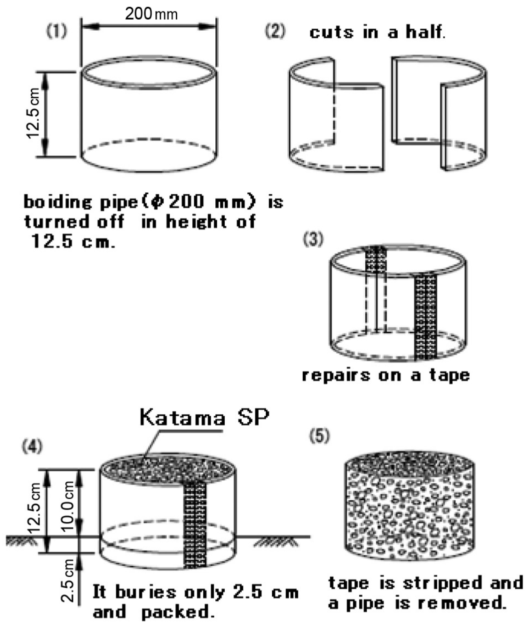


Fig. 11 Preparation of a test piece

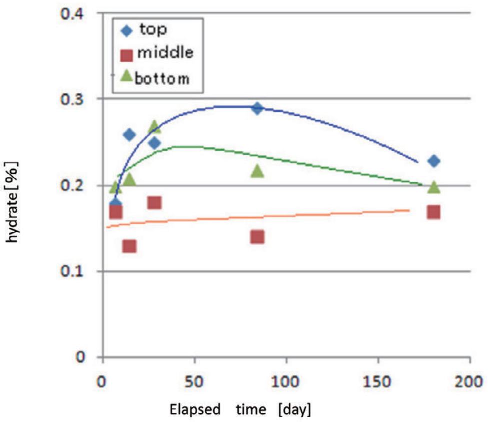


Fig. 12 Relation between amount of hydrate and elapsed time

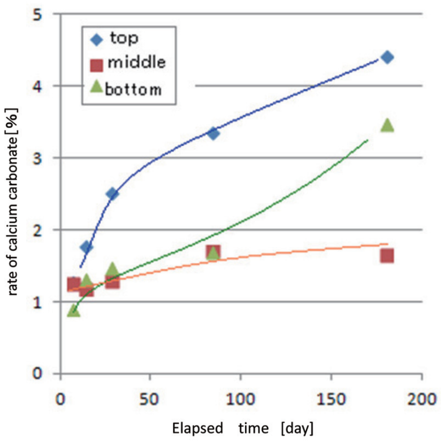


Fig. 13 Relation between amount of calcium carbonate and elapsed time

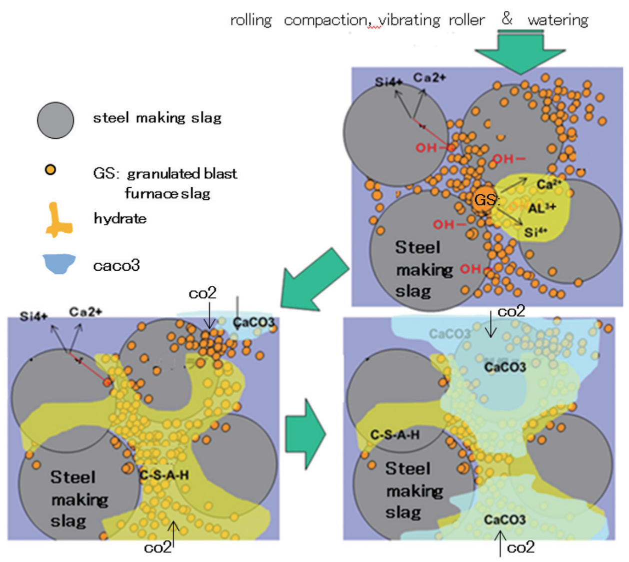


Fig. 14 Mechanism of production of calcium carbonate

higher than that in the steelmaking slag aged in the atmosphere for six months. Thus, the phenomenon whereby KATAMA™ SP solidifies in several months as shown in Fig. 7 is considered due to the gradual formation of calcium carbonate ($CaCO_3$) after the formation of the hydrate of calcium silicates and the hydrate of calcium aluminates (C-S-H, C-A-S-H). On the other hand, the formation of $CaCO_3$ is considered due to the carbonation of Ca^{2+} dissolved in water by carbon dioxide supplied from the atmosphere and soil air.

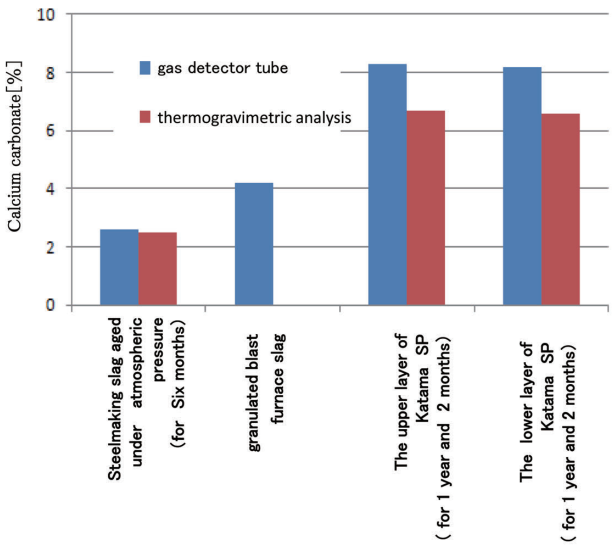


Fig. 15 Calcium carbonate contents of slag and paved materials

4. Investigation of Environmental Impact of KATAMA™ SP

4.1 Effects on the environment

When slag is used uncovered for simple pavement, it may increase the pH of surface and rain seepage water, posing adverse effects on the enamoring vegetation that adopted to the acid soil. Even if the alkaline seepage water is neutralized temporarily by the neutralizing soil, the risk to the environment does not disappear completely because the soil's buffer capasity is limited. Concerning the risk of alkali elution from KATAMA™ SP schematically shown in **Fig. 16**, we shall consider the factors described below: (1) the elutability of seepage water, (2) the alkalinity of surface water, and (3) the alkalinity of eluted seepage water.

(1) Discussion on elutability of seepage water from KATAMA™ SP

The pavement prepared from KATAMA™ SP has low permeability. Therefore, the seepage water hardly occurs and the risk of elution of alkali water is extremely low. Assume, for example, that the permeability coefficient of a finished pavement is 1×10^{-4} cm/s. Then, as shown in **Fig. 17**, the depth of permeation of water into the pavement is not more than 100 mm as long as the intensity and duration of rainfall are not unusual (e.g., max. 200 mm/h for 10-plus hours). Because KATAMA™ SP is finished to a thickness of 100 to 150 mm, the rainwater will, in most cases, remain in the pavement temporarily. After that, the rainwater flows out from the top of the pavement, evaporates from the pavement surface, or flows downward. Compared with conventional pavement materials, this KATAMA™ SP hardens rapidly and becomes impermeable. Therefore, it does not allow the highly alkaline seepage water to be eluted easily from the pavement. At present, the actual permeability coefficient of KATAMA™ SP is being measured accurately at several construction sites. According to the imformation obtained to date, it is smaller than anticipated.

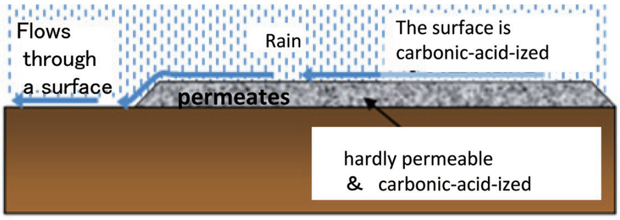


Fig. 16 Hypothesis preventing flowing high alkali water

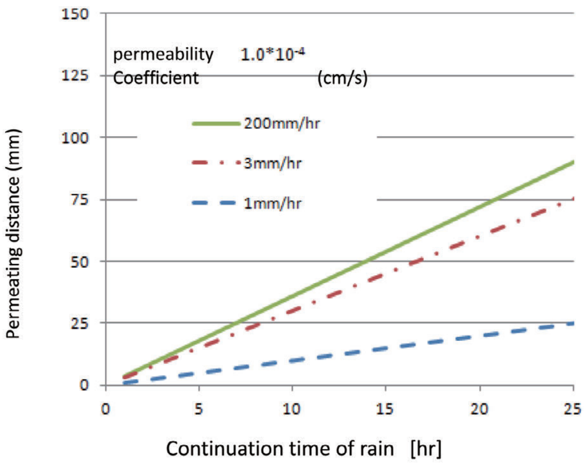


Fig. 17 Permeation depth of rain water (case of permeability coefficient of 1 × 10^{-4} cm/s)

(2) Examples of measurement of alkalinity of surface water

We measured the alkalinity of surface water at a site where pavement work was executed using KATAMA™ SP. The measurement results are shown in **Fig. 18** and the scenes of measurement are shown in **Photo 6**. In the test, tap water was poured over the pavement to make artificial puddles, whose alkalinity was measured with a litmus paper (Whatman Type CS). The puddles of water were observed to be neutral.

Oita National College of Technology conducted a similar test, in which drops of distilled water on the pavement were collected from the surface with a pipette and their alkalinity was measured with a pH meter (TwinpH AS-212 of Horiba, Ltd.). The test results[3] are shown in **Fig. 19**. The pH values measured with the pH meter were higher than those obtained with the pH test paper. The reason for that is unknown. In the latter test, however, the pH of the water was equal to or lower than that of soapy water (pH = about 10), suggesting that the alkalinity of surface water decreased markedly after execution of the pavement work. It is considered due to the progress of carbonization described in 3.2. As a result, as schematically shown in Fig. 16, the possibility that highly alkaline surface water will flow into the surrounding soil has decreased significantly.

(3) Discussion on alkalinity of seepage water

As mentioned in 4.1 (1), KATAMA™ SP is almost impermeable to water. Even so, we discussed the seepage water that flows downward through the pavement, as follows.

For evaluating the neutralization of concrete, the progress of concrete neutralization is diagnosed with the concrete core sprinkled with a phenolphthalein solution. According to a study report,[7] the neutralization of concrete progressed to a depth of about 100 mm from the surface in about 100 years. Using a specimen prepared by

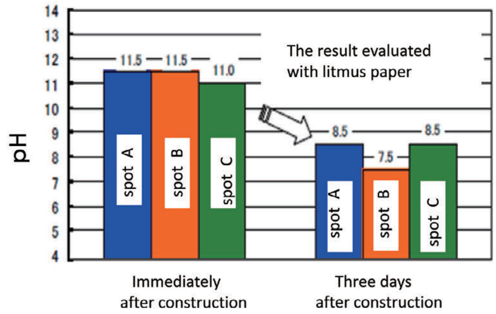


Fig. 18 Change of pH of the puddle

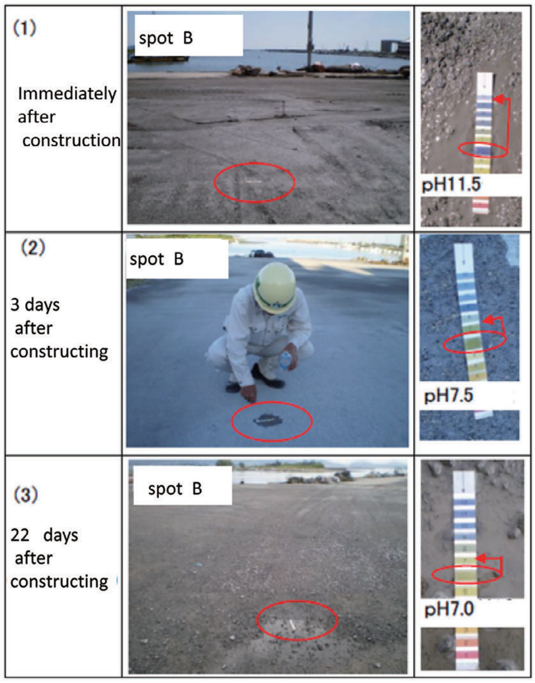


Photo 6 Change of pH of the puddle

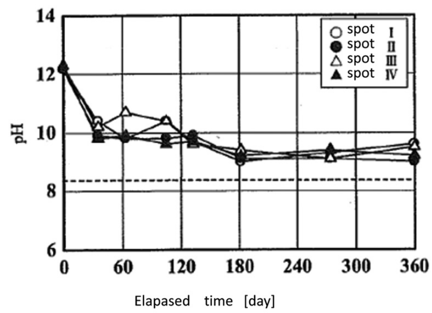


Fig. 19 Change of pH of the puddle (measuring method follows at The Japanese Geotechnical Society)

packing KATAMA™ SP in a cylindrical frame and aged indoors for four months, we evaluated the alkalinity of the specimen by spraying phenolphthalein solution. The appearance of the specimen is shown in **Photo 7**. It was found that the portion of the specimen down to about 10 mm from the surface was neutralized with a speed about 100 times faster than in the case of concrete.

A block of pavement made from KATAMA™ SP was sampled after 4 month after the construction and sprayed with phenolphthalein solution to examine the alkalinity (**Photo 8**). The colourless, i.e., near neutral, zone extended down to about 40 mm from the surface even without coloring the pavement. A 40 mm thick sample of compacted KATAMA™ SP collected at the site and a small block of 6 month-aged steelmaking slag were soaked in phenolphthalein solution and the color of the solutions was compared (**Photo 9**). The phenolphthalein solution did not turn red, indicating that the sample of KATAMA™ SP had been completely neutralized.

In addition, when a sample of KATAMA™ SP collected from a three-year-old pavement was soaked in phenolphthalein solution with a liquid-solid ratio of about 3:1, the pH value of the upper layer (about 25 mm from the top) was 8.5 and that of the lower layer (about 75 mm from the top) was 9.8. At many other sites too, the progress of carbonization of KATAMA™ SP could be confirmed. Thus, KATAMA™ SP is neutralized in several years. Therefore, it is considered that the seepage water eluted from the pavement has minimal effect on groundwater.

Photo 7 Appearance of test piece after spraying solution of phenolphthalein

Photo 8 Appearance of KATAMA™ SP after spraying solution of phenolphthalein

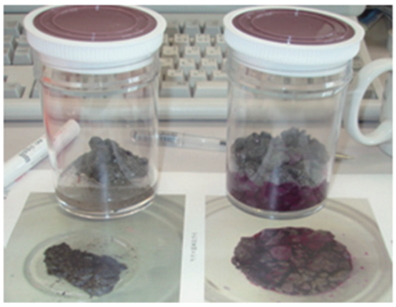


Photo 9 Comparison of the color of paved KATAMA™ SP and steelmaking slag after soaked in solution by phenolphthalein

4.2 Risk of elution of highly alkaline water

As mentioned earlier, KATAMA™ SP is so impermeable to water that it hardly elutes seepage water. In addition, because the surface of the pavement is carbonized after execution of the pavement work, a large amount of highly alkaline water is not produced as surface. Furthermore, because KATAMA™ SP is neutralized about 100 times faster than concrete, the pH value of seepage water, though it does not occur in large volumes, decreases with the lapse of time, thereby reducing the environmental impact of KATAMA™ SP.

In addition, if a pavement made from KATAMA™ SP becomes unnecessary and is demolished tens of years after it is constructed, its alkalinity will have decreased to allow easy recycling.

Although the risk of elution of highly alkaline water from KATAMA™ SP is low, the company gives due consideration to the environmental impact of the product even at the stage of marketing. Namely, when selling the material, the company explains the salient characteristics of the product to the customer, designer, and contractor and requests them to pay attention to the environmental impact of the product at the stages of design and work execution. For example, it is possible to significantly reduce the environmental impact of the product by selecting a suitable paving site (e.g., leaving sufficient clearance between pavements if there are tea trees, etc. which prefer acid soil or rivers in the neighborhood) or providing a buffer zone utilizing the soil's ability to neutralize alkalis. From planning to the completion of pavement work, our sales staff maintains close communications with the customer to minimize the environmental impact of the product.

5. Summary and Application Examples

As has been described above, exploring attention to the phenomenon that a mixture of steelmaking slag and granulated blast furnace slag solidifies rapidly, we could found the optimum blending conditions to develop a new pavement material with the desired strength and stability. At the same time, we found that hydrates of calcium silicate and calcium aluminate (C-S-H, C-A-S-H) and calcium carbonate ($CaCO_3$) are gradually produced in the material and they contribute to hardening. Next, we demonstrated that our newly developed material is almost impermeable to water and that the material—an eco-friendly slag product—helps reduce the risk of elution of highly alkaline water. Eventually, the new pavement material was introduced in the market under the trade name "KATAMA™ SP (special)". At present, the organization for manufacturing the new product is being reinforced on a companywide basis to further expand the sales.

Several examples of application of KATAMA™ SP are shown in **Photos 10** through **13**.

6. Conclusion

As long as the new pavement material is designed, manufactured, and used in the optimum way, it is possible to secure civil engineering performance and customer satisfaction, minimizing the impact of pavement work on the environment. Therefore, on the basis of the knowledge regarding the environmental impact discussed in Section 4 and the related know-how (not presented in the text), we provide our customers with a detailed information about of the

(Under construction) (After construction)

Photo 10 Construction examples [1)]
- **Constracted by the Beppu City Office of Oita Prefecture in Japan**
- **Fishing port maintenanse (completed in 2010)**

(Before construction) (After construction)

Photo 11 Construction example [2)]
- **Constructed by 'Mori Net Oita' (public utility foundation corporation in Oita Prefecture in Japan)**
- **Construction material which manufactures the road for improving a forest (completed in 2012)**

salient characteristics of the new product and proper guidance in product design and execution of pavement work.

In conclusion we would like to describe our belief that we entertain about the social and economic importance of the product. As mentioned at the top of this report, simple and inexpensive pavement materials are of significant demand, especially in the field of public works. Today, in the resources-scarce Japan in particular, there is a very strong demand for economical civil engineering materials and methods for the maintenance and repair that will increasingly be required of social civil structures in the future. Steelmaking slag is a valuable resource that is newly producted from iron ore imported from abroad. Therefore, recycling and reusing it as a useful civil engineering material is considered very meaningful, especially from a social standpoint. Fortunately, Nippon Steel & Sumitomo Metal has steelworks throughout the country and can build and maintain an organization for supplying the new product on a stable basis. In fact, the company has already started establishing such an organization. We believe that the simple pavement material "KATAMA™ SP (special)" can contribute considerably to our society as a low-cost, easy-to-use public material that is assessed to have little adverse impact on the environment.

Because of its excellent characteristics described above, the product was certified as a new technology in 2013 by the NETIS system of the Ministry of Land, Infrastructure and Transport (registration number: QS-130016-A). It is being increasingly used in both public and private civil engineering works.

(After construction)

Photo 12 Construction examples [3)]
- **Construction of the Ministry of Land, Infrastructure, Transport and Tourism of Japan (between the Nobeoka Junction and Kitagawa Interchange)**
- **Preventing grass growth (completed in 2013)**

(After construction)

Photo 13 Construction examples [4)]
- **Constructed by a private sector (Ushimado Megasolar in Okayama Prefecture in Japan)**
- **Preventing grass growth (completed in 2011)**

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