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STUDY ON EFFECTIVE USE OF COAL CINDERS MIXED SOIL-STRENGTH PROPERTIES OF CEMENT STABILIZED SOIL

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ABSTRACT: Coal had been used as fuel for steam locomotives, and coal cinders (coal waste) had been buried underground for disposal, many years. In recent years, redevelopment projects around train stations have been planned for the land where coal cinders was once disposed of. In the redevelopment projects, buried coal cinders is increasingly being excavated, and the disposal and treatment of the excavated coal cinders are becoming an issue for developers. Excavated coal cinders must be treated and disposed of as industrial waste, not as excavated soil. In other words, even though the soil is excavated from the ground, it cannot, in principle, be used as backfill material to its original location (railroad sites) and is disposed of as industrial waste at a high disposal cost. Moreover, the high cost of disposal, along with the shortage of final disposal sites, has led to an increase in the project cost of redevelopment projects. For railroad operating companies such as East Japan Railways Company, the increase in development costs poses a major problem for the implementation of their projects in Japan. Therefore, the purpose of this study is to reuse coal cinders dumped underground with the backfill material. Laboratory solidification experiments were conducted to determine the initial water content, the cement added ratio, etc., as design parameters for the strength of backfill materials. From the experimental results, the strength characteristics of the improved soil mixed with coal cinders also changed as the various mixing ratios were varied- the possibility of applying the improved soil containing coal cinders as backfill materials were clarified.

Keywords: Coal cinders, Cement solidification, Backfill material, Unconfined compressive strength

1. INTRODUCTION AND BACKGROUND

In Japan, the railroad network was extended throughout the country with the opening of the Shinagawa-Yokohama railroad in 1872 [1]-[3]. Coal-fired steam locomotives operated for about 100 years from the opening of the railroad until around 1975. Although coal cinders used for steam locomotives have been buried underground as land formation material for railroad sites, the extent, amount, and depth of coal cinders buried are unknown.

In recent years, coal cinders have been increasingly excavated as a result of the rebuilding of railroad facilities and the redevelopment of station areas. Basically, coal cinders, including mixed local soil, excavated during construction cannot be backfilled as it is treated as waste (if backfilled, it violates Waste Management and Public Cleansing Act and constitutes illegal dumping) or disposed of as general residual soil (as it requiring disposal as industrial waste), which increases the cost of construction due to the high disposal cost [4-5]. Further, most of the excavated coal cinders are landfilled at final disposal sites, and the environmental impact of their transportation and disposal is also significant. East Japan Railway Company is currently planning and implementing large-scale initiatives, including the redevelopment projects in various locations. However, the urgent issue is to reduce the cost of disposal of excavated coal cinders since the excavation of huge amounts of coal cinders in the construction process puts pressure on the project budget.

Many studies on coal waste have been conducted on coal ash emitted from coal-fired power generation [6-9], not coal cinders. There are

Fig. 1 Picture of “Illustration of Tokyo Steam Train” (woodblock print, Yoshitora Utagawa, 1871, [2])

also application examples as a backfill material by cement stabilization treatment [10]. However, the material dealt with as the subject of this paper is mixed with coal cinders and local soil that have been dug up for redevelopment after many years of backfilling in the ground. There are not much researches deal with coal cinders other than the authors' papers [12-13].

Therefore, the authors effectively started a project to utilize coal cinders as construction materials. In this paper, the authors focus on the strength properties of cement-stabilized coal cinders through experiments. It is the project's first step to obtaining fundamental characteristics of stabilized coal cinders.

2. RESEARCH SIGNIFICANCE

This research aims to focus on the coal waste that has yet to be implemented so far and to refer to its practical use. For example, much research has been carried out on coal ash discharged from thermal power plants, which is also the same coal waste. Coal ash emissions from coal-fired power generation have become a pressing problem. However, coal cinders are expected to be dug up in the future redevelopment project, and the current emissions are insignificant.

3. THE SAMPLES AND TEST METHODS

3.1 The Samples

The coal cinder mixed soil (after this referred to as “coal cinders”) used in this study was collected from the construction site of East Japan Railway Company (see Photo 1) and is classified as "coal cinders A" and "coal cinders B" based on the sampling point and types of mixed local soil.. The coal cinders mixed soil were collected during excavation work for a redevelopment project in the station areas. The coal cinders A contains sandy soil while coal cinders B is silty and clayey soils.

Photo 1 Excavated Coal cinders from redevelopment project in the railroad site

The main physical characteristic values of coal cinders and clay are shown in Table 1 [6][7]. It was found that the density of soil particles in the coal cinder mixed soil (coal cinders A and B) decreased with the addition of coal cinders. Both coal cinders are shown in Photos 2 and 3, respectively. From these photos, “A” sample is mixed with sand, while “B” is silt and clay respectively.

Table 1 Typical properties of used coal cinders and soil

Tyipical Soil properties		Coal cinders A	Coal cinders B	Kasaoka clay
Soil particle density	ρ_s (Mg/m^3)	2.44	1.94	2.87
Liquid limit	w_L (%)	NP	50.5	54.7
Plastic limit	w_P (%)	NP	43.1	33.7
Plastisity index	I_P (-)	NP	7.42	21.0
Natural water content	w_n (%)	3.17	18.44	4.65
Ignition loss	L_i (%)	16.71	8.83	5.85

Photo 2 Coal cinder A (local mixed soil: sandy soil)

Photo 3 Coal cinder B (local mixed soil: silty and clayey soil)

The results also showed that the consistency properties and water content ratios varied significantly depending on the type of local soil contained in the coal cinder mixed soil

3.2 The Test Method and the Test Piece Preparation Method

The tests performed in this study is unconfined compression strength test standardized by Japanese Industrial Standard (JIS A 1216 [15]). The size of specimens are 35mm in diameter and 70 mm in height.

The test piece preparation method was based on the Japanese Geotechnical Society Standard (JGS 0821 [16]) without compaction of stabilized soil. Coal cinders that passed through a 2 mm sieve were used as samples. Commercially available Kasaoka clay (powder) and blast furnace cement type B were used as additional agents. The test piece was obtained by mixing Kasaoka clay, coal cinders, and blast furnace cement type B for about 10 minutes using a mixer to make the mixture uniform. An acrylic mold with a diameter of 3.5 cm and a height of 10 cm was used. The lower end was sealed with a rubber stopper, and the test piece was divided into five layers and tapped 100 times per layer to let the air out while filling the samples. After filling, the upper end was covered with plastic wrap and cured for a predetermined period of time. Cement and water were added to the dry mass of coal cinder mixed soil and Kasaoka clay at a predetermined ratio. The parameters used in this study (cement addition rate a_w and coal cinder addition rate D_w) were defined as shown in “Eq. (1)” and “Eq. (2)”, respectively. The curing period of the test piece was 7 and 28 days (T_c=7 days and T_c=28 days, respectively), and they were cured in a constant-temperature room at 20 ℃. The compositions of the test piece are shown in Table 2. For coal cinders A, the cement addition rates a_w were set to 10% and 35%, while the coal cinder addition rate D_w was set to only 50% to make the test piece. For coal cinders B, the cement addition rates a_w were set to 5%, 10%, 20%, and 35%, while the coal cinder addition rates D_w were set to 50%, 75%, and 100% to prepare the test piece. For the initial water content w_0, it required water addition because the Kasaoka clay used was in a powdery state with a water content ratio of about 4.7%. w_0 set below 30% makes uniform mixing difficult due to drying. On the contrary, if w_0 exceeds 60% (near the liquid limit), the test piece is not strong enough to stand on its own after being cured, so in this experiment, the water content ratios were set within the 40-60% range.

$$a_w = \frac{m_s'}{m_g + m_s} \times 100 \ (\%) \tag{1}$$

$$D_w = \frac{m_g}{m_g + m_s} \times 100 \ (\%) \tag{2}$$

m_s' : Mass of blast furnace cement type B
m_s : Dry mass of Kasaoka clay
m_g : Dry mass of coal cinder mixed soil

Table 2 Test Programs

Coal cinder addition rate D_w (%)	Cement addition rates a_w (%)			
	5	10	20	35
50	40 A	40-60 A, B	40 A	40-60 A, B
75	40 A	40 A	40 A	40 A
100	40 A	40 A	40 A	40 A

Note: A: Coal cinders A, B: Coal cinders B

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Relationship between Unconfined Compressive Strength and Types of Coal Cinders

The relationship between unconfined compressive strength and cement addition rate for coal cinders A and B are shown in Fig. 2. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 are 40% and 50%, coal cinder addition rate D_w is 50%, cement addition

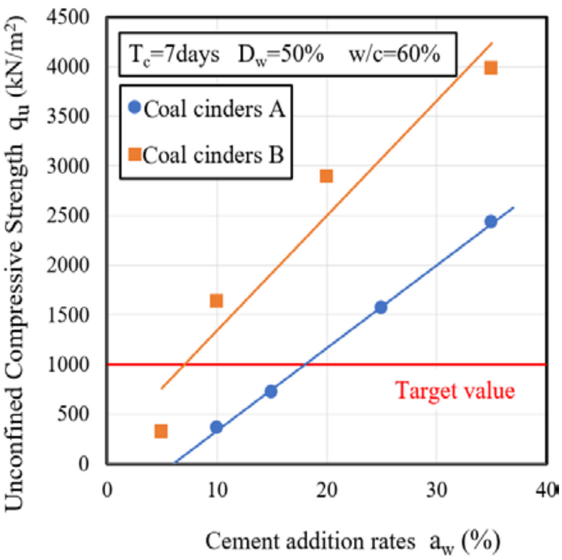

Fig. 2 Relationship between cement addition rates and unconfined compressive strength (Coal cinders A and B)

rate a_w is 35%, and water-cement ratio w/c is 60%.

The unconfined compressive strength was found to vary in the range of 350-4,000 kN/ m^2 depending on the cement addition rate. In both types of coal cinders, the unconfined compressive strength tended to increase linearly with increasing cement addition rate, and a comparison of coal cinders A and B showed that B had a greater value than A. The reason for the difference in strength between the two is considered to be due to the nature of the soil or the water content in the soil. In the same figure, the standard values for the roadbed are compared, and it is found that the target value (1,000 kN/m^2) is met with D_w = 50% and cement addition rate of 15% or more for coal cinders A, and with a_w = 10% or more for coal cinders B. The strength varies depending on the sample used. The observed differences in strength depending on the samples used suggest that unconfined compressive strength is closely related to the physical characteristic values of the samples.

4.2 Relationship between Initial Water Content and Unconfined Compressive Strength

The relationship between unconfined compressive strength and initial water content of coal cinders A is shown in Fig. 3. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 are 40-60%, coal cinder addition rate D_w is 50%, cement addition rate a_w is 35%, and water-cement ratios w/c are 60% and 100%.

Comparing the water-cement ratio of w/c=100% and w/c=60%, the strength was greater at w/c=60%. In terms of the change in the initial water content of the clay, the unconfined compressive strength tended to decrease with an increase in the water content ratio for both w/c, and a 20% increase in the water content ratio for w/c=60% resulted in a decrease in the unconfined compressive strength by half. The same trend was observed at w/c=100%. These results show how much water content affects the strength of cement solidification. It is thought that a higher water content facilitates uniform mixing of the samples and improves workability in the field. However, the strength decreases as water content increases, indicating that it is important to maintain an appropriate balance between water content ratio and strength.

4.3 Relationship between Water Content Ratio, Curing Period, and Unconfined Compressive Strength

Figs. 3 and 4 show the relationship between unconfined compressive strength and initial water content of coal cinders, and Fig. 3 shows the unconfined compressive strength obtained under the following conditions: curing period T_c are 7 and 28 days, initial water content w_0 are 40-60%, coal cinder addition rate D_w is 50%, cement addition rate a_w is 35%, and water-cement ratio w/c is 100%. Fig. 4 shows the results obtained for a test piece by changing the water-cement ratio w/c to 60%. 7-day and 28-day strength comparison tests showed that unconfiding compressive strength was greater at 28 days than at 7 days, although some cases could not be performed. For the 7-day strength, values were obtained by varying the initial water content, and a similar trend was observed for the 28-day strength.

The 28-day strength decreased as the initial water

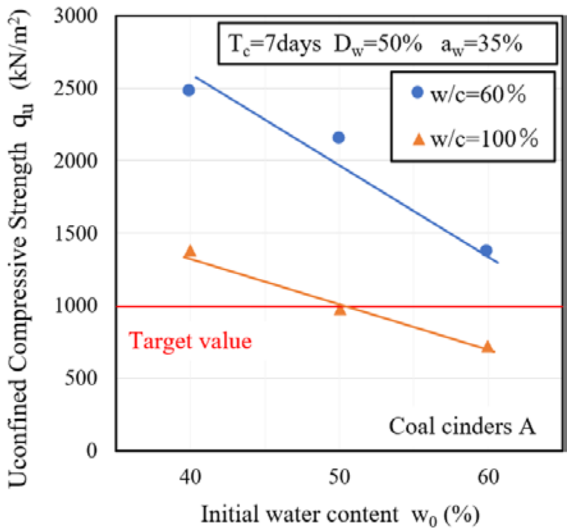

Fig. 3 Relationship between initial water content rate and unconfined compressive strength (Coal cinders A, w/c=60 and 100%)

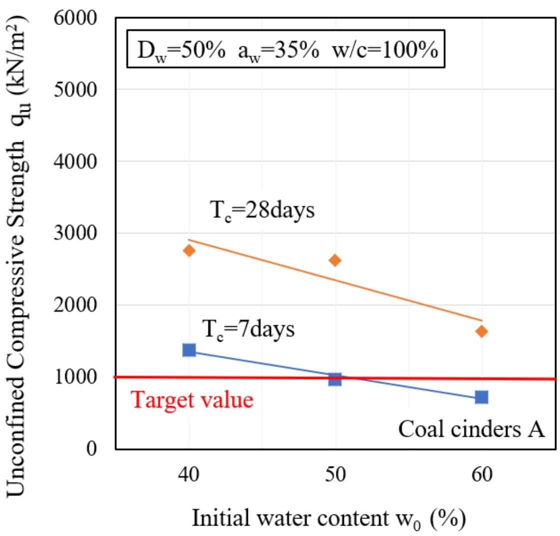

Fig. 4 Relationship between initial water content rate and unconfined compressive strength (Coal cinders A)

content increased, as did the 7-day strength. Figs. 5 and 6 show the relationship between the rate of increase in unconfined compressive strength and the curing period from the results of Figs. 3 and 4 above, showing the percentage increase for each condition at Tc = 28 days for the unconfined compressive strength qu (28 days) when qu (7 days) at Tc = 7 days is used as a reference. Strength increases of 2.0-2.7 times and 1.8-1.9 times were observed for w/c=100% and w/c=60%, respectively. The increase in strength was not affected by changes in the initial water content or other conditions. The increase in strength was greater in "w/c=100, w_0=50%" compared to other conditions, but further study is planned with an increased number of samples.

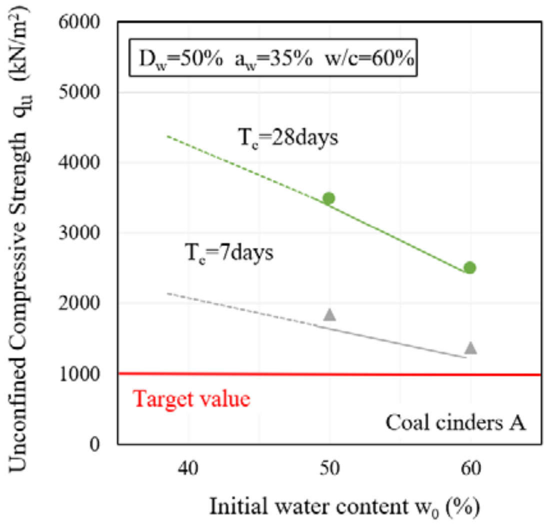

Fig. 5 Relationship between initial water content rate and unconfined compressive strength (Coal cinders A)

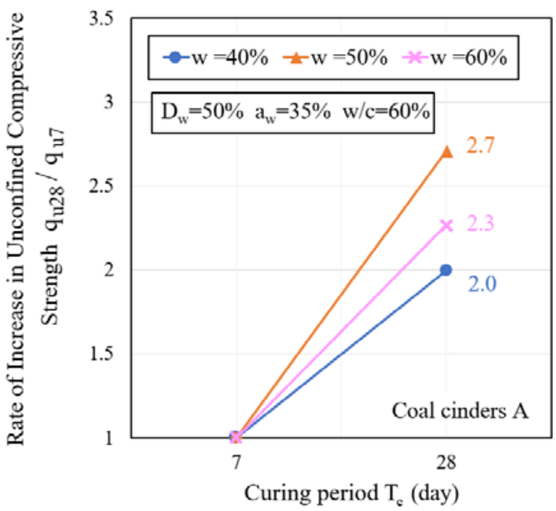

Fig. 6 Relationship between curing period and increase rate of unconfined compressive strength q_{u28}/q_{u7} (Coal cinders A)

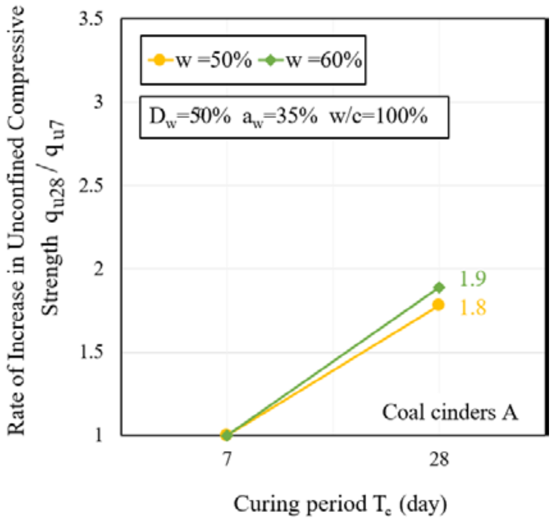

Fig. 7 Relationship between curing period and growth rate of unconfined compressive strength q_{u28}/q_{u7}(Coal cinders A)

4.4 Relationship between Coal Cinder Addition Rate and Unconfined Compressive Strength

The relationship between unconfined compressive strength and coal cinder addition rate for coal cinders A is shown in Fig. 8. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 is 50%, coal cinder addition rates D_w are 0%-71%, cement addition rates a_w are 15% and 35%, and water-cement ratio w/c is 60%. In the case of coal cinders A, the unconfined compressive strength of the improved soil reached a maximum at a coal cinder addition rate of about 13%, after which the 7-day strength of

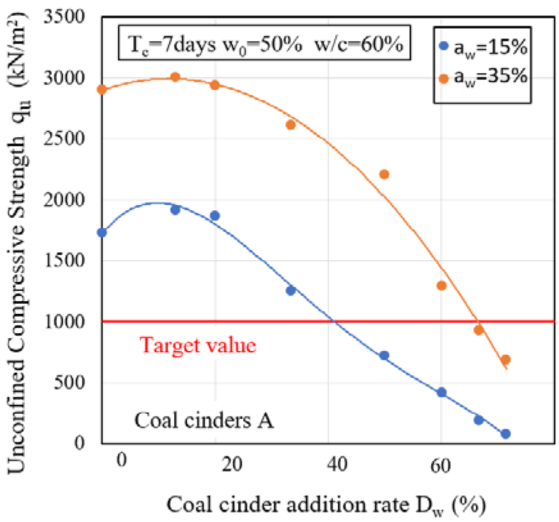

Fig. 8 Relationship between cement addition rate and unconfined compressive strength (Coal cinders A)

the improved soil decreased as the coal cinder addition rate increased.

The strength development of clay alone, i.e. D_w =0%, was also observed, but the addition of coal cinders increased the strength, albeit slightly. The relationship between unconfined compressive strength and coal cinder addition rate for coal cinders B is shown in Fig. 9. For comparison, data for coal cinders A (curves in Fig.8) are also shown. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 is 40%, coal cinder addition rates D_w are 50%-100%, cement addition rates a_w are 5-20%, and water-cement ratio w/c is 60%. The data obtained for coal cinders B is only for those with the addition rate of 50% or more, but as with coal cinders A, the unconfined compressive strength decreased with increasing coal cinder addition rate, but unlike coal cinders A, the strength was found to be high even at 100% coal cinders content. The strength of the clay alone is lower than the maximum strength, which is considered to be due to the increase in strength caused by the coal cinders acting as fine aggregate. To increase the coal cinder addition rate, it is important to understand the characteristics of the samples and to determine the composition based on the optimum water content ratio and cement addition rate.

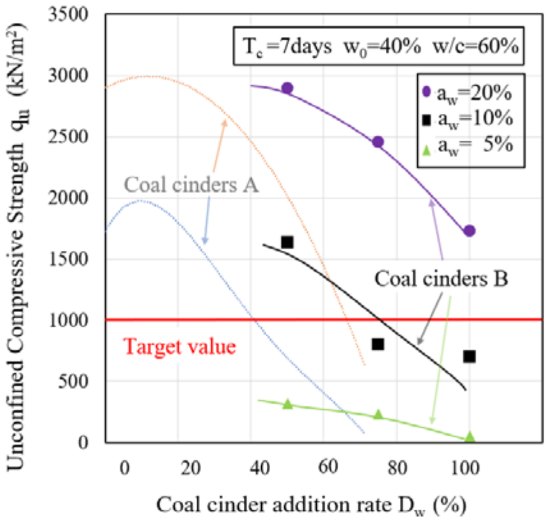

Fig. 9 Relationship between coal cinders addition rate and unconfined compressive strength (Coal cinders A and B)

4.5 Results and Discussion on Coal Cinders A

Based on the results for coal cinders A as described above, the water-cement ratio w/c was fixed at 60% for easy mixing and expected strength, and the initial water content w_0 was fixed at 40% for sufficient mixing and expected strength of the test piece. The cement addition rate was varied at 35% or less, while test pieces were prepared at coal cinders site B to compare each condition.

4.6 Results and Discussion on Coal Cinders A

Based on the results for coal cinders A as described above, the water-cement ratio w/c was fixed at 60% for easy mixing and expected strength, and the initial water content w_0 was fixed at 40% for sufficient mixing and expected strength of the test piece. The cement addition rate was varied at 35% or less, while test pieces were prepared at coal cinders site B to compare each condition.

4.7 Relationship between cement addition rate and unconfined compressive strength

The relationship between unconfined compressive strength and cement addition rate for coal cinders B is shown in Fig. 10. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 is 40%, coal cinder addition rates D_w are 50-100%, cement addition rates a_w are 5-35%, and water-cement ratio w/c is 60%. Although the unconfined compressive strength decreased as the coal cinder addition rate increased, it was found that the target value of 1,000 kN/m^2 could be exceeded by setting certain conditions. Moreover, it was found that the strength exceeding the target strength can be obtained by varying the amount of cement added. The target strength was not exceeded even when the coal cinder addition rate was varied at a cement addition rate of a_w=5%, suggesting that a cement addition rate of 15% or more would be desirable.

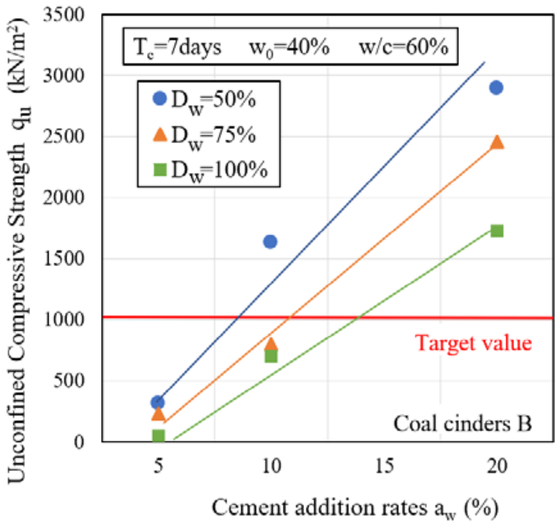

Fig. 10 Relationship between cement addition rates and unconfined compressive strength (Coal cinders B)

4.8 Relationship between Coal Cinder Addition Rate and Unconfined Compressive Strength

The relationship between unconfined compressive strength and the coal cinder addition rate for coal cinders B is shown in Fig. 11. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 is 40%, coal cinder addition rates D_w are 50, 75 and 100%, cement addition rates a_w are 5, 10 and 20%, and water-cement ratio w/c is 60%.

As with coal cinders A, there was a tendency for the strength to decrease as the coal cinder addition rate D_w increases. A plot of the results under the same conditions as those of coal cinders A shows a graph indicating a greater decrease in strength with an increasing coal cinder addition rate compared to the graph for coal cinders B.

The reason for this is that unlike coal cinders A, coal cinders B contain not only coal cinders but also clay from the extraction site. Therefore, the coal cinders are considered to have a significant effect on the unconfined compressive strength.

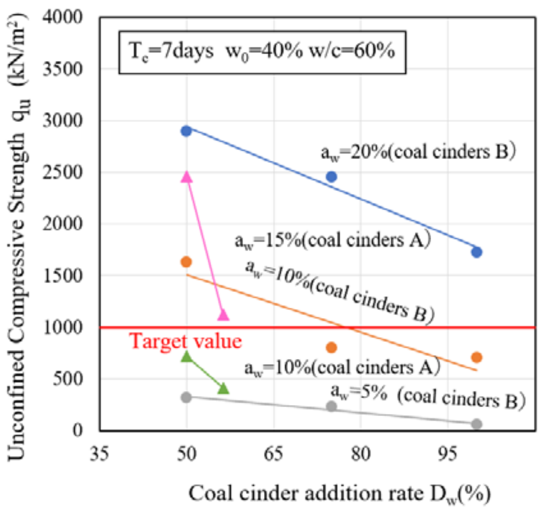

Fig. 11 Relationship between coal cinders addition rate and unconfined compressive strength (Coal cinders A and B)

4.9 Comparison of Coal Cinders Used

The relationship between unconfined compressive strength and initial water content for coal cinders A and B is shown in Fig. 12. The unconfined compressive strength was obtained under the following conditions: curing period T_c is 7 days, initial water content w_0 are 30-60%, coal cinder addition rate D_w is 50%, cement addition rate a_w is 35%, and water-cement ratio w/c is 60%. The strength of coal cinders B was about 1.8 times greater than that of coal cinders A. Although experiments with coal cinders B under the same conditions of initial water content w_0 = 50 % and 60 % were not conducted, the trends of the coal cinder addition rate and cement addition rate are similar for both coal cinders A and B. Therefore, the unconfined compressive strength is considered to decrease with the increase of the initial water content, as in the case of coal cinders A.

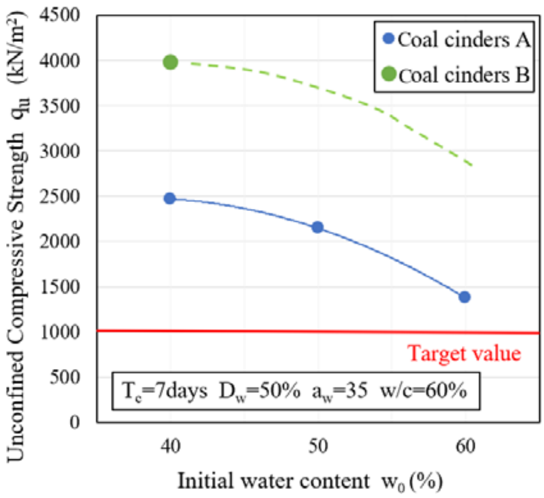

Fig. 12 Comparison of unconfined compressive strength and initial water content (Coal cinders A and B)

5. CONCLUSION

Based on the experimental results of this study, the following results were obtained:

- Understanding the characteristic values of the samples to be used is important, as they affect the unconfined compressive strength.
- The unconfined compressive strength decreases as the initial water content w0 and water-cement ratio increase. w_0 of 40% or less is considered desirable.
- Unconfined compressive strength increases with a longer curing period.
- Cement addition rate aw of 10% or more is considered desirable.

In order to reduce the cost of actual construction, it is considered necessary to find the most economical composition that meets the target strength of 1,000 kN/ m^2 by reducing the amount of cement and increasing the content of coal cinders, which are waste materials. The type of soil and water content ratio contained in coal cinders also affected the unconfined compressive strength. When the content of fine particles was small, the addition of fine particles increase in strength.

Coal contains many harmful substances. Among them, hazardous substances specified in the

Japanese Soil Contamination Countermeasures Law are Benzene, lead, cadmium, mercury, cyanide, chromium, selenium, arsenic, fluorine, boron, etc. it is necessary to discuss detoxification when hazardous substances are included, too.

6. ACKNOWLEDGEMENT

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