



APPLICATION OF EXTEMPORANEOUS BENTONITE-MIXED COLD ASPHALT

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ABSTRACT: Cold mix asphalt has recently been developed as an ecologically friendly and low-cost material. It is available for purchase in market shops and widely used not only to repair potholes in pavements and parking lots but also to construct simple flat spaces in private yards. Various types of novel and improved cold asphalts have been prepared using industrial machines. Previous studies have shown that cold asphalt pavements have relatively high permeability. Specifically, high permeability is required for national highways but not for general roads. Additionally, cold asphalt can be used as a simple ground structure cover. This study developed an instant bentonite-mixed cold asphalt with low permeability. It was prepared by mixing bentonite with cold asphalt on site. Pavement construction was completely manual without special equipment. Performance evaluations such as long-term on-site monitoring, permeability and hardness tests, and uniaxial tests were conducted. The results suggested that the bentonite-mixed cold asphalt exhibited low permeability, and therefore, effectively resisted water penetration. This effect appeared immediately after pavement construction and was maintained for at least one year, including in summer and winter. The hardness was not sufficient for use in pavements, and hardness improvement should be investigated in future studies. It could be used for emergency treatments to cover ground surface following further improvements.

Keywords: Cold mix asphalt, Bentonite, Long-term investigation, Permeability reduction

1. INTRODUCTION

Cold mix asphalt is produced without heating and regarded as ecofriendly, safe, and low-cost compared to traditional hot mix asphalt [1,2]. Cold mix asphalt is primarily used to repair pavements, especially potholes. Potholes cause many problems such as traffic accidents, vehicle damage, and environmental effects [3,4]. Various studies have been conducted on cold mix asphalt; for example, Gómez-Mejide and Pérez [5] proposed new methods to study mechanical properties of cold asphalt, including unconfined compression strength. Al-Hdabi et al. [6] developed a novel cold asphalt by adding Portland cement instead of mineral fillers. Shanbara et al. [7] examined high-performance cold asphalts using natural and synthetic fibers. Dong et al. [8] investigated cold asphalt using cement and bentonite to reduce moisture susceptibility. Baker et al. [9] revealed that bentonite-mixed asphalt concrete reduces damage caused by freeze-thaw cycles. Moses et al. [10] examined a self-healing asphalt including sunflower oil capsules as a rejuvenating agent. Recently, some commercial cold asphalts have exhibited higher strength compared to widely sold inexpensive ones.

The aforementioned proposals and products of

cold asphalt are prepared from raw materials using industrial equipment. On the other hand, various commercial products are sold in markets and widely used not only for rehabilitation of pavements but also for pavement construction in private yards. Kato et al. [11] evaluated mechanical properties of commercial cold asphalt products in Japan.

Based on long-term on-site investigations, Fukuma and Sato [12] revealed that the volumetric water content (VWC) in a ground consisting of a commercialized surface cold asphalt pavement and lower crushed rock layer is relatively high. Saadoon et al. [13] conducted dynamic water evaporation and hydraulic conductivity tests on cold asphalt and revealed the relationship between pore size distribution and evaporation rate during curing.

Large and public earth structures are commonly managed by the government; however, some earth structures such as small agricultural reservoirs are maintained by individuals in these regions. Many agricultural reservoirs were constructed in the Edo period in Japan, which have since deteriorated. Some suffer from water leakages [14]. Matsui et al. [15] investigated them in detail by installing various sensors. After heavy rain and increased water levels, easy methods are required to prevent dikes from eroding and rapid water penetration. Common

penetration-prevention methods use clay materials because some clay types have a water-stop effect; one of the most well-known clays is bentonite. Xu et al. [16] studied properties of backfills for soil-bentonite cutoff walls. This study revealed the optimal mixing content of bentonite. Yang et al. [17] investigated the waterproofing effect of bentonite-mixed cement and showed that it reduced the porosity and refined the pore structure. Sakoda et al. [18] confirmed the impervious effect of bentonite-mixed soil and showed that two construction methods using bentonite-mixed soil lowered the infiltration lines at a practical embankment.

Decreasing the permeability of commercial cold asphalt is sometimes required to prevent lack of uniformity and use it for surface protection from precipitation. We previously found that the permeability of cold asphalt decreased on mixing bentonite like other materials. This study developed an easy and novel permeability-reduction treatment method that adds bentonite to a commercial cold asphalt. The cold asphalt was mixed with bentonite on site, and no special equipment or materials were required. First, the mixing method was established and then long-term investigations and fundamental performances were evaluated on site. In addition, a laboratory stiffness test was conducted to determine the preferable mixture ratio of liquid. Data analysis of a long-term investigation revealed not only the effect of decreasing permeability but also the necessity to improve pavement construction methods. Finally, potential future on-site applications were considered and identified.

2. RESEARCH SIGNIFICANCE

This study contributes to the development of new and easy treatment methods for cold asphalt. Cold asphalt having low permeability can be used to repair narrow roads and prevent rapid surface injections. Various technologies have been proposed for novel cold asphalts, but this study aimed to improve a widely sold cold asphalt by mixing simple materials on site using general equipment. After improvement, the cold asphalt could be used especially for emergent repair, because the materials can be easily acquired.

3. TESTING MATERIALS AND SENSORS

A commercially available cold asphalt and bentonite, which are inexpensive, were used. In the trial stage, bentonite absorbed the volatile oil contained in the asphalt, and the asphalt was then scattered owing to the reduction in oil. This suggested that bentonite should be relatively wet.

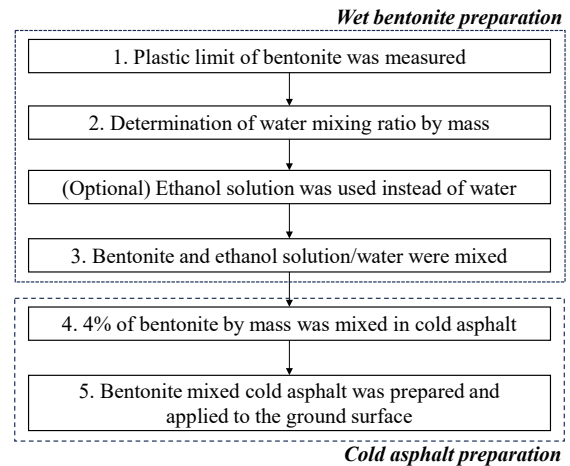


Fig. 1 Flowchart for preparation of the bentonite-mixed cold asphalt

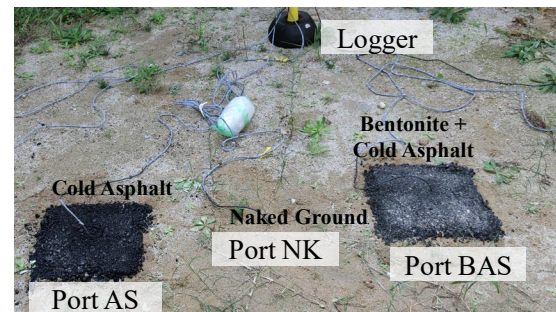


Fig. 2 Long-term measurement at Shimane University

Table 1 Conditions of the measured sites

Site	Pavement	Mixture
AS	Cold Asphalt	Cold Asphalt 5000 g
NK	Naked Ground	None
BAS	Bentonite-Mixed Cold Asphalt	Cold Asphalt 5000 g Bentonite 200 g Water, Ethanol 50 mL (total 100 mL)

The amount of mixed water was determined using the plastic limit test for bentonite. The water content of bentonite was adjusted close to the measured plastic limit of 45.4%. A smaller ratio is preferable to prevent bentonite swelling. In this study, bentonite-mixed asphalt pavements were constructed on a ground surface without a crushed rock layer. A 4% weight ratio of bentonite to asphalt was used. The weight ratio of bentonite to asphalt was selected referring to an existing bentonite-mixed soil [19]. A common but minimum ratio that could decrease the permeability was chosen in this study. In addition, the water in bentonite did not mix with the oil in the asphalt. Ethanol was tentatively mixed with water to prevent separation of materials. The total volume of

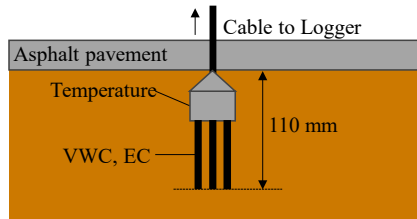


Fig. 3 Schematic of a buried sensor

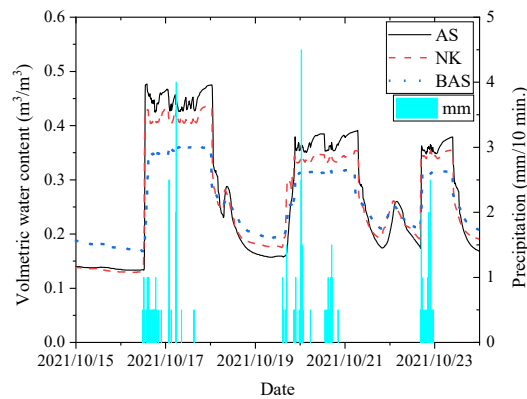


Fig. 4 VWC change in Period I

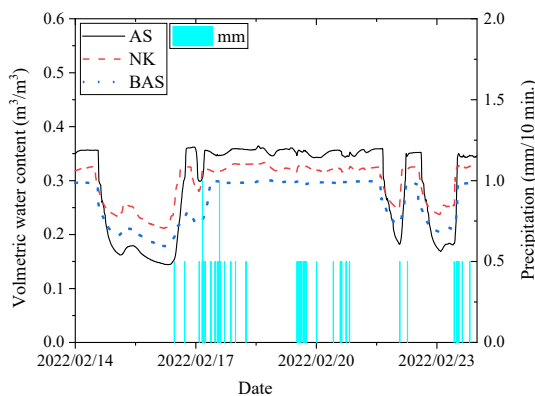


Fig. 5 VWC change in Period II

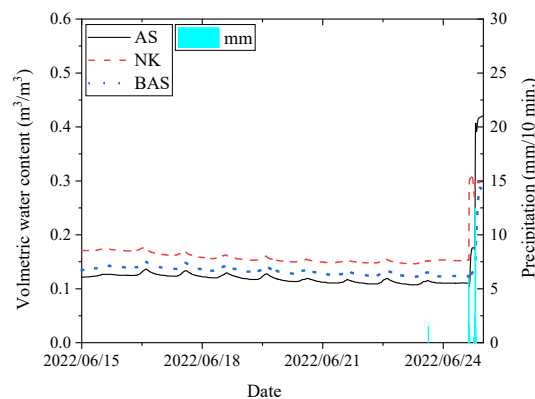


Fig. 6 VWC change in Period III

the mixed water, calculated from the plastic limit and specific gravity of water ($=1.0$), was not changed, even though a portion was replaced with ethanol, which has a lower specific gravity. A flowchart of the

preparation process is shown in Fig. 1.

This study used five moisture content sensors (5-TE manufactured by METER Group, Inc). The sensors are capable of measuring moisture content, ground temperature, and electrical conductivity (EC). The moisture content was automatically calculated from the voltage using the fitting equation provided in the 5TE sensor for the shortage of the examined soil. The calibration provided was the well-known Topp equation [20] for sandy materials.

4. LONG-TERM MEASUREMENT ON SITE

4.1 Preparation and Methodology

Bentonite-mixed cold-asphalt pavements were constructed at Shimane University, Japan (Fig. 2). The 5TE sensors were buried at depths of approximately 110 mm at three locations. A schematic is shown in Fig. 3. The sensors were fully buried in the ground to control the buried depth at the three locations. Note that the recommendation was to bury approximately 10 mm deeper for a more precise measurement. The temperature was measured in the upper portion, and the VWC and EC were measured in the lower pins. The horizontal measurement effected range was less than 600 mm. After the sensors were set, the ground was refilled with the original soil to the original surface height. Subsequently, a cold asphalt pavement was constructed at site "AS." The surface ground was just leveled at site "NK." A bentonite-mixed cold asphalt pavement was constructed at site "BAS." Both AS and BAS pavements were 350 mm square and 30 mm in thickness and consisted of approximately 5000 g of the cold asphalt. The asphalt was compacted manually using concrete blocks. The instant framework was prepared using concrete blocks, and the cold asphalt was evenly spread before compaction. At site BAS, 200 g of bentonite, 50 mL of water, and 50 mL of ethanol were mixed with the cold asphalt before pavement construction, and bentonite containing water and ethanol were prepared before mixing bentonite with the asphalt (Fig. 1). Table 1 summarizes the conditions of each port.

Preparation of the bentonite-mixed cold asphalt and pavement construction took several hours and were completed on October 13, 2021. The sensor values were logged every 10 min. This study referred to the 10-min precipitation data at the Matsue Meteorological Observatory published on the website of the Japan Meteorological Agency [20]. Measurements were conducted from October 13, 2021 to April 19, 2023. The garden at the university

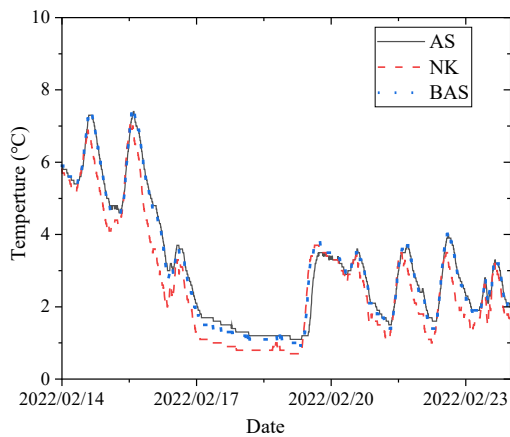


Fig. 7 Ground temperature during Period II

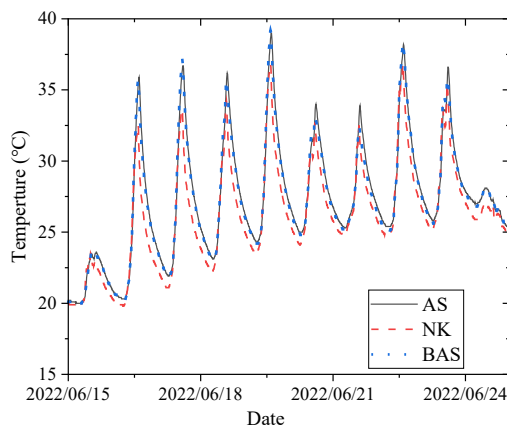


Fig. 8 Ground temperature during Period III

was reconstructed approximately a year before the investigation started, and the ground close to the surface was under almost uniform conditions. The surface ground was well-graded soil of less than 26.5 mm. The average particle size D_{50} was 2.45 mm. Fine content of less than 0.075 mm was 11.6%. Weeds did not grow, which can be seen in Fig. 1, because herbicides were used at the construction sites. During the investigation, weeds grew again around the cold asphalt but did not grow on the asphalt. In winter, snow accumulated on the asphalt but was not removed.

4.2 Measured Results

4.2.1 Moisture content

The measurement results for Periods I, II, and III are shown in Fig. 4–6, respectively. Specifically, Period I ranged from October 15, 2021 to October 25, 2021, which was immediately after construction of the pavement. Period II was from February 14, 2022 to February 24, 2022, which was four months after the pavement construction. Period III was from June 15, 2022 to June 25, 2022, which was eight months

later. Each period lasted 10 days and included precipitation. Snow was the precipitation that occurred during Period III.

Moisture content tendencies could be classified into three types: a) constant low values without precipitation, b) increase and decrease at the start and end of precipitation, and c) constant high values with continuous precipitation. The moisture content was partially affected by the initial non-uniformity of the ground, such as the density and disturbance surrounding the sensors, which has also been suggested in previous studies [12,15]. The values without precipitation in case (a) were almost similar for all the sites. In Period I, the AS site exhibited slightly lower values than the other ports, but no obvious differences due to the permeability-reduction effect were observed. The BAS site had the highest value, probably because a wet pavement covered the ground. The AS site had the highest values with continuous precipitation in case (a), and the BAS site had the smallest due to permeability-decreasing effect. In Period II, the moisture content of the NK site in case (c) was high during the precipitation intervals; however, its cause was not revealed by this study. The values with continuous precipitation in case (c) differed between the sites, but trends were similar to those in Period I. In Period III, precipitation was limited, and the NK site value was the highest in case (a).

The changes in VWC in case (b) are subsequently discussed; but the increasing and decreasing speeds at the BAS site were lower than those at the other sites. The absolute changes were also smaller at the BAS site, which can be attributed to the permeability-decreasing effect of bentonite during precipitation. The abovementioned results were roughly consistent throughout the periods. The cold asphalt solidified within one day and its quality was maintained, although the warranty period was one year.

4.2.2 Ground temperature

The changes in ground temperature are shown in Fig. 7 and 8. Only two periods are considered: Period II in winter and Period III in summer.

In Period II, temperatures at all sites were almost similar. In Period III, the NK site, which was not covered by asphalt, exhibited a lower temperature than the other ports covered by asphalt. A previous study [12] suggested that the ground temperature under asphalt pavements decreases when a crushed rock layer is constructed under the asphalt surface.

4.2.3 Electrical conductivity

Fig. 9 and 10 depict the variations in EC in Periods I and II. EC is generally known to be proportional to

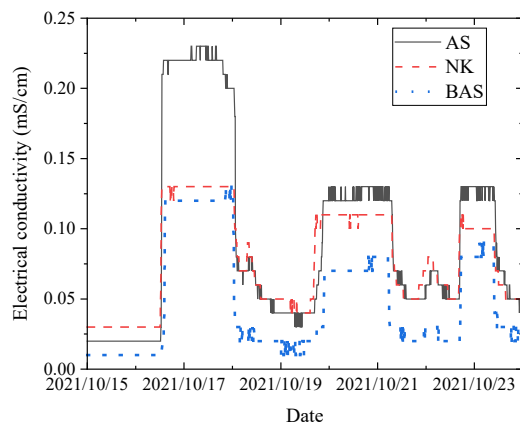


Fig. 9 Electrical conductivity during Period I

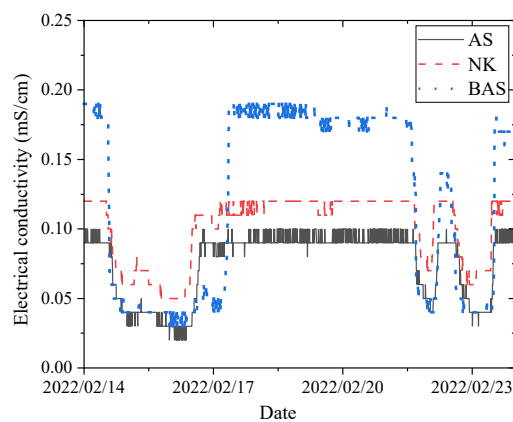


Fig. 10 Electrical conductivity during Period II

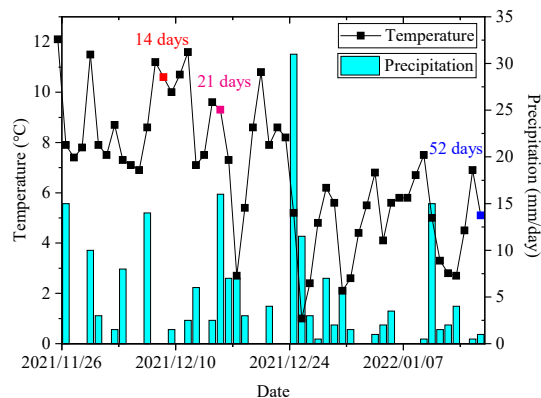


Fig. 11 Weather conditions during investigation

moisture content because the permittivity of water is higher than that of air and is also affected by the ion content of water. The results did not show steady trends in the moisture content and EC throughout the year, except for a simultaneous increase and decrease. The tendency was similar for the two properties in Period I; however, the AS site sometimes exhibited a much higher EC with precipitation than the other sites. Conversely, the EC of the BAS site was evidently high during Period II,

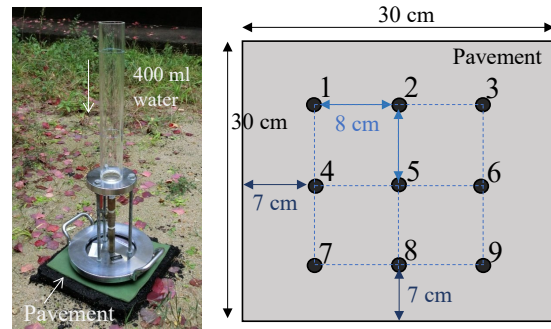


Fig. 12 (left) Field asphalt permeability test

Fig. 13 (right) Measured points of the soil hardness test

Table 2 Results of the field asphalt permeability test

	Cold Asphalt		Bentonite-Mixed Cold Asphalt	
	14 days after	21 days after	14 days after	21 days after
Field Permeability (mL/15 s)	1176	1071	411	196
Minimum	1115	1032	399	176
Maximum	1274	1099	418	225

even though the moisture content was lower than that of the other ports. The reason for this was not determined in this study. However, intermittent snow was observed during that period, and the snow covered the pavements and ground, which probably influenced the EC.

5. ON-SITE PERFORMANCE EVALUATION

5.1 Testing Asphalt Pavements

Two types of asphalt pavements were constructed in the vicinity of the long-term measurement location: a cold asphalt pavement, which was the same as for the long-term measurement, and a bentonite-mixed cold asphalt pavement for two types of field tests. The mixed proportions and amounts were the same as those in the long-term measurements, except for the amounts of ethanol and water. Water (20 mL) and ethanol (60 mL) were mixed to improve the hardness of the bentonite-mixed asphalt for long-term measurements. The asphalt pavements were 300 mm square and 40 mm thick; this thickness was slightly different from that in the long-term measurements as the pavements were manually constructed on November 26, 2021. The weather conditions during the on-site tests are shown in Fig. 11. Applied data was One-day cumulative precipitation and average temperature of Matsue Local Meteorological Observatory [21]. Temperature

Table 3 Results of the soil hardness test

Point	Cold Asphalt (kg/cm ²)	Bentonite-Mixed Cold Asphalt (kg/cm ²)
1	10.01	0.65
2	37.73	1.40
3	13.97	1.18
4	10.01	3.02
5	30.14	1.92
6	10.01	0.98
7	13.97	0.98
8	11.79	0.98
9	20.09	0.51
Avg.	17.52	1.29

and precipitation were not significantly different between 14 and 21 days after the permeability test was conducted. Temperature was approximately 8–12 °C. No heavy rainfall was observed before soil hardness measurement 52 days after the construction.

5.2 Field Asphalt Permeability Test

MLIT Japan has established road pavement standards, and the volume of water penetration for 15 s was measured to evaluate the asphalt permeability [22]. As shown in Fig. 12, the field permeability test apparatus is placed on the asphalt. Water (400 mL) was allowed to penetrate from the apparatus cylinder into the asphalt pavement, and the volume of water penetration per 15 s was measured. The inflow was repeated four times, and three measurements, except the first inflow, were averaged. The test series was conducted twice: two and three weeks after construction. The results are summarized in Table 2. The values were almost uniform throughout the test, and the maximum and minimum values calculated from the three measurements are listed in the table. Two weeks after construction, the cold asphalt pavement exhibits high permeability, beyond the standards required for Japanese national roads. The permeability slightly decreased but did not change significantly after three weeks. The bentonite-mixed cold asphalt exhibited a significantly lower value: approximately one-third of the cold asphalt value after two weeks. These values were similar to those of the standards set for general roads in Japan. The permeability decreases sharply between two and three weeks after pavement construction.

5.3 Soil Hardness Test

A soil hardness test was conducted because the cold asphalt was not very hard. A normal Yamanaka soil hardness tester was used, in which the conical tip penetrates the ground, and the string resistance is measured to convert the penetration resistance. The test was performed 52 days after solidification. Nine points at intervals of 8 cm are measured on each asphalt pavement, as shown in Fig. 13.

The penetration resistance values are listed in Table 3. The average of nine points was calculated for each type of pavement. Resistance to the bentonite-mixed pavement was clearly smaller than of that without bentonite; the bentonite-mixed asphalt exhibited only 7% resistance to the cold asphalt. A dense ethanol solution may promote a decrease in the soil hardness, as discussed in the following chapter. During the long-term measurements, we observed that the bentonite-mixed pavement repeatedly expanded and softened with precipitation. Therefore, the strength development was not adequate when the bentonite was mixed. This is potentially because the bentonite swelling interrupts the cold asphalt solidification.

5.4 Summary of Permeability and Soil Hardness test

From Table 2 and 3, bentonite decreases the permeability by 20 % 21 days after the construction. On the other hand, soil stiffness of the bentonite-mixed cold asphalt is just 7% of that without bentonite 52 days after the construction. The permeability of the bentonite-mixed cold asphalt gradually decreases over time, but the soil stiffness is lost because bentonite swells on absorbing water. Soil hardness varies with the measured points. The maximum stiffness at the measured points is 3.02 kg/cm² for the bentonite-mixed cold asphalt. The minimum stiffness of the cold asphalt without bentonite is 10.01 kg/cm². If we consider the local distributions caused by the insufficiency of mixing and compaction for the bentonite-mixed cold asphalt, the loss of soil stiffness is obvious, and improvement methods should be proposed in the future.

6. EFFECTS OF THE RATIO OF ETHANOL AND WATER ON THE STRENGTH

6.1 Test Procedures and Conditions

To evaluate the effect of the ratio of mixed ethanol and water, unconfined compression tests were performed under various conditions. First, each

Table 4 Mix conditions of the uniaxial test

	W4E4	W2E6	W8E0
Cold Asphalt (g)	500	500	500
Bentonite (g)	20	20	20
Ethanol (mL)	4	6	0
Water (mL)	4	2	8

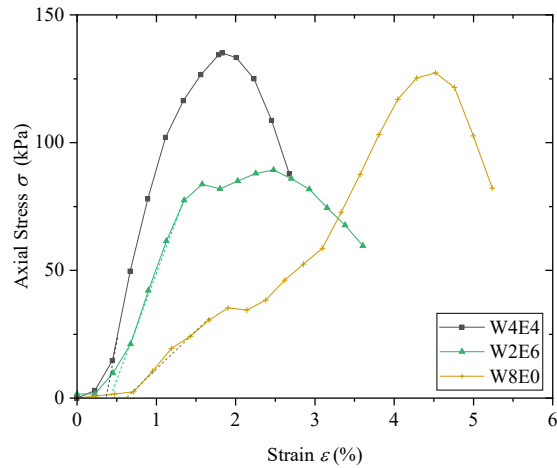


Fig.14 Stress-strain curves

Table 5 Results of the uniaxial test

Case	q_u (kPa)	ϵ_t (%)	E_{50} (MN/m ²)
W4E4	135.1	1.63	10.1
W2E6	89.3	2.27	4.5
W8E0	127.4	3.75	2.3

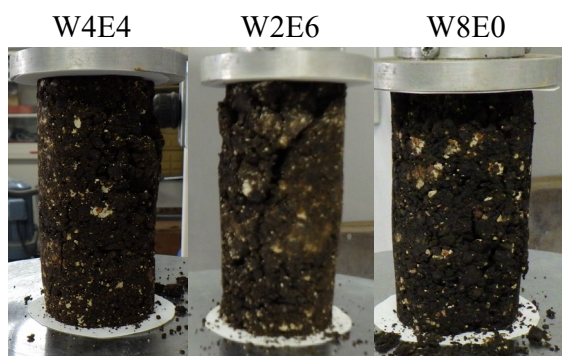


Fig. 15 The specimens after shearing

test specimen was formed in a metal mold with a diameter of 50 mm. The height of each specimen was approximately 100 mm. First, 500 g of the cold asphalt was mixed with 20 g of bentonite and small amounts of water and ethanol, as listed in Table 4. The compounding conditions for water and ethanol are in the table as W4E4, W2E6, and W8E0. The total

amount of water and ethanol used was 8 mL in all cases. Then, the bentonite-mixed cold asphalt was compacted by a 2.5 kg rammer tamping the wooden pile above the surface soil. The number of tappings corresponded to 37.5 in the standard compaction test, JIS A 1210 [23]. Specifically, the tamping was performed 9 times and each specimen was densely compacted. All specimens were demolded one day later and air-cured for 28 days in a temperature-controlled room. After the curing, the specimens were sheared under 1% compressive strain per min.

6.2 Stress-Strain Curves and Stiffness

The stress-strain curves for the three cases are shown in Fig. 14. The compressive strength q_u , failure strain ϵ_t , and deformation modulus E_{50} are listed in Table 5. The failure strain and deformation moduli were calculated using an adjusted origin.

The modulus was E_{50} according to JIS A 1216 [23]. The specimens were imaged after shearing, and examples are shown in Fig. 15. The unconfined compressive strength was low for W2E6, whereas the other two cases exhibited similar strengths. The deep failure cracks after shearing suggested that the solidification was weaker than that in the other cases. The high concentration of the ethanol-water solution potentially caused a decrease in the strength. The failure strain was the smallest for E4W4. The deformation modulus of E4W4 was clearly larger than that of E8W0 even though their strengths were similar. Hence, the stiffness was probably improved by the mixture of ethanol.

The number of cases was limited to determine the overall influence of the ethanol solution on the mechanical properties. Watanabe et al. [24] suggested that examining the unconfined compression strength of asphalt is difficult because of various factors, e.g., temperature, production technique, crude oil production area, specimen preparation method, and loading speed. Our series of experiments was conducted under the same conditions, and we estimated the differences in mechanical behaviors among the tests caused by the concentration of ethanol solutions. The test specimens were not submerged to prevent swelling of bentonite and strength reduction. The initial compaction and solidification brought the differences. Approximately 50% ethanol solution was profitable because both stiffness and strength were high when we did not consider onsite applicability. Details of this mechanism that ethanol solution brought are discussed in the following chapter.

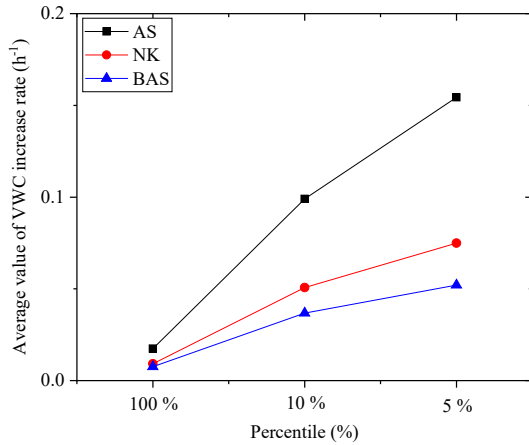


Fig. 16 Average of the VWC increase rate

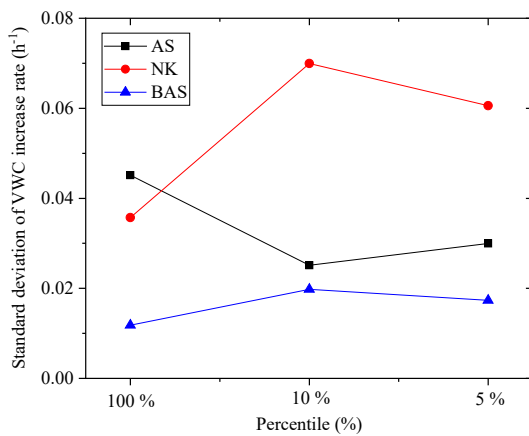


Fig. 17 Standard derivation of the VWC increase rate

7. DISCUSSIONS

7.1 Data Analysis of Long-term measurement

To reveal the constant trends of the permeability-decreasing effect, massive data of the long-term measurements were extracted and analyzed. The VWC variation rate over time by precipitation was estimated from all measurement data from October 13, 2021 to April 19, 2023 using the following method:

1. The data were extracted every 1 h, and the time interval was changed from 10 min to 1 h to remove fluctuations in a short period.
2. The data that three measurements of AS, NK and BAS were completed for one measurement, were extracted. In other words, the data containing invalid values were removed.
3. Absolute values of the VWC variation per hour were calculated.
4. To obtain obvious changes, variations of 0.02 or more were extracted.

Using these steps, the number of remaining data was 1574 and analyzed. The analytical method regarded that the remarkable changes were derived from

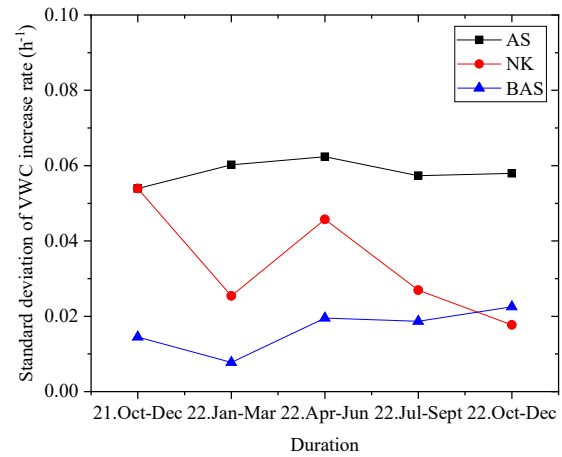


Fig. 18 Temporal variations of the average VWC increase rate

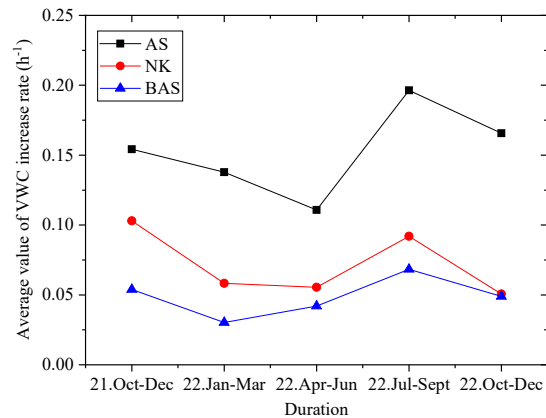


Fig. 19 Temporal variations of the standard derivation of VWC increase rate

precipitation. Because the beginning of the increase by precipitation was not the same at the three sites, extraction using the precipitation data was difficult.

The average variation rate at each measurement site is shown in Fig. 16. 5% and 10% percentiles were extracted and averaged and were assumed to largely increase during heavy rainfall. The AS site had the highest and the BAS site had the lowest values, regardless of the percentile. The value at the BAS site was lower than that at the NK site, especially for 5% percentile. The standard deviation is depicted in Fig. 17. The standard deviation of all extracted data was the highest for the AS site and smallest for the BAS site. On the other hand, the NK site showed the highest standard deviations for 5% and 10% percentile. The BAS site had the lowest value regardless of the percentile. These tendencies suggested that the AS site caused the most rapid increase in the VWC. The reason for this was not revealed by this study; however, the surface evenness may not be adequate, causing water to collect in small hollows. Nevertheless, the average

rate of increase at the NK site was smaller than that at the AS site, and standard deviation was the largest. This trend revealed that water was not collected in hollows like at the AS site. However, precipitation, especially heavy precipitation, directly influenced the VWC under the ground at the NK without covering. The BAS site showed the smallest average rate and standard deviation, which indicated that the permeability-decreasing effect was effective and that the increase in the VWC was gradual.

Fig. 18 and 19 depict the temporal variations in the average and standard deviation over three months during the investigation. The last three months of the study duration, from January to March 2023, were excluded because many null values appeared and the amount of data extracted was limited. The tendencies during the investigation period were not significantly changed, similar to the tendencies in the entire duration. However, the average and standard deviation of the NK and BAS sites were similar after October 2022. One year after construction, the permeability-decline effect may disappear owing to the washout of bentonite due to repeated precipitation.

7.2 Advantages and Application to the Practical Sites

The developed instant bentonite-mixed cold asphalt is inadequate for practical use because various issues remain unresolved. The most significant issue is the lack of stiffness and hardness, because bentonite swells with precipitation. The bentonite-mixed cold asphalt is soft, especially after precipitation.

However, the bentonite-mixed cold asphalt can be easily and rapidly prepared by simply mixing bentonite with the cold asphalt. Unconfined compression tests revealed that ethanol improves the deformation modulus, but is not always required. Both field investigation and field permeability tests clearly showed that bentonite decreases the permeability, even though only 4% mass ratio of bentonite is mixed. Bentonite can swell and cause water to absorb in pores of the cold asphalt. When water penetrates from the surface, some portion of water is absorbed, and the VWC increase becomes gradual. The effect of the ethanol solution is not clearly determined; however, ethanol may prevent segregation between the cold asphalt and bentonite during compaction. The bonding between bentonite and cold asphalt does not affect the strength but does affect the stiffness. In addition, ethanol volatilizes fast after preparation, thereby decreasing the total amount of water and increasing the suction

of bentonite [25]. Dense ethanol induces insufficient water content in bentonite, which could cause a lack of dense compaction and absorption of the surrounding oil, which could probably decrease the strength. However, bentonite swelling collapses the structure of the cold asphalt and bentonite during compaction, and this effect limits its practical use. Tamping equipment is not required, although sufficient tamping may improve the performance. This is applicable within one day of construction. Removal is also easy and possible using shovels when the pavement is constructed with the bentonite-mixed cold asphalt only. Additionally, cold asphalt and bentonite are cheap materials and are widely available for sale.

Further studies are needed to apply this method at practical sites. Bentonite-mixed cold asphalt will be able to be used in the emergency treatment of earth structures. For example, covering ground surfaces prevents intense water penetration during heavy rainfall; however, it cannot completely stop water seepage. The bentonite-mixed asphalt can cover specific weakened parts, such as cracks, where water preferentially infiltrates. These possess narrow and complex shapes.

Pavement permeability is generally high for traffic, especially on highways. However, sinkholes are caused by the rapid generation of underground cavities with high permeability in subgrade soil [26-28]. Cold asphalt is often used to fill potholes. The differences between reburied potholes and pavements may induce nonuniform and concentrated seepage from the surface. Bentonite-mixed cold asphalt can be used as a pavement with a permeability similar to that of the surrounding pavement. However, its stiffness should be improved.

8. CONCLUSIONS

This study aimed to develop an easy-to-prepare low-permeability cold asphalt. A bentonite-mixed cold asphalt was prepared, and its properties were investigated. However, certain issues must be resolved for practical applications. The conclusions are summarized below.

1. Mixing of bentonite decreased the cold asphalt permeability, which was clearly revealed by the field permeability tests. The same tendency was constantly obtained from the data analysis of long-term investigation. The increase in the VWC rate with respect to precipitation was gentle under the bentonite-mixed cold asphalt pavement and was maintained for a year. Therefore, the bentonite-mixed cold asphalt was placed for approximately one year,

- including summer and winter, and the permeability-decreasing effect was maintained.
2. Water should be mixed with bentonite before construction because it absorbs oil from the cold asphalt. Water and oil are immiscible, and an ethanol solution was used instead of water. Strength and stiffness were evaluated using an unconfined compression test. The strength decreased as the ethanol solution became denser. However, the deformation modulus of the specimen was low when only water was added. The effects of ethanol solutions should be investigated in the future because of the lack of experiments in this study. For onsite applications, adding only water is recommended.
 3. The most severe issue for the bentonite-mixed cold asphalt was the decrease in stiffness, as suggested by the onsite soil hardness tests. This was because the bentonite swelling disturbed the asphalt solidification. This improvement should be discussed in future studies. For example, low-plasticity clay, which was not addressed in the present study, may remedy this issue. However, certain clay materials are difficult to purchase.
 4. The optimal combination ratio of the materials was not evaluated in this study. It was estimated that an increase in the bentonite content caused a decrease in the permeability, similar to the bentonite-mixed soil. The bentonite-mixed cold asphalt is easily prepared and removed, and has low permeability. After improvement in further studies, it could be practically applicable, such as in emergency treatment and prevention of rapid penetration. After stiffness improvement, it can be used for road pavements.

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