DEVELOPMENT OF LONG-TERM UNDERGROUND THERMAL ENERGY STORAGE ROADWAY SNOW-MELTING SYSTEM

Etsuhiro Isobe, Kazuyuki Minda,Tsukuru Keino and Minoru Yamamoto

Waterworks Engineering Dept., Environment and Waterworks Division,
Nippon Steel Corporation
TEL:+81-3-3275-7047 / FAX:+81-3-3275-6781
E-mail : isobe.etsushiroh@eng.nsc.co.jp

1. Abstract

The cold, snow-covered regions in Japan account for nearly 61% of the total area of the slender Japanese archipelago extending from north to south. The expansion of distribution networks in recent years has been driving up the demand for non-water spraying type snow-melting systems, ensuring mobility and creating a safe living environment even in extreme snow-belt and mountainous areas during the winter months. The authors have been actively involved in the technical development of snow-melting systems that make effective use of natural energy, aiming to construct an eco-friendly snow-melting system and to cut down running costs of non-water spraying type snow-melting systems. Among its projects, The authors have developed the new snow-melting system incorporating long-term (seasonal) thermal energy storage technology that harnesses solar energy, which has no detrimental effects on the region's ecology, and which can be collected in adequate amounts in the summer season. The features of the new snow-melting system are: (1) A snow-melting system in which road heating pipes buried under roads are used for collecting solar energy during the summer season and for raising the temperature of the water circulating in them. Thus, the solar energy is collected and stored as thermal energy under the ground. In winter, the heat stored underground is recovered effectively and used to melt the snow on the road through the heating pipes. (2) Borehole thermal energy storage (BTES) that is very economical and generally unaffected by constraints of the installation location and the excavation cost. Multiple boreholes are excavated vertically into which heat exchanger pipes are inserted for exchange of heat between hot water and underground heat. (3) By backfilling the space between the heat exchanger pipe and the borehole with a heat-transfer filler (filler containing grout mixed with carbon or iron particles) having high thermal conductivity, effective heat exchange becomes possible.

Results as given below were obtained from tests carried out to evaluate this system.

(1) The amount of solar energy collected by the asphalt pavement was 3.4 [MJ/m2] in August, 1.2 [MJ/m2] in September and -0.2 [MJ/m2] in October. The amount of solar energy collected by the asphalt pavement was about 20% of the unobstructed solar radiations received by the pavement.

(2) The borehole heat recovery rate varies depending on the input temperature of the heat exchange pipes but this rate was stable over the long term.

(3) It is possible to improve the heat transfer rate underground by using a heat-transfer filler. Compared to conventional fillers, the heat recovery performance increases by a factor of about 1.16 when mixed with carbon particles and by a factor of 1.43 when mixed with iron particles.

2. Introduction

Existing non-water spraying type roadway snow-melting equipment generally make use of an electrical heating system. Or, the equipment may use a hot water circulation system, with a road heating pipes and a hot-water boiler used as the heat source. The electrical heating system requires an enormous amount of power and running costs are extremely high. Moreover, the hot water circulation system makes use of fossil fuels because of which the discharge of CO_2 and NO_x gases to the atmosphere becomes an environmental problem. After the Kyoto Convention (UNFCCC;COP3), there is a worldwide demand to cut down fossil fuel, which is one of the main reasons for the generation of gases that cause global warming.

The authors have been actively involved in projects related to snow-melting systems for roads and railways. The authors have developed and realized numerous eco-friendly energy-saving roadway snow-melting systems aiming to activate cold regions that are covered with snow in winter. To achieve effective use for the natural energy expected in recent years, the authors have developed a new roadway snow-melting system that effectively harnesses solar energy and is generally unaffected by constraints on the installation

This report discusses the new snow-melting system and the results of field tests carried out to evaluate its performance.

3. Long-term Underground Thermal Energy Storage (UTES) Roadway Snow-melting System

3.1 Selection of natural Energy

Among various forms of energy available in nature such as wind power and river water, solar energy is a source of energy that is generally unaffected by regional constraints. If solar energy is to be utilized in cold regions, however, issues such as seasonal variations and low density need to be tackled because in such regions, the solar energy available for use in the winter season may be inadequate even though it may be available in profusion in the summer season. Consequently, thermal energy storage of solar energy over a long period (throughout the season) is necessary if it is to be used for melting snow on the roads.

The method of storing heat underground has been widely used in the west for long-term thermal energy storage. Thermal energy storage methods may be classified into aquifer, borehole and rock thermal energy storage methods [1,2]. Among these, BTES, which is generally unaffected by constraints on the installation location and can be constructed most economically, was. This BTES consists of installing heat exchanger pipes in multiple bore holes excavated vertically, storing underground the collected solar energy and heat emitted during cooling, and recovering the heat stored underground when necessary. The space between the bore hole and the heat exchanger pipes is backfilled using grout such as mortar or bentonite, or excavated soil or sand. Although the ability of mortar or bentonite to fill up the space is good, its thermal conductivity is poor. This is one factor that obstructs the exchange of heat underground, and is therefore a topic that needs to be investigated.

3.2 System Configuration

Fig. 3.1 shows the newly-constructed long-term underground thermal energy storage (UTES) roadway snow-melting system. This system uses road heating pipes, which are buried under the road for melting snow in winter, as the solar energy collection medium. By circulating hot water in these pipes, the solar energy can be collected and stored underground. In winter, the heat stored

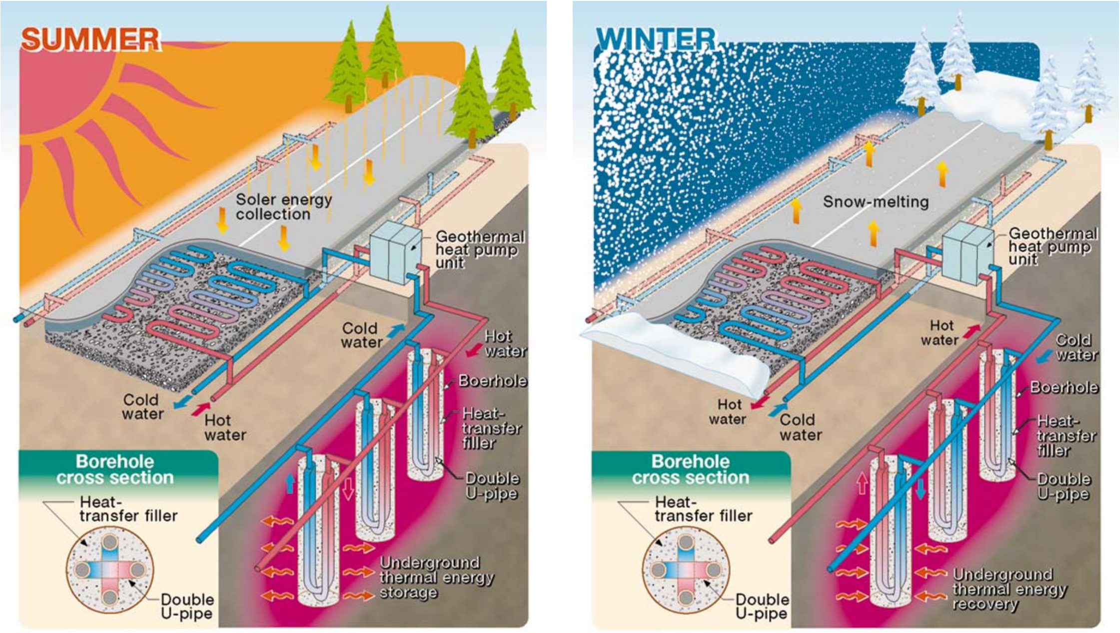

Fig. 3.1　Long-term UTES Roadway Snow-melting System

underground is retrieved and used to effectively melt the snow on the road through the heating pipes.

To enhance the heat transfer performance underground, which is an issue in BTES, the space between the bore hole and the heat exchanger pipes in this system is backfilled with a heat-transfer filler with good thermal conductivity (filler consisting of grout mixed with carbon particles or iron particles). The properties required of the heat-transfer filler are good flowability so that all spaces are properly filled, and high thermal conductivity so that heat is adequately transferred underground. To satisfy the properties mentioned above, the grout (cement, bentonite, water), which is a filler, and carbon or iron particles, which enhance thermal conductivity, need to be mixed at the optimum mixing ratio.

To evaluate the reliability of this system, field tests were carried out using a test plant.

4. Overview of Tests

4.1 Test Plant

4.1.1 Overview of Equipment

The test plant was installed within the premises of the Research Center of Nippon Steel Corporation at Futtsu. Fig. 4.1 shows the flow chart of the test plant. The test plant consists of bore holes for UTES, the asphalt pavement for collecting the solar energy in summer, heat pump and cooling tower for cooling the heat recovered in winter, etc.

The asphalt pavement that collects solar energy in summer was made of drainable asphalt and used steel heating pipes (SGP-PIC 15A) at a

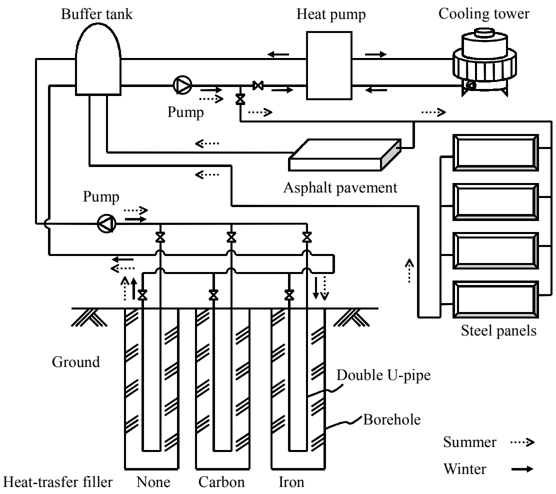

Fig. 4.1　Flow Chart of the Test Plant

pitch of 200 mm. The area of the pavement was 10 m^2 (4 m x 2.5 m), and consisted of 3 layers with a thickness of 150 mm. The heating pipes were laid 80 mm from the surface of the asphalt. Not only asphalt pavement but also panels made of steel plates were used for collecting the solar energy in summer.

4.1.2 Boreholes

Three boreholes of diameter 150 mm and depth 31 m were excavated. The three boreholes were arranged at the corners of an equilateral triangle at a spacing of 5 m. Since the soil consisted of fine sand layers with an N-value of 50 at 20 m below the ground level, the rotary percussion method was used to excavate the boreholes. The heat exchanger pipes to be inserted in the boreholes had a diameter of 16 mm (outside diameter 22 mm, thickness 2.4 mm), length of 30 m and were made of polybutene doubleU-pipe.

4.1.3 Heat-transfer Filler

The space between the borehole and the heat exchanger pipe was backfilled by three kinds of filler: (1) grout only(None); (2) carbon particles + grout(Carbon); and (3) iron particles + grout(Iron). Grout containing a mixture of water, cement and bentonite was used. To increase the heat transfer rate, a higher percentage of carbon or iron particles needs to be mixed. However, if this percentage is too high, flowability is lost and the original objective of adequately filling all the spaces may not be satisfied. Therefore, laboratory tests were carried out beforehand to confirm the mix proportion and to ensure that adequate flowability is maintained during the backfilling operation. The results of tests [3] carried out at the authors showed that the thermal conductivity of each of the heat-transfer fillers was as follows: (1) None: 0.19 [W/mK]; (2) Carbon: 1.13 [W/mK]; and (3) Iron: 1.14 [W/mK].

4.2 Test Method

4.2.1 Measurement Method

Table 4.1 shows the schedule of all the tests. Measured items include various temperatures and flow rates, and the power consumption of various equipment. Resistance thermometer element (Pt100 ohms) was used for temperature measurements. The measured temperature data was automatically stored using the data logger and the personal computer. A flapper type local indicating flowmeter was used, the flow rate visually observed and recorded. The power consumption was measured by an integrating wattmeter. Data could not be measured and recorded during a 12-day period from 2001/03/15 to 2001/03/26 because of the breakdown of the data logger in this period.

4.2.2 Solar Energy Collection and UTES Tests

Solar energy was collected in summer by circulating anti-freezing solution in the heating pipes. The heated anti-freezing solution circulating in the heating pipes is sent to the buffer tank. UTES is performed by transferring the anti-freezing solution from the buffer tank to various boreholes.

The solar energy collection tests were

Table 4.1 Overall Test Schedule

Test	Period	Days
Underground heat recovery in the 1st year	2000/01/21 ～ 2000/03/31	71
No operation	2000/04/01 ～ 2000/07/29	120
UTES test in the 1st year	2000/07/30 ～ 2000/10/17	80
No operation	2000/10/18 ～ 2000/12/29	73
Underground heat recovery in the 2nd year	2000/12/30 ～ 2001/04/06	98

performed by varying the heat collection time and the circulation flow rate in the asphalt pavement. Heat was collected at the timings mentioned below considering the daylight time: 05:00 to 17:00, 05:00 to 19:00, 0:00 to 24:00 (round the clock). Tests were also carried out by varying the circulation flow rate through 10 [l/min.], 12 [l/min.] and 15 [l/min.] On the other hand, during UTES tests, the circulation flow rate in all the boreholes was kept constant at 15 [l/min.] The thermal storage timings of the boreholes were kept the same as the solar energy collection timings.

4.2.3 Underground Heat Recovery Tests

During the underground heat recovery tests in winter, the anti-freezing solution was cooled and delivered to the buffer tank using the heat pump. The anti-freezing solution was circulated from the buffer tank to the boreholes and heat was recovered. The heat generated in the heat pump was radiated to the atmosphere in the cooling tower.

Table 4.2 shows the conditions of the underground heat recovery tests. Tests carried out included "continuous tests" in which heat was recovered continuously from the bore holes and "intermittent tests" in which heat was recovered for a certain fixed duration in a day and stopped. The temperature of flow into the heat exchanger pipe varies for each operation. Tests were carried out in the high temperature range during "continuous operation" and in the low temperature range during "intermittent operation". The actual temperature measured during the tests was 8.7°C in the first year and 9.1°C in the second year in the high temperature range; it was -0.1°C in the first year and 1.8°C in the second year in the low temperature range.

Table 4.2 Conditions of Underground Heat Recovery Test

	First Year		Second Year	
Operating period	2000/01/21 ～2000/03/06	2000/03/07 ～2000/03/31	2000/12/30 ～2001/02/04	20001/02/05 ～2001/04/06
Operating condition	Continuous	Intermittent	Continuous	Intermittent
Temp. range of circulating liquid	High temp. range (8.7°C)	Low temp. range (-0.1°C)	High temp. range (9.1°C)	Low temp. range (1.8°C)

5. Test Results and Discussion

5.1 Solar Energy Collection and UTES Tests

5.1.1 Amount of Solar Energy Collected

Fig. 5.1 shows the amount of solar energy collected by the asphalt pavement. The values of amount of unobstructed solar radiations shown in the graph have been extracted from monthly meteorological data of the Meteorological Agency (edited by the Meteorological Agency). The Tokyo observation site, which is the site closest to the test location, was taken. The ratio of amount of unobstructed solar radiations and the amount of energy collected by the asphalt pavement is indicated as the energy collection rate of the asphalt pavement.

The amount of energy collected by the asphalt pavement is maximum in August when the number of days on which unobstructed solar radiations is received is maximum. The average value of solar energy recovered in August was 3.4 [MJ/day]. The average value of solar energy recovered in September was 1.2 [MJ/day] (about 35% of the value in August). The average value of energy collected in October is -0.2 [MJ/day], indicating that heat is radiated from the asphalt pavement rather than being collected. The energy collection rate of the asphalt pavement before the second half of September was about 20%. After the second half of September, the value of amount of unobstructed solar radiations decreases, radiation of heat from the asphalt pavement can also be observed, and the energy collection rate becomes extremely small. Though tests were carried out from August to October, in the Hokkaido and Tohoku districts, where snow on the roads needs to be melted, the number of days on which unobstructed solar radiations are received becomes maximum in May or June. Thus, in practice, solar energy needs to be collected starting from May and June.

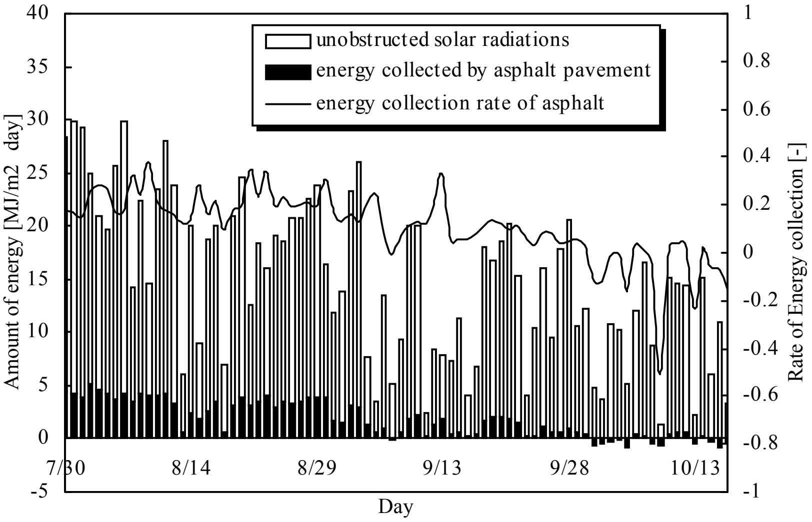

Fig. 5.1 Amount of Energy Collected by Asphalt Pavement

Fig. 5.2 shows the test data for August 23. This graph indicates the amount of energy collected by the asphalt pavement, the amount of unobstructed solar radiations, the temperature of outside air, and the temperature of the buffer tank. On this day, the circulation pump was operated round the clock (0:00 to 24:00) and energy was collected. The time period at which unobstructed solar radiations could be received was from 5:30 to 19:30. The collection of solar energy started from around 7:30 and even after unobstructed solar radiations could no longer be received after 19:30, energy was collected until around 24:00. This indicates that even after the sun sets, the energy stored in the asphalt pavement can be collected. Until the pavement temperature increases, solar energy cannot be collected because the thermal capacity of the asphalt pavement is large. Accordingly, if a system is constructed that operates automatically according to the temperature of the asphalt pavement or the amount of unobstructed solar radiations, then heat can be collected efficiently.

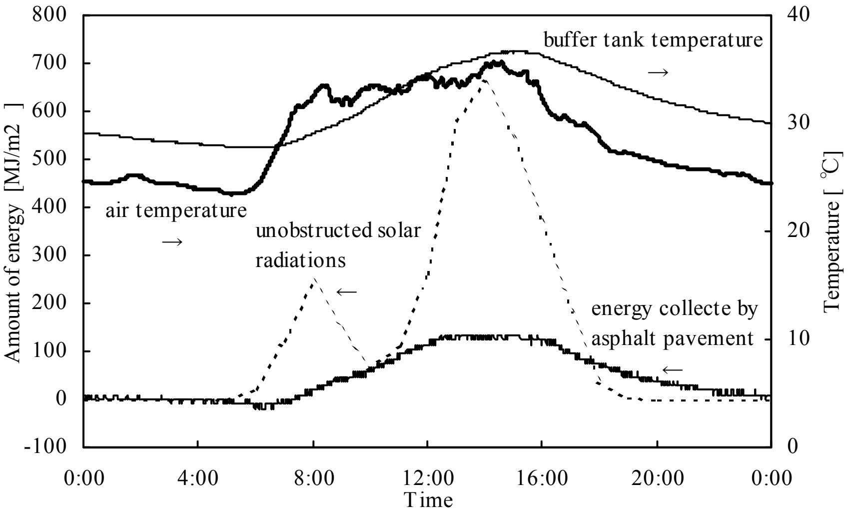

Fig.5.2 August 23, 2000 - Test Data

5.1.2 Amount of Heat Stored Underground

Fig. 5.3 shows the heat injection rate underground for three kinds of heat-transfer fillers and the cumulative amount of heat stored underground in the three boreholes. The heat injection rate mentioned here, is a value that indicates the amount of heat injection per unit excavated depth (length of heat exchanger pipe). The heat injection rate is highest when Carbon is used, followed by the case when None is used, and then by the case when Iron is used. The cumulative underground heat storaged amount during these tests was 12.1 [GJ].

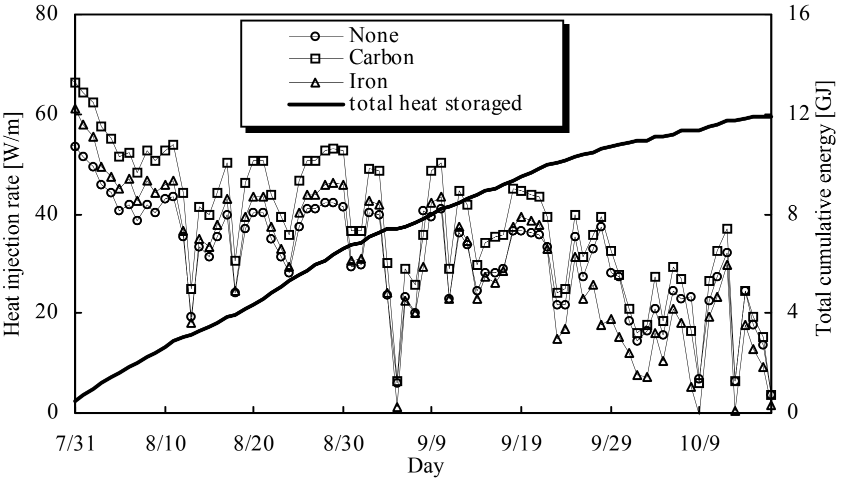

Fig.5.3 Heat Injection Rate / Total Cumulative Energy

5.2 Underground Heat Recovery Tests

5.2.1 Amount of Underground Heat Recovered

The amount of underground heat recovered during the first year and the cumulative values are shown in Fig. 5.4. Fig. 5.5 shows the amount of underground heat recovered during the

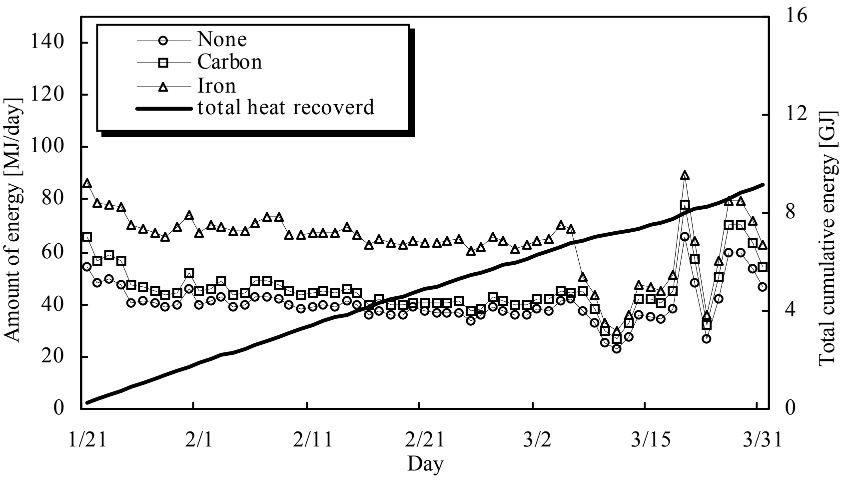

Fig.5.4 Underground Heat Recovery in the First Year

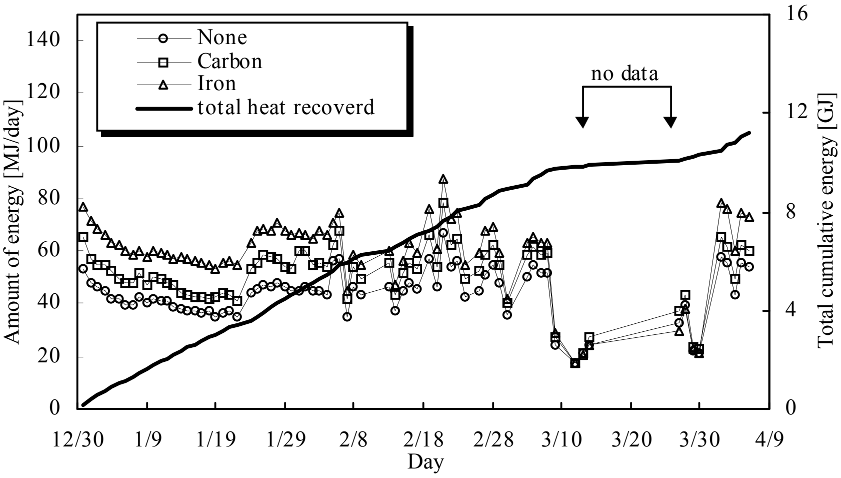

Fig.5.5 Underground Heat Recovery in the Second Year

tests carried out in the second year and the cumulative values.

The underground heat recovered was comparatively stable during continuous operation, but some variation could be observed during intermittent operation depending on the day on which it was recovered. However, if the operating period is averaged out, the amount of heat recovered was almost identical in both cases (refer to Table 5.1). The amount of heat recovered during the tests was 50.1 [MJ/day] in the first year and 51.2 [MJ/day] in the second year. The total amount of heat recovered was 9.2 [GJ] in the first year and 15.5 [GJ] in the second year. In the first year, heat was recovered without storing it in summer, therefore this is the amount of underground heat recovered. The amount of heat recovered in the second year is the value of heat that has been stored in the summer (amount stored: 12.1 [GJ]) and it includes the long-term UTES amount. Since the recovery period and operating condition differ in the first and second years, a quantitative comparison is difficult. However, from the tests, it is clear that the amount of underground heat recovered after long-term thermal energy storage increases.

5.2.2 Underground Heat Recovery Rate

Fig. 5.6 and Fig. 5.7 show the heat recovery rate for various heat-transfer fillers. The heat recovery rate is a value that indicates the amount of underground heat recovered per unit excavated length (length of heat exchanger pipe). For both the first and second years, the heat recovery rate was low during continuous operation and was high during intermittent operation. This is because the heat recovery rate varies depending on the temperature of the anti-freezing solution that circulates underground. The lower is the temperature, the higher is the heat recovery rate. Table 5.1 shows a summary of the temperatures in the heat exchanger pipes and the heat recovery rate. If the overall average is observed, it is seen that the temperature in both the first and second years is almost the same for

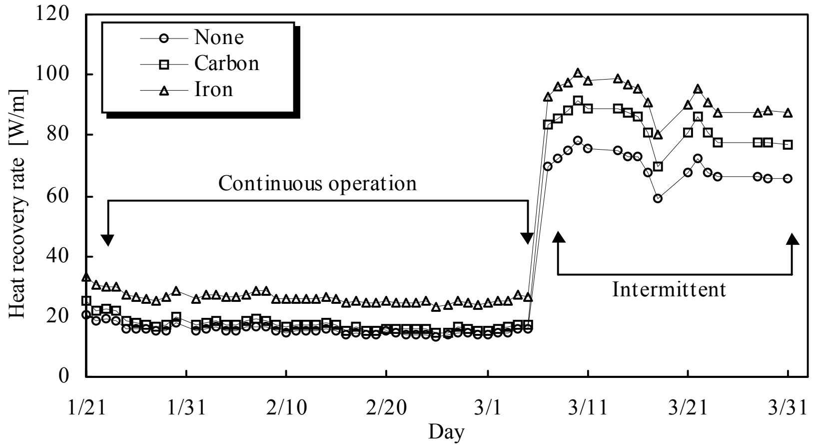

Fig.5.6 Underground Heat Recovery Rate in the First Year

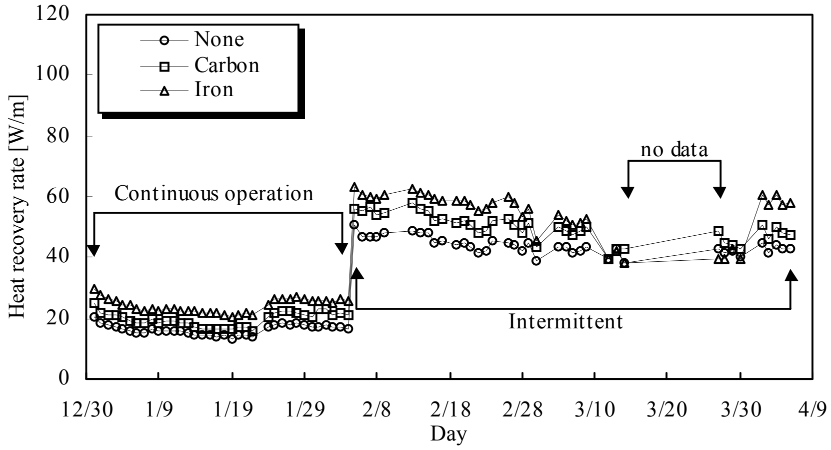

Fig.5.7 Underground Heat Recovery Rate in the Second Year

continuous operation. Therefore, the heat recovery rate is also identical. On the other hand, in the case of intermittent operation, the temperature in the first year is -0.1 [°C] and in the second year is 1.8 [°C]. Thus, the heat recovery rate also differs with values of 81.8 [W/m] and 43.9 [W/m] respectively. However, although the value of heat recovery rate at different operating modes is different because of the temperature in the heat exchanger pipe, this value remains almost constant during the operating period and does not decrease appreciably. This suggests that even if underground heat is recovered for a period of at least one month, the heat recovery rate will not decrease and that underground heat can be recovered steadily.

Table 5.1 Comparison of Temperature in Heat Exchanger Pipe, Heat Recovery Rate and Amount of Heat Recovered (Annual Average Values)

Heat-transfer filler	Underground heat recovery in 1st year						Underground heat recovery in 2nd year					
	Temp. in heat exchanger pipe (°C)		Heat recovery rate (W/m)		Amount of heat recovered (MJ/day)		Temp. in heat exchanger pipe (°C)		Heat recovery rate (W/m)		Amount of heat recovered (MJ/day)	
	Cont.	Inter.	Cont.	Inter.	Cont.	Inter.	Cont.	Inter.	Cont.	Inter.	Cont.	Inter.
None	8.6	-0.2	15.5	44.0	40.1	40.1	9.1	1.7	16.3	44.0	42.3	44.7
	6.2		30.6		40.3		5.3		30.7		43.5	
Carbon	8.8	0.0	17.4	49.9	45.1	48.3	9.2	1.9	19.7	49.9	51.0	51.0
	6.32		35.6		46.0		5.4		35.4		51.0	
Iron	8.5	-0.2	26.2	54.2	68.0	54.2	9.0	1.9	24.1	54.2	62.5	56.2
	6.1		44.8		64.2		5.4		39.8		59.2	
Aver.	8.7	-0.1	19.7	49.3	51.1	47.7	9.1	1.8	20.0	49.3	51.9	50.6
	6.2		37.0		50.1		5.4		35.3		51.2	

5.2.3 Heat-transfer Filler

From Fig. 5.6 and Fig. 5.7, if the rates of recovery of heat-transfer fillers, None, Carbon, Iron, are compared, the values can be observed to vary depending on the day of the test. However, the heat recovery rate is constant and highest in case of Iron, followed by Carbon and then by None. This trend is the same for both continuous and intermittent operations. Also, the trend remains the same in both the first and the second years. The above findings suggest that the rate of heat transfer underground can be enhanced by using heat-transfer filler containing carbon and iron particles for backfilling the spaces. Furthermore, this effect appears over the long term only and not over a short term. Even if the temperature of water fed into the heat exchanger pipe changes and the heat recovery rate changes, the effect remains without any change. Table 5.2 shows the underground heat recovery performance due to the heat-transfer filler. This

Table 5.2 Heat Recovery Performance (Annual Average Value)

Heat-transfer filler	Underground heat recovery in 1st year		Underground heat recovery in 2nd year	
	Cont.	Inter.	Cont.	Inter.
Carbon	1.12	1.19	1.20	1.13
	1.15		1.17	
Iron	1.70	1.33	1.48	1.23
	1.51		1.35	

table shows the increase in the heat recovery rate when Carbon or Iron, taking the heat recovery rate for None as 1.0. The results above verify that mixing a material with good thermal conductivity in the backfilling material by appropriate method is beneficial in enhancing the underground heat recovery rate.

The COP (energy consumption rate) of the heat pump used in the tests was 4.8, taking the average of the first and the second years.

6. Conclusion

A test plant was constructed to confirm the performance of the long-term UTES snow melting system. Field tests were performed to verify the solar energy collection performance of asphalt pavement and to verify the performance of BTES. Attempts were made to enhance the underground heat transfer rate using heat-transfer filler containing carbon and iron particles in BTES.

The following were concluded from the results of the field tests:

(1) The amount of solar energy collected by the asphalt pavement was 3.4 [MJ/m^2] in August, 1.2 [MJ/m^2] in September and -0.2 [MJ/m^2] in October. The amount of solar energy collected by the asphalt pavement was about 20% of the unobstructed solar radiations received by the pavement.
(2) The asphalt pavement can collect heat even outside the daylight time because of its heat collection ability.
(3) By using the borehole method for long-term UTES, heat can be stored underground for a long duration.
(4) The heat recovery rate varied depending on the temperature of water fed into the heat exchange pipes but it was stable over a long term.
(5) It is possible to improve the heat transfer rate underground by using a heat-transfer filler. Compared to conventional fillers, the heat recovery performance of the grout increases by a factor of about 1.16 when mixed with carbon particles and by a factor of 1.43 when mixed with iron particles.

Future topics of study should include mainly the following:

(1) Study of operating conditions for heat collection in order to enhance the heat collection rate in asphalt pavement
(2) Study of long-duration continuous heat recovery rate in the low temperature region from bore holes
(3) Establishment of a design method for long-term UTES in boreholes.

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