Development of an on-vehicle type salinity measurement sensor for controlling winter roadway surfaces

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In Japan, anti-icing chemicals are used to secure the safety and smoothness of vehicular traffic in the winter season. Especially since the use of spike tires on roads was prohibited, the consumption of such chemicals has been increasing year after year. On the other hand, the desire to reduce the amount of such chemicals to be salted has been mounting in recent years for cost reduction as well as for our concern for the road environment. In turn, the Japan Highway Public Corporation (JH) developed a salinity measurement sensor which can be mounted in a patrol car or a pre-wetted salt spreader to measure salinity in real time and control the amount of chemicals to be salted, and confirmed the measurement accuracy through verification testing in the field. The JH also conducted verification testing on a new method of salinity measurement to optimize the salting amount of chemicals even when the roadway surface is not adequately wet and confirmed that measurement by this method could be achieved.

Keywords: *Salinity measurement sensor, On-vehicle, Real time measurement*

1. Introduction

In the winter season, we at the Japan Highway Public Corporation (JH) have been tackling operations day and night to remove snow as well as salt anti-icing chemicals (such as NaCl) to secure safe and smooth vehicular traffic on expressways. Since the use of spike tires on roads was prohibited in 1991, the consumption of such anti-icing chemicals has been on the increase year after year. To reduce the cost involved in the salting operations of such chemicals, remove fear for injury from salt along the roadway, and prevent the deterioration of road structures, a demand for reducing the amount of ice-control chemicals to be salted has been mounting.

The anti-icing chemicals are salted in order to prevent that the water of a roadway surface from freezing by using the nature in which a freezing point falls so that the concentration of the solution becomes high. Therefore, in order to carry out roadway surface management and secure safety, it is necessary to get to know the salinity and the temperature of a roadway surface.

We at the JH used to employ a handheld type salinometer to confirm the continued effectiveness of anti-icing chemicals. With this method of measurement, however, the information we obtained was only at particular points, so we could not cover the entirety of an expressway. Since we could not get information in real time, the method could not be used to determine the optimum amount of chemicals to be salted. Furthermore, this method is dangerous since a worker must dismount from the vehicle to perform measurements on an expressway.

Under such circumstances, we developed an on-vehicle type salinity measurement sensor which allows the collection of linear information in real time and we have been looking into the creation of a system which would control the amount of chemicals to be salted [1]. If the concentration of the residual salt content on the roadway surface is adequate, the salting amount of chemicals can be reduced. We think that we can secure the safety of vehicular traffic in the winter season by controlling the concentration of the residual salt content.

However, for salinity measurements, the roadway surface must be wet. On a dry roadway surface, even when the residue of anti-icing chemicals looks white, such chemicals need to be salted additionally for the sake of safety if rain or snow is expected to fall subsequently, which is far from actually controlling the concentration of the residual salt content. Therefore, to allow salinity measurements even when the roadway surface is dry, we verified a method of salinity measurement which calls for salting the minimum amount of water necessary for salinity measurements with the sensor and melting the residual salt content on the roadway surface. In this paper, we will also report the results of the verification testing.

2. Salinity measurement sensor

2.1. Principle of measuring operation

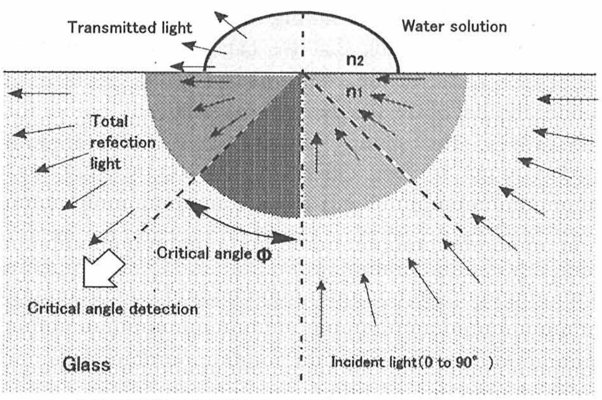
A water solution is characterized by its refractive index which varies almost proportionally with a change in the concentration of its medium. The relationship between the concentration and refractive index of NaCl water solution is as shown in Table 1 [2]. This salinity measurement sensor measures the salinity of a water solution by using a method of optical measurement of the refractive index of the water solution. The refractive index of the water solution can be found in the model shown in Figure 1 by detecting a boundary angle (critical angle ϕ) at which light from inside a glass with a known refractive index causes total reflection at its contact surface with the water solution. The relationship between the critical angle ϕ and salinity is as shown in Figure 2. Based on the foregoing principle, salinity can be determined by finding the critical angle ϕ. Although the refractive index of a NaCl water solution changes with temperature slightly, the margin for error can be reduced by comparing with the temperature of a thermometer installed outside the vehicle.

2.2. Configuration of sensor

The salinity measurement sensor consists mainly of a sensor section which is installed outside a vehicle to generate a signal corresponding to the salinity of the water solution upon receiving water splashes from the revolving tire and a controller section which is installed inside the vehicle to determine the salinity of the roadway surface from the signal output from the sensor section. The sensor section and the controller section are interconnected with dedicated wires.

Table 1. Refractive index per salinity of NaCl water solution (17.5℃)

Salinity		Refractive index
g/100 cm^3	% (Approx.)	
2	2.0	1.33667
4	3.9	1.34002
10	9.4	1.34963
20	17.7	1.36446



$$\text{Critical angle } \Phi = \sin^{-1}\frac{n2}{n1}$$

n1:Refractive index of glass
n2 :Refractive index of water solution

Figure 1. Relationship between critical angle and refractive index

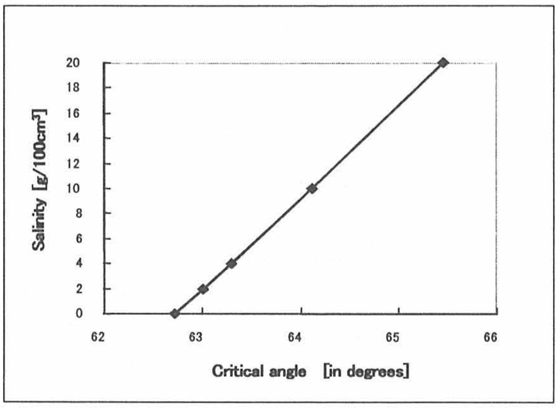


Figure 2. Relationship between salinity and critical angle

Figure 3 shows a block diagram of the salinity measurement sensor. A near-infrared LED is used as the light source for critical angle detection. A CCD camera is employed as the light-receiving element. An image signal is sent from the CCD camera to the controller section for signal processing to determine salinity.

An image which has a border line between its bright and dark parts is obtained from the CCD camera as shown in Figure 4. This border line varies with the salinity of the water solution (that is, critical angle ϕ), thus salinity determination can be made by detecting the border line between the bright and dark parts of the image. The measurement values of the sensor are likely to be affected by the frozen mud adhered to the detection surface of the sensor or by the residual salt content on the roadway surface when exposed to snow, muddy water, or cold wind because of the principle of its measuring operation. Therefore, the following measures were taken to avoid such measurement errors: the sensor was equipped with a wiper which prevents snow, mud, or residual salt content from adhering to its detection surface and a heater was built inside the detection surface which prevents the sensor from freezing.

Table 2 shows the main specifications of the salinity measurement sensor. Figure 5 shows the hardware

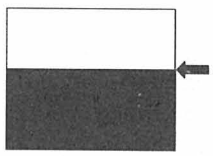


Figure 4. Image picked up by CCD camera

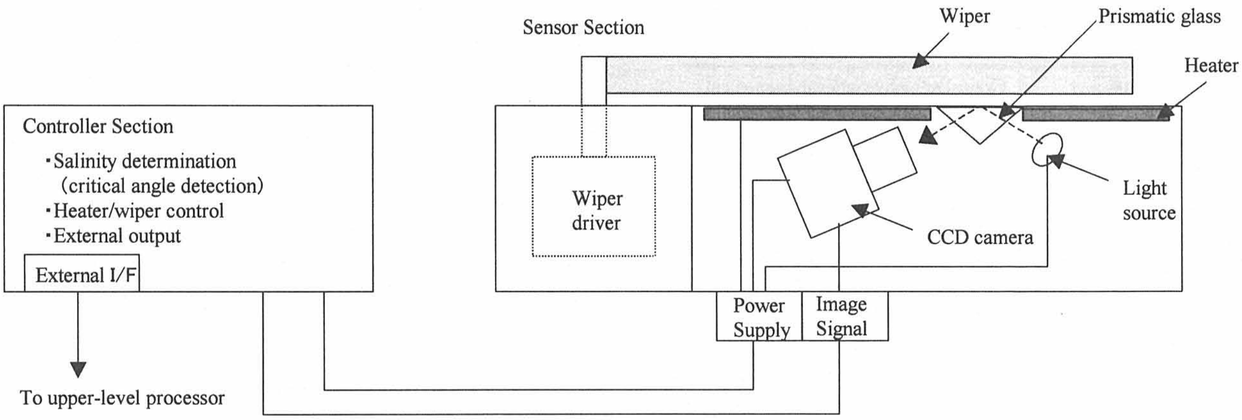


Figure 3. Block diagram of salinity measurement sensor

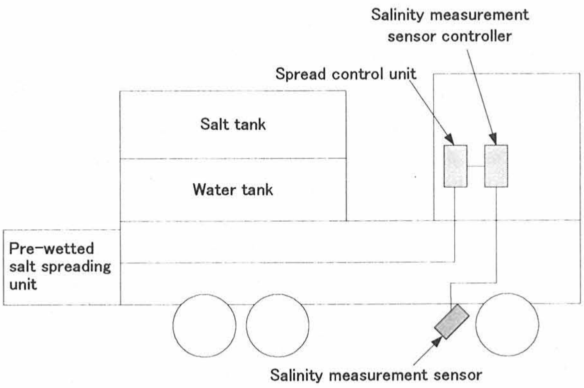


Figure 5. Hardware configuration of pre-wetted salt spreader

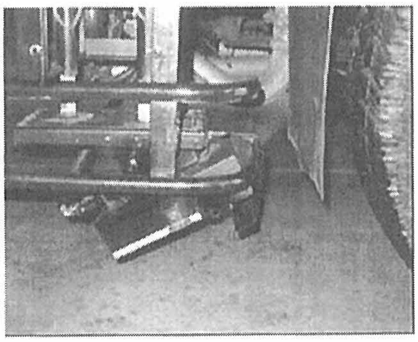


Figure 6. Appearance of salinity measurement sensor

configuration of the pre-wetted salt spreader used for the performance verification of the sensor and in Figure 6, the appearance of the sensor.

3. Performance verification of salinity measurement sensor

3.1. Method of verification

3.1.1. Particulars of verification

To verify the performance (i.e., measurement accuracy) of the salinity measurement sensor, as well as to confirm its correlation with the results of measurements by the handheld type salinometer, we conducted verification testing to determine whether or not linear information obtained by the on-vehicle type salinity measurement sensor can be applied to the actual ice-control chemical salting operations. Table 3 shows the general specifications of the handheld type salinometer we used in this verification.

Table 2. Main specifications of salinity measurement sensor

Item	Specification
Detection method	Optical refractive index measurement
Light source	Red LED (λ=850 nm)
Light-receiving element	Charge-coupled device (CCD)
Object to be measured	NaCl solution
Measurable salinity range	0 to 15%
Measurement error	±3% max. (relative error)
Roadway surface to be measured	Wet asphalt- or concrete-paved roadway surface with water splashes
Supply voltage	12/24 VDC
Power consumption	155 W max. (including the heater)
External output	RS-232C (9,600 bps, Start-stop synch) Output intervals: Approx. 1 sec
Temperature/humidity ranges	a) Sensor section Operating temp: -15°to 30°C Storage temp: -35°to 70°C Humidity: 40 to 90% RH b) Controller section: Operating temp: 0°to 50°C Storage temp: -30°to 70°C Humidity: 40 to 90% RH
Outline dimensions	a) Sensor section: 282 mm (W) x 180 mm (D) x 165(H) mm b) Controller section: 300 mm (W) x 200 mm (D) x 107 mm (H)
Weight	(a) Sensor section: Approx. 6.1 kg (b) Controller section: Approx. 4.2 kg

Table 3. Specifications of handheld type salinometer

Item	Specification
Detection method	Optical refractive index measurement
Object to be	NaCl solution
Measurable salinity range	0 to 28%
Outline dimensions	40mm(W) x 180mm(D) x 40mm
Weight	170g

3.1.2. Locations of verification testing

The performance verification testing of the salinity measurement sensor was conducted between Bandai Atami Interchange and Inawashiro Bandai Kogen Interchange on Banetsu Expressway.

We also conducted testing to confirm correlations between the results of measurements by the salinity measurement sensor and those by the handheld type salinometer at the following three locations:

① At or around 86.4 kilo-post – Nigata-bound lane, west of Shin Nakayama Tunnel (Coarse graded asphalt)
② At or around 90.4 kilo-post – Nigata-bound lane, west of Kurateyama Tunnel (Drainage asphalt)
③ At or around 89.9 kilo-post – Koriyama-bound lane, west of Sekito Tunnel (Drainage asphalt)

3.1.3. Test vehicles

Two vehicles were used for the performance verification of the salinity measurement sensor: One is a pre-wetted salt spreader and the other, a patrol car. Figure 7 shows the appearance of the pre-wetted salt spreader.

3.2. Results of performance verification testing

3.2.1. Measurement error

Figure 8 shows the correlation between the results of the observations with the handheld type salinometer in the field and the results of the measurements by the salinity measurement sensor. This data represents the results of 36 successful measurements with the sensor thanks to the ample water content on the roadway surface when the pre-wetted salt spreader and patrol car passed a fixed observation point in addition to the results of the measurements with the handheld type salinometer in the field. The average measurement error of the sensor with the results of the measurements by the salinometer taken as true values is 0.73%. At 70% or more of the number of measurements, the results of the measurements were favorable with an error of ±1% max. As one factor for these measurement errors, non-uniformity existed at one measuring point or another because anti-icing chemicals were salted in the pre-wetted (solid) state. Moreover, there is no major difference between the measured value of the patrol car and the salt spreader.

Figure 7. Appearance of pre-wetted salt spreader

3.2.2. Results of measurements before and after the salting of anti-icing chemicals

Figure 9 shows the results of the measurements before and after the salting of anti-icing chemicals within each roadway section subject to performance verification.

The result of each measurement by the pre-wetted salt spreader is indicated by ▲ and that by the patrol car, ●. The spreader salted the anti-icing chemicals from the vehicles rear after measuring the salinity concentration from behind the front wheel, and the patrol car ran about 1km behind the spreader and measured salinity. From Figure 9, we can see that the concentration of the residual salt content on the roadway surface increased without fail. Within each of the five tunnels between Inawashiro Bandai Kogen Interchange and Bandai Atami Interchange, salinity measurements were impossible to attain due to lack of water content on the roadway surface. However, a high percentage of salt content was detected for some time after the salting vehicle or patrol car entered the tunnel. This is due mainly to the salt content attached to the tires of the traveling vehicles that was drawn inside the tunnel by such vehicles. Thus, the drier the roadway surface becomes, the higher the

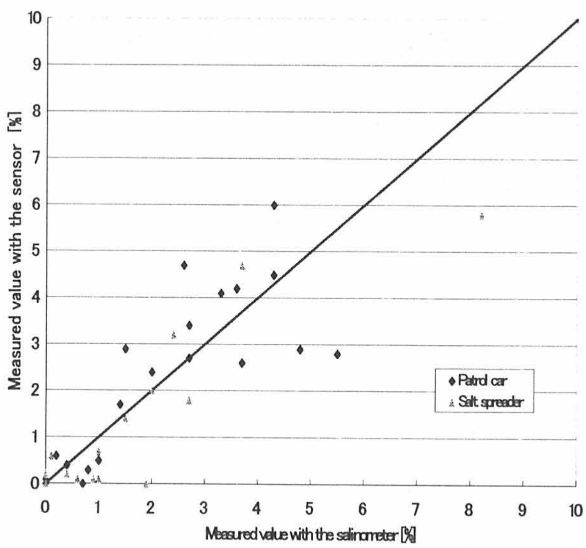


Figure 8. Correlations between field observation values (with the salinometer) and salinity measurement values (with the sensor)

Inawashiro Bandai Kogen IC to Bandai Atami IC (up-bound lane)

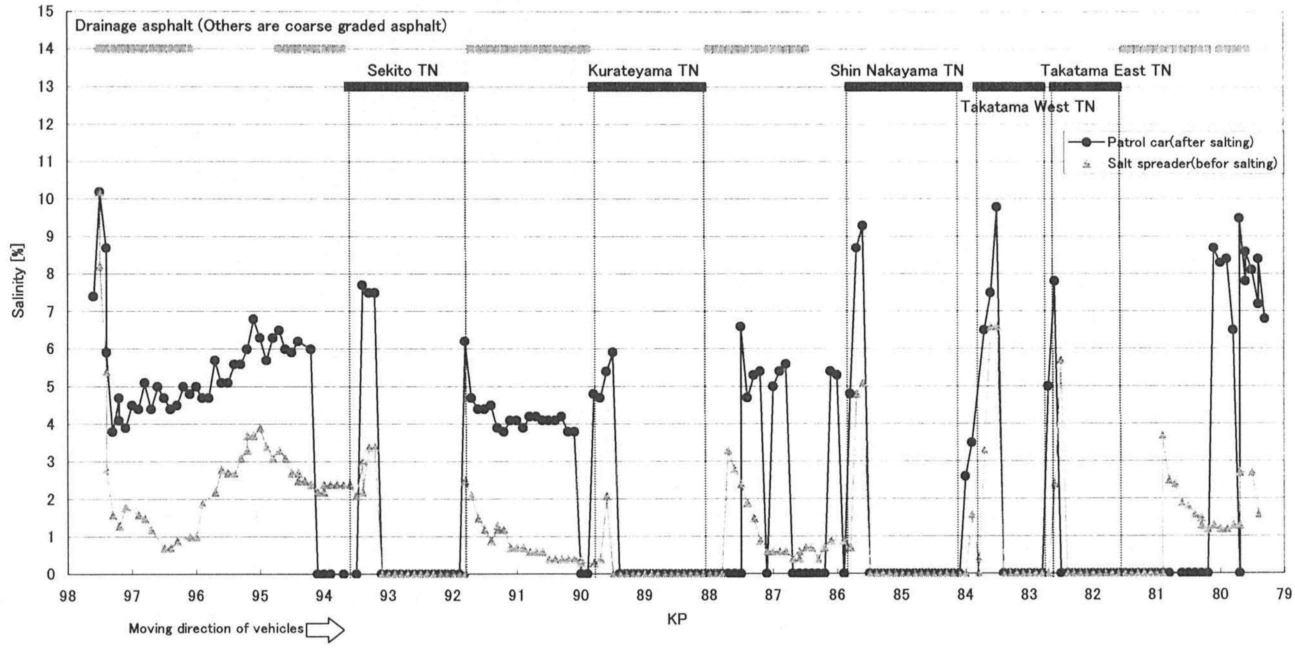


Figure 9. Changes in measured values of the sensor within each section

salinity of the residual salt content. Although a high percentage of salt content was also detected near 97.5 kilo-posts (KP), this is due to interchange and is considered to be the result of more anti-icing chemicals being salted for safety. Moreover, the value near 92KP, 88KP and 81KP was a little high since there was little water on the roadway surface just before that, so we speculate that the remaining salt became concentrated. The salt spreader is able to obtain better measurements than the patrol car since the salt spreader is heavier, and it is equipped with bigger tires, therefore more water becomes splashed.

As shown in the figure, on the roadway sections subject to salinity measurement, including those with drainage asphalt, successive measurements were achieved. We were able to confirm that the salinity measurement sensor is suitable for a wide area of salinity control.

4. Verification of salinity measurement sensor on dry roadway surfaces

Because the salinity measurement sensor we developed makes the best use of water splashes from the tire mounted on the front wheel of a vehicle, it cannot perform measurements when the roadway surface is dry. According to the results of measurements shown in Figure 9, salinity measurements were in general successful, but at measuring points (For example, 80 to 81KP) where the amount of water content on the roadway surface was insufficient, salinity measurements with the patrol car were unsuccessful due to its smaller tires in comparison with the spreader. To control the amount of anti-icing chemicals to be salted at an optimum vale, it is preferable to perform salinity measurements on all routes, including dry roadway surfaces. Described here are the results of our verification testing on the sensor performance when salinity measurements were conducted while salting water in front of the tire.

4.1. Configuration of water-spraying unit

Figure 10 shows the appearance of a water-spraying unit. Figure 11 shows the hardware configuration of the salt spreader with the water-spraying unit. This unit has been designed for installation in front of the right-hand front wheel of a vehicle. To simplify the configuration of the hardware for performance verification, a switch for water-spraying operations is manually turned on and off and the flow of water is made adjustable with a valve. A water tank normally used when salting pre-wetted salt is also used for such water-spraying operations.

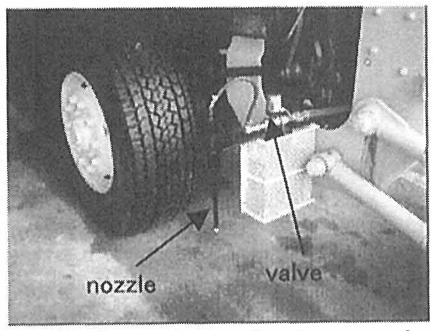


Figure 10. Appearance of water-spraying unit

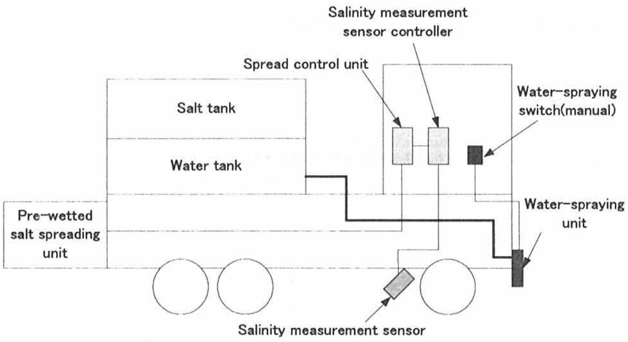


Figure 11. Hardware configuration of pre-wetted salt spreader with water-spraying unit

4.2. Verification method

To conduct the verification testing on the actual roadway, we decided on the following two conditions: (1) For the sake of safety, salt water shall be used as water to be salted on the roadway surface and (2) Testing shall be conducted in the daytime at high temperatures to reduce the possibility of road frost or ice forming. Beforehand, we measured the concentration of salt water to be salted from the water-spraying unit and if the concentration of salt water measured with the salinity measurement sensor became higher than that of the salted salt water, we assumed that the residual salt content on the roadway surface had melted and had then been measured.

Table 4 shows the water spraying conditions. Figures 12 and 13 show how salt water was sprayed and the traces of salt water sprays when the spraying vehicle traveled at 40 km/h, respectively.

4.3. Results of verification testing

Verification tests were conducted on roadways between Bandai Atami Interchange and Koriyama Junction on Banetsu Expressway and between Koriyama Junction and Koriyama Interchange on Tohoku Longitudinal Expressway.

Table 4. Water spaying conditions

Item	Condition
Salinity	4.5%
Amount of water to be sprayed	Approx. 200ml/sec
Spread of water spray	Approx. 10cm

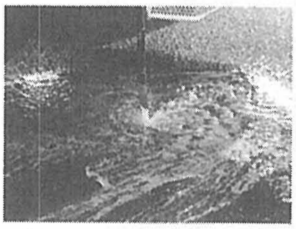


Figure 12. Water being sprayed from the nozzle

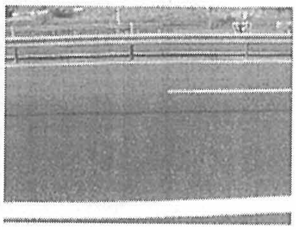


Figure 13. Traces of water sprays

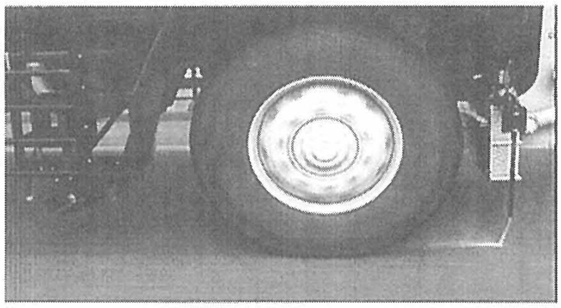


Figure 14. Example of salinity measurement with the sensor

Figure 14 shows an example of the salinity measurement and Figure 15, the results of the salinity measurements on the dry roadway surface, respectively. Measurement points with salinity of 0% were those points at which salinity measurements were unsuccessful due to an insufficient amount of water content. We found that measurements were successful at more than 90% of all the measurement points. In regards to how the residual salt content melted, we saw an increase of approximately 1% in salinity, judging from the fact that the concentration of sprayed salt water was 4.5% at most. So, we were able to confirm that the measurements of the residual salt content were possible even on a completely dry roadway surface by having the pre-wetted salt spreader run while spraying salt water.

As for the amount of salt water to be sprayed, at the amount setting of approximately 100 ml/s, salinity measurements were unsuccessful due to an insufficient amount of water content. At the amount setting of 200 ml/s, no water content enough for salinity measurement was remaining even when a patrol car mounted with the same salinity measurement sensor followed about 100m behind the salt spreader. This amount can be said to be appropriate as a necessary minimum which does not create a slippery surface on the roadway.

The next aspect of the study this report will examine is the amount of the residual salt content. The salinity of the roadway surface, needless to say, varies with the amount of water. If the amount of salt content is per unit area, though, it can be quantized. The traveling speed of the pre-wetted salt spreader was approximately 40 km/h when salinity measurements were conducted. Based on the traveling speed and the water spraying conditions shown in Table 4, we can assess that we sprayed approximately 180 ml/m^2 of salt water. Converting this quantity into the weight of salt content per 1m^2, it is approximately 8.1 g at a salinity of 4.5% and approximately 9.9 g at a salinity of 5.5%. The difference between the two is approximately 1.8 g/m^2, indicating that we had that much residual salt content. In the current chemical spraying operations, NaCl is sprayed in units of g/m^2. If we know the amount of the residual salt content per unit area, it can be reflected directly on the control amount of NaCl to be salted.

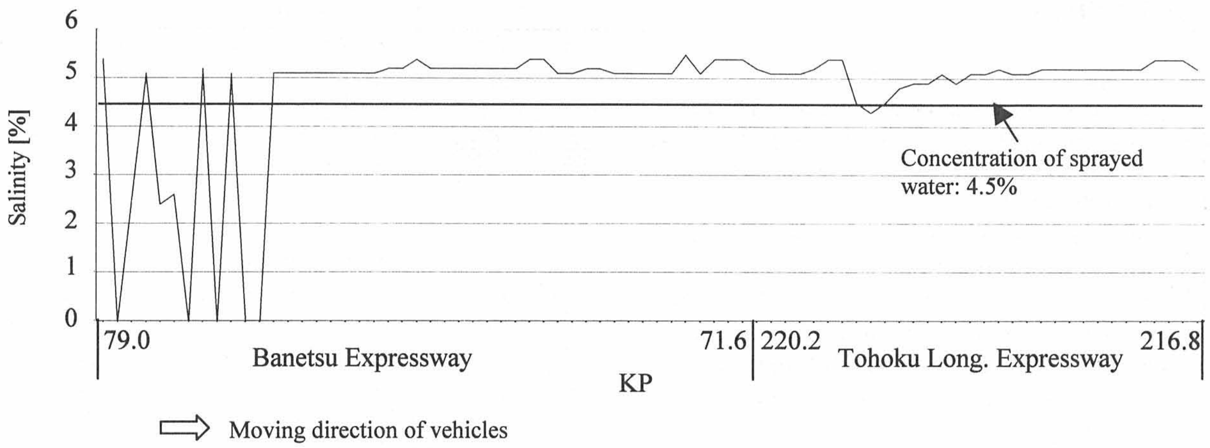


Figure 15. Results of salinity measurements on dry roadway surface

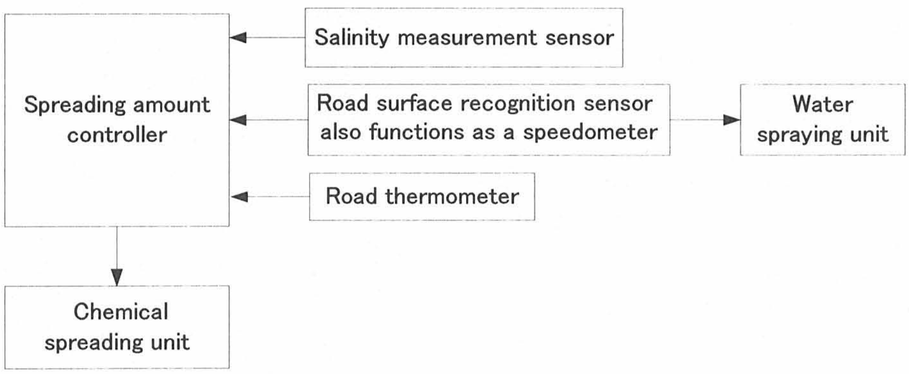


Figure 16. Block diagram of chemical spraying control system

To measure the concentration of residual salt content on the roadway surface by water spraying, it is preferable to have an ample amount of time to allow the salt content to melt after water spraying. During the verification testing, the water-spraying unit was installed as far forward as possible. However, because of the limited amount of distance between the water spraying position and the salinity measurement position, the faster the traveling speed of the salting vehicle, the shorter the amount of time became for the salt content to melt. Thus, it is likely that salt content was not melted sufficiently. We need to look into handling the increased salinity value by taking into account this salt content melting time.

4.4. Model for the salting system

During the verification testing, we salted a fixed amount of salt water manually. However, our eventual goal is to automatically perform salinity measurements on all the routes. Figure 16 is a block diagram of an anti-icing chemical salting control system conceived by assuming automatic salinity measurements.

Fundamentally, based on both the salinity value of the roadway surface measured with the salinity measurement sensor and the road temperature value measured with the road thermometer, the salting amount controller determines the amount of anti-icing chemicals to be salted. With the road surface recognition sensor (it detects dry or wet or ice or snow by un-contacting)[3], the roadway surface condition is identified. When the roadway surface is found to be dry, the water-spraying unit is made to spray water in front of the salinity measurement sensor so that the concentration of the residual salt content on the roadway surface can be measured. The road surface recognition sensor employs an optical spatial filter; therefore it can also function as a speedometer. To salt anti-icing chemicals or water continuously per unit area, the speed information measured with the road surface recognition sensor is transmitted to both the salting amount controller and the water spraying unit so that the amount of chemicals to be salted may be adjusted according to the traveling speed of the vehicle.

With such a system configuration, we think salinity measurements can be performed automatically throughout the entire route, although a slight time lag may occur.

5. CONCLUSION

We developed an on-vehicle type salinity measurement sensor which can be applied to controlling the amount of chemicals to be salted, conducted tests on the sensor in the field to verify its performance, and found the following results:

- The average measurement error of the sensor with the results of measurements by the handheld type salinometer taken as true values is 0.73%. The accuracy is sufficient for roadway surface management.
- The salinity measurement sensor can be continuously measured even on drainage asphalt and is suitable for a wide area of salinity control.
- The measurements of the residual salt content were possible even on completely dry roadway surface by having a pre-wetted salt spreader run while spraying salt water. However, it is necessary to examine the treatment of the measured concentration and the structural realization method.

We intend to continue verification testing on the amount control of salting while also considering roadway surface temperature in the winter season and confirming the effect of the system on reducing the consumption of anti-icing chemicals.

If it can control the proper amount of salting automatically, the efficiency of road surface management will increase, and we will be able to provide drivers with safer travel.

Furthermore, although this paper concentrated mainly on the salinity measurement sensor, the observation data of the various sensors carried in vehicles could be transmitted in real time with mobile communications equipment with position data using GPS to a central control center. By carrying out unitary management of the data, a road surface situation and the proximity of maintenance vehicles can be available to a driver through an information board or VICS. With such a system, we expect to secure the safety of vehicular traffic.

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