FEASIBILITY STUDY ON THE SUITABILITY OF AUTOMATED ACETIC ACID CRYOPROTECTANT DISPERSION SYSTEMS ON URBAN EXPRESSWAYS

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ABSTRACT

Sodium chloride is currently used on the Hanshin Expressway as a de-icing agent to prevent surface icing during winter. However chlorides tend to adversely affect life cycle costs by encouraging corrosion of roadway structures such as steel members and steel reinforcement in reinforced concrete, as well as in peripheral facilities such as toll booths. The negative environmental impact of chloride agents is also a concern. Meanwhile, there is a pressing need for automated systems as part of an overall effort to develop a more streamlined and efficient approach to the prevention of surface icing during winter. This report evaluates acetic acid based cryoprotectant agents as an alternative to the problematic sodium chloride agents, on the basis of experiments using a pilot automated dispersion system installed on the Hanshin Expressway in the vicinity of the Kyoto Expressway Inariyama Tunnel. The study considers the suitability of automated de-icing for local conditions and provides recommendations on the feasibility of automated dispersion systems on urban expressways.

KEYWORDS

Prevention of surface icing during winter/Acetic acid cryoprotectant/Expressway maintenance/Life cycle cost

1. INTRODUCTION

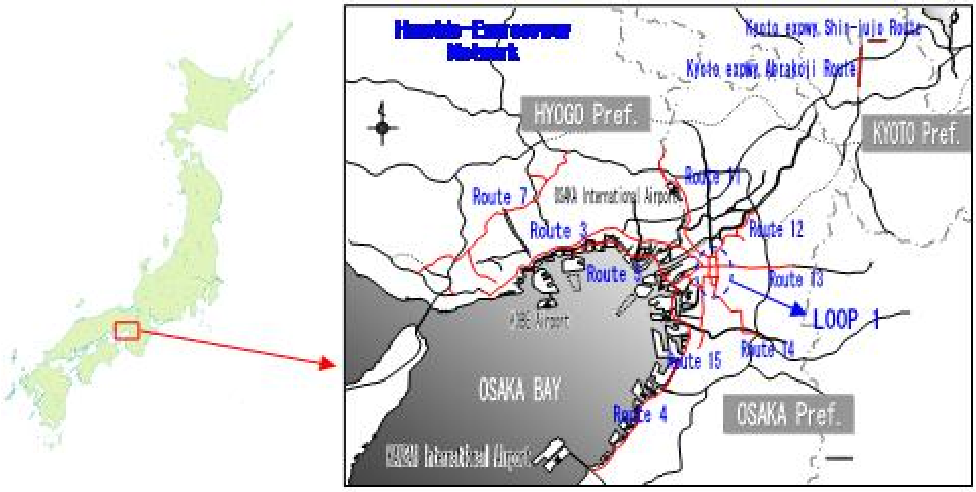

Figure 1 Location of Hanshin Expressway

The Hanshin Expressway is an urban expressway linking together the metropolitan networks of the Kansai region of Japan. It currently measures 242.0 km in length. Given the urban setting of the Hanshin Expressway, road closures due to snow and ice in winter can have a major economic impact, and are therefore to be avoided wherever possible. The use of chains is considered impracticable in terms of road surface maintenance. Despite concerns about the adverse environmental impact of sodium chloride on structural members and the fact that steel bridge structures account for some 86% of the total expressway length, sodium chloride is still used to prevent surface icing during winter. A total of 2,987 tons of sodium chloride de-icing agent was applied to the Hanshin Expressway during FY2007; the corresponding figure in FY2008, a warmer than average winter, was 1,911 tons.

The corrosive effect of chlorides on steel structures and steel reinforcement in concrete and the associated impact on the LCC is well known. Alternative de-icing agents such as urea and acetic acid, however, tend to be costly. Unless these alternatives can be demonstrated to provide added value in terms of benefits other than de-icing performance, they will have little chance of gaining general public acceptance.

The proposed solution is a mechanized and automatically controlled system that provides an efficient means of dispersing acetic acid based cryoprotectant agents, which unlike sodium chloride do not cause corrosion. This study examines efficiencies generated through automated control of application timing (which is currently determined by human operators based on temperature monitoring) as well as cost savings in application operations, and presents recommendations regarding the feasibility of automated systems on urban expressways.

2. DE-ICING AGENTS

De-icing agents are broadly divided into two groups: conventional chloride-based agents, which have been in use for many years, and environmentally-friendly acetic acid based agents, which do not cause salt damage. For the purpose of the study, we used an acetic acid cryoprotectant product known as CAMAG (a liquid agent based on potassium acetate with glycerin additive), which has become increasingly popular in recent years.

2.1. Main components and performance

The main constituent components of CAMAG are potassium acetate (the cryoprotectant agent) and glycerin (used to extend performance, boost water retention, and improve dispersion). CAMAG has a freezing point of –75° C or below at an aqueous concentration of 50%; this is far superior to conventional sodium chloride, which has a freezing point of –20° C at the standard aqueous concentration of 20%.

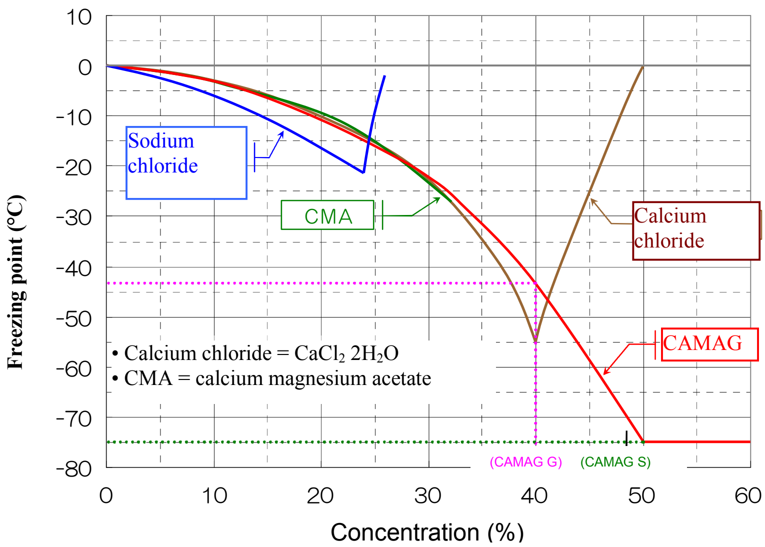

Figure 2 Concentration versus freezing point for various de-icing agents

2.2. Benefits and dispersion methods

CAMAG contains a glycerin additive. Glycerin is an organic compound whose viscosity increases as the temperature decreases. This characteristic of glycerin helps to extend the performance of CAMAG. The viscosity increases tire drag, which allows the de-icing agent to be carried forward by vehicles, therefore extending its effective range.

Whereas chloride-based de-icing agents are spread across the entire road surface by dedicated vehicles, CAMAG is applied only to short sections of the road. Thanks to the viscosity of the glycerin additive, vehicle traffic effectively disperses the cryoprotectant along the road surface, which is more efficient.

2.3. Corrosion

CAMAG contains no chloride compounds and therefore has no adverse environmental impact on plants and other ecosystems, and negligible corrosive effect on metal components of vehicles, bridges and buildings and concrete materials. While CAMAG has been used successfully in the snow-affected northern region of Japan, particularly Hokkaido and Aomori prefectures, the effectiveness of this product in urban regions has yet to be established.

2.4. Usage in conjunction with automated dispersion systems

The advantages of using an automated dispersion system to apply CAMAG to the road surface are the simplicity of the automated system and reduced maintenance workload, as well as more reliable coverage of the road surface. Any product that remains in the storage tank, pipes and nozzles at the end of the snow season can be left in place for use the following year. This eliminates the need to clean the tank and nozzles, thereby reducing the maintenance workload. Unlike chloride de-icing agents, which tend to get blocked in the nozzles during the season, CAMAG does not cause blockages. Corrosion of the equipment is virtually non-existent, which helps to prolong the equipment life.

Currently, de-icing operations are coordinated on the basis of ongoing monitoring of weather forecasts, with operators on stand-by until the decision is made. The operators then have to mix the sodium chloride with water and load it into tanks on the de-icing vehicles, and travel to the required locations to begin the de-icing procedure. Afterward, the tanks must be cleaned out. The automated dispersion approach eliminates these processes and is therefore more efficient.

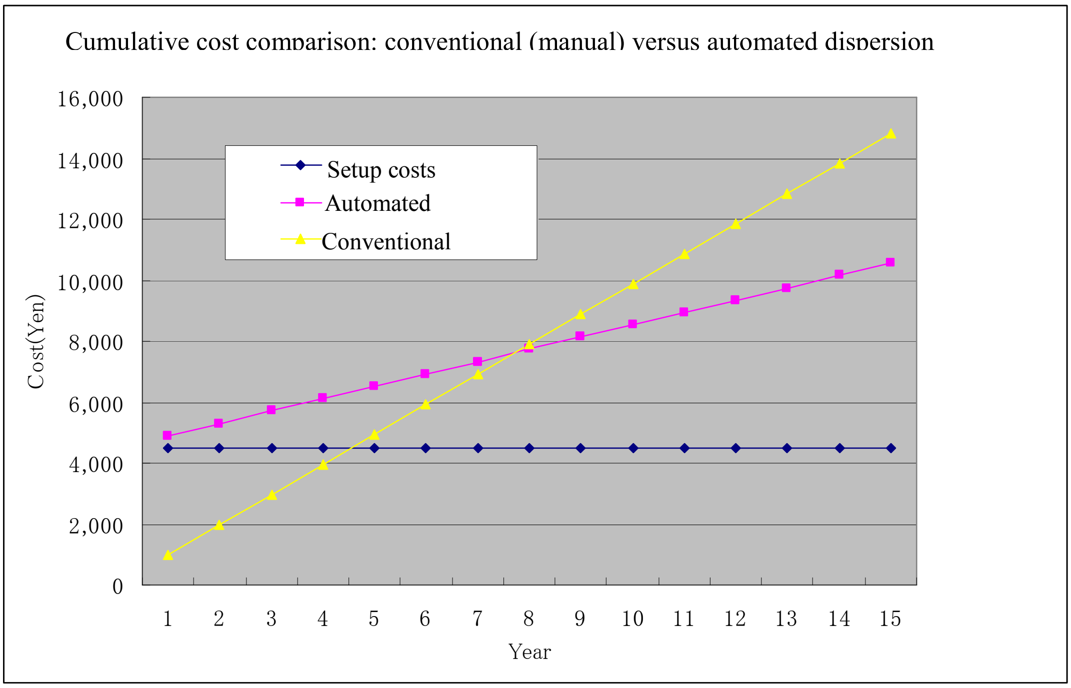

Figure 3 Cumulative cost comparison: conventional (manual) versus automated dispersion (assuming setup = ¥45.0 million, equipment maintenance = ¥4.04 million, conventional de-icing expenses = ¥9.87 million)

Another advantage of automated dispersion is that the cryoprotectant agent is applied automatically in response to temperature, rather than relying on operator monitoring of weather forecasts. This reduces wastage and ensures optimum results.

2.5 Biological decomposition

Potassium acetate and glycerin are biodegradability. Potassium acetate degraded into hydrogen, carbon dioxide, and potassium and glycerin degraded into hydrogen and carbon dioxide.

In the case of biological decomposition, oxygen will not used directly. Therefore, the amount of carbon dioxide generated by this biological composition will not affect environment.

Potassium acetate $CH_3COOK \rightarrow H_2O, CO_2, K$

Glycerin $C_3H_5(OH)_3 \rightarrow H_2O, CO_2$

3. AUTOMATED DISPERSION SYSTEM

3.1. Overview of system and positioning

The automated dispersion system sprays liquid cryoprotectant from nozzles directly onto the road surface. The main components of the system are: a storage tank, which holds the cryoprotectant; independent nozzles, which spray the cryoprotectant onto the road; a controller, which regulates the supply of cryoprotectant to each nozzle as well as the spray timing; and a vehicle sensor, which prevents vehicles from being sprayed with cryoprotectant by shutting off the spray as vehicles approach.

Once the cryoprotectant has been sprayed onto the road by the automated dispersion system, it is spread along the road via the tires of passing vehicles.

An experimental system was installed on the Yamashina side of the Inariyama Tunnel (opened to traffic in June 2008) on the Kyoto Expressway, which is part of the Hanshin Expressway system. The Inariyama Tunnel links the Fushimi and Yamashina wards of Kyoto City. Fushimi ward is located on the flat plain that extends to Osaka Bay, while Yamashina ward is part of the mountain ranges beyond Mt. Inariyama. This location was chosen because it experiences relatively cold temperatures during winter.

In order to evaluate the benefits of acetic acid based cryoprotectant, a new automated acetic acid cryoprotectant dispersion system was installed at the mountainous (low-temperature) end of the tunnel while conventional chloride based de-icing agent was applied at the other end to enable direct comparison of the two methods.

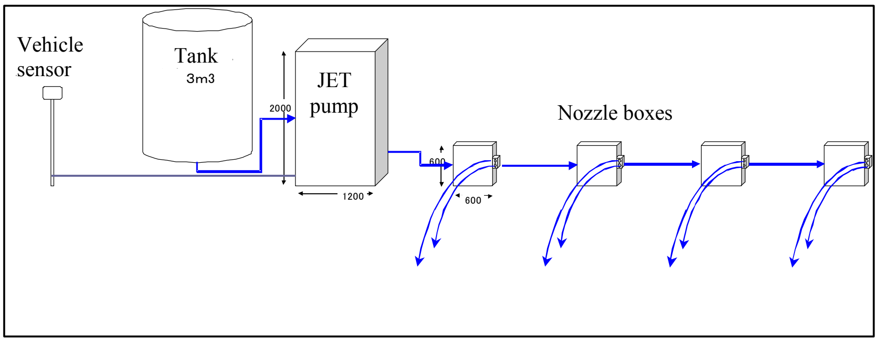

Figure 4 Automated cryoprotectant dispersion system

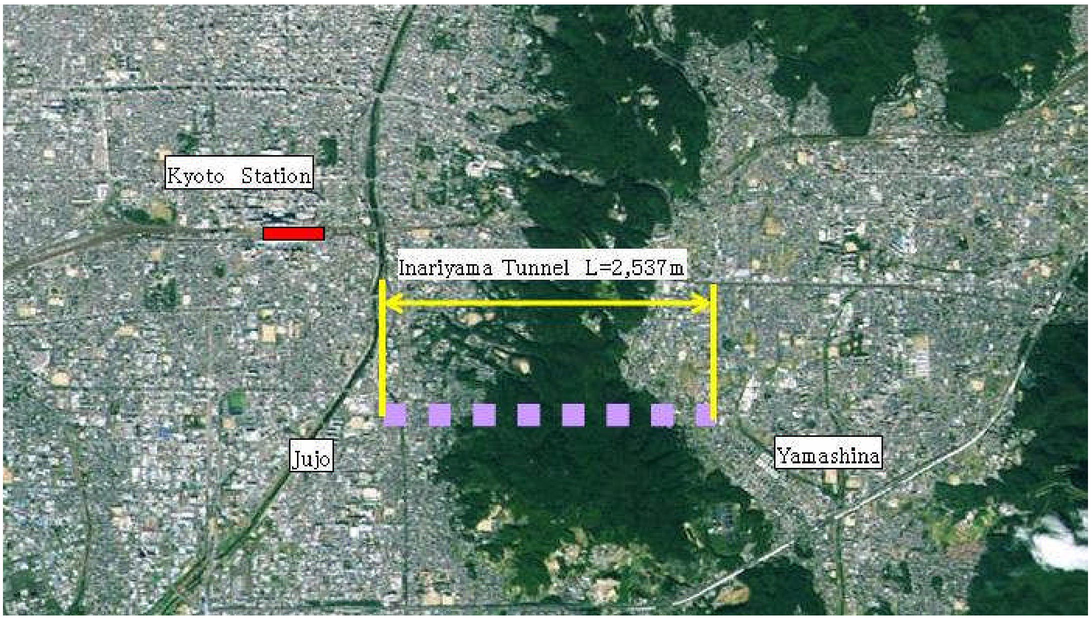

Figure 5 Inariyama Tunnel

3.2. System operation

3.2-a)Storage tank and controller

The controller and liquid storage tank were installed at the Yamashina exit of the Inariyama Tunnel. A 3,000-liter capacity tank was chosen. Based on the standard dispersion rate of approximately 20 liters per nozzle per day, and assuming operation for 50 days over the length of the winter season, total consumption of cryoprotectant agent per season was estimated at 4,000 liters. Thus, the 3,000-liter tank would need to be refilled only once during the season.

The controller unit incorporates a temperature sensor and is programmed to start and stop the system in accordance with changes in temperature. The controller also regulates the delivery of cryoprotectant agent in accordance with the temperature. The temperature threshold settings and spray delivery rates can be adjusted as required to suit site conditions.

Figure 6 Controller

Figure 7 Storage tank

3.2-b) Independent nozzles

The most important aspect of system setup is the positioning of the nozzles used to spray cryoprotectant onto the road surface. Two nozzles were installed on the inbound lanes in the tunnel exit direction. The pressure was adjusted such that one nozzle sprayed onto the through traffic lane and the other onto the overtaking lane. Two more nozzles were installed on the outbound lanes just before the entrance toll collection points, providing coverage of the road surface from both sides. The nozzles on both inbound and outbound lanes were located in positions where traffic restrictions would not be required.

Figure 8 Location of inbound lane nozzles   Figure 9 Inbound lane nozzles

Figure 10 Location of outbound lane nozzles

Figure 11 Outbound lane nozzles

3.2-c)   Vehicle sensor

To prevent passing vehicles from being sprayed with cryoprotectant agent, vehicle sensors were installed 30 meters ahead of the spray nozzles. The sensors were set to shut off the spraying system for a set period of 10 seconds whenever an approaching vehicle was detected.

Figure 12 Inbound lane sensor

Figure 13 Outbound lane sensor

3.3.   Equipment initialization

System operation is dictated by the temperature sensor. When the ambient temperature as detected by the temperature sensor falls to 1° C below the pre-set threshold value, the system automatically begins spraying cryoprotectant agent. When the ambient temperature returns to the threshold value, the system shuts off again. Currently on the Hanshin Expressway, sodium chloride de-icing agent is applied when the forecast temperature supplied by the Bureau of Meteorology drops to 2° C or less. Based on operational conditions at the site, it was decided to set the threshold value to 3° C.

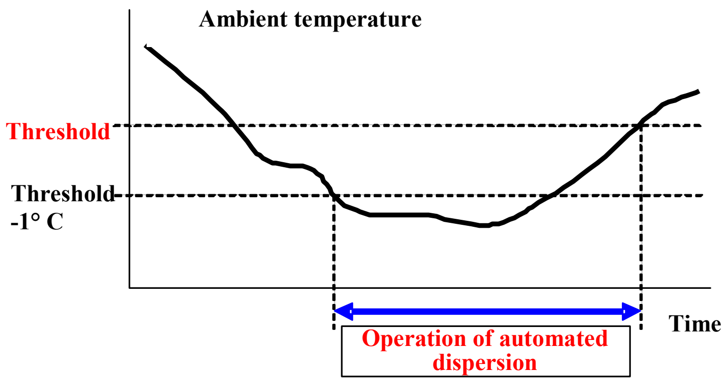

Figure 14 System operation based on threshold temperature setting

4. BENEFITS OF AUTOMATED DISPERSION SYSTEM

4.1. Days of operation

The automated dispersion system operated for a total of 14 days during the winter season, with the first day of operation being February 11, 2009. During this time, conventional sodium chloride was applied on one occasion only in response to an unexpectedly severe cold snap; on all other days, the road surface was maintained in acceptable condition without need for sodium chloride.

4.2. Road surface conditions

Acetic acid based cryoprotectant agent produces a mild vinegar odor. To assess the dispersion of cryoprotectant agent along the road, we conducted a visual inspection of the road surface at a point approximately 100 meters from the spray nozzles (which were located near the tunnel exit) and also checked for the vinegar odor. Traffic volume on the day of inspection was approximately 10 vehicles between the hours of 1:00 am - 5:00 am for the two lanes combined. The inspection indicated that the cryoprotectant agent had been properly dispersed, and the system was deemed to be effective.

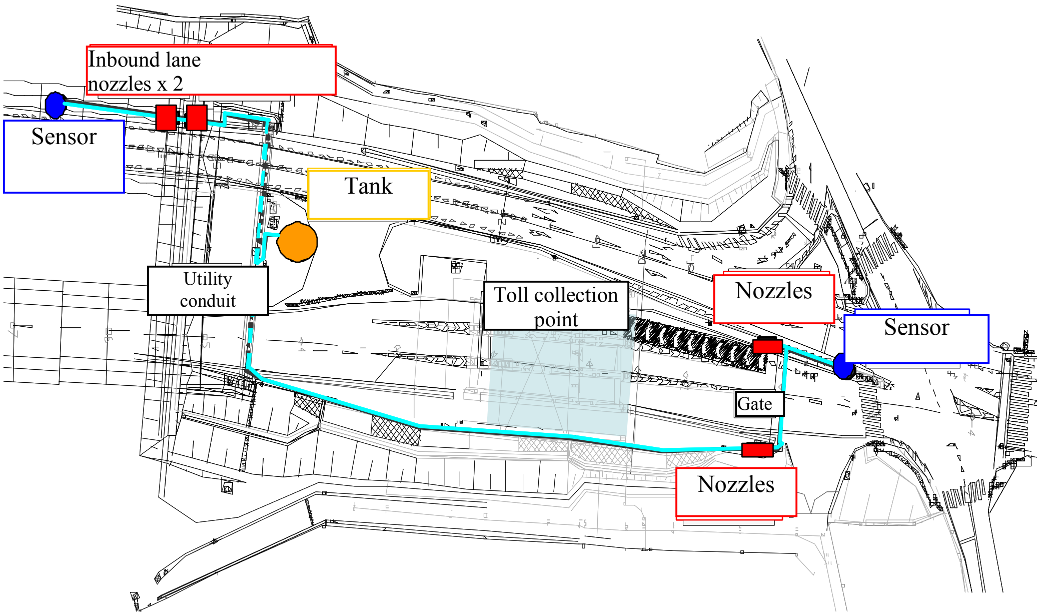

Figure 15 Equipment layout

5. PRELIMINARY LIFE CYCLE COST STUDY

5.1. Sample selection for comparison study

We considered the impact of the cryoprotectant agent on the interior tunnel infrastructure compared to conventional chloride-based de-icing agents, by examining the respective locations of use. Three conventional de-icing locations were selected for the purpose of comparison with the Inariyama Tunnel: the Arima-Kita Tunnel (opened to traffic 2002), Shin-Karato Tunnel (1998) and Aina Tunnel (1982) on the Kita-Kobe branch of the Hanshin Expressway in Hyogo Prefecture. Of the three, the Aina Tunnel and vicinity tends to require less de-icing agent than the other two.

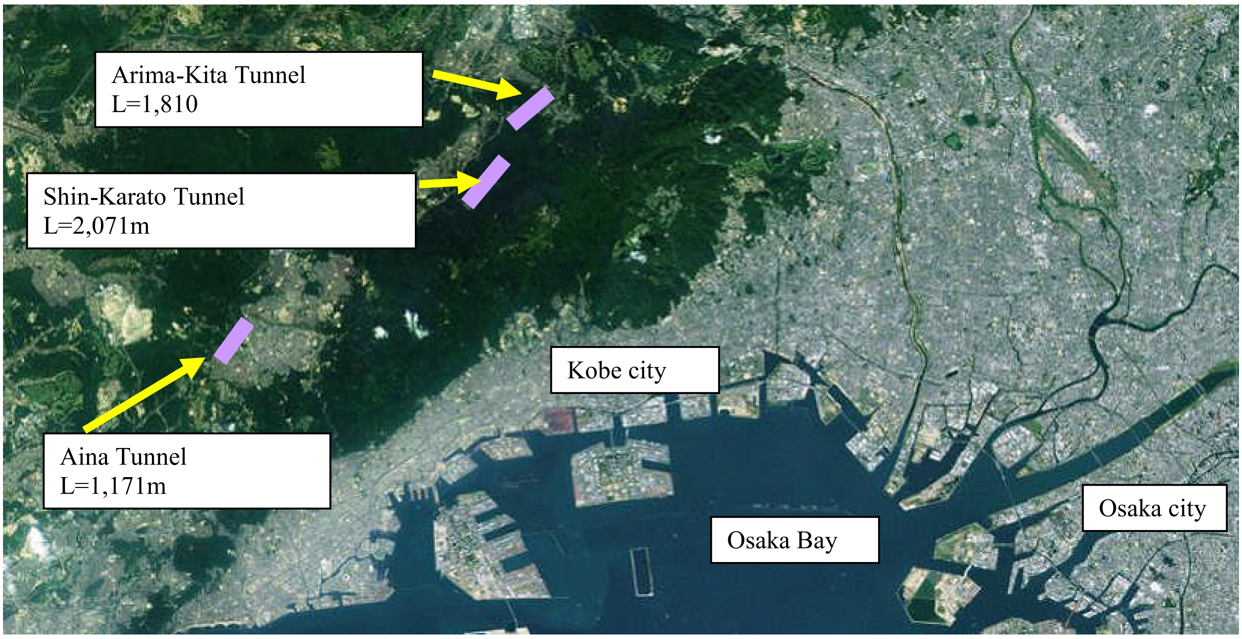

Figure 16　Aina Tunnel, Shin-Karato Tunnel and Arima-Kita Tunnel

5.2. Comparison items

For the purpose of comparison six items were evaluated:

(a) Visual inspection of the current state of the tunnel interior;
(b) Extraction of samples for future salt content analysis;
(c) Carbonation depth testing to determine the current extent of carbonation;
(d) Measurement of salty matter on the interior walls of the tunnel to assess the extent of salt damage to the tunnel interior;
(e) Water testing to determine the salt content of outflow in the vicinity; and
(f) Basic compression strength testing to assess the tunnel body and strength thereof.

In the Inariyama Tunnel, where the acetic acid cryoprotectant was used, analysis of salty matter on the tunnel walls and water quality at plumbing fixtures was carried out twice - directly prior to the commencement of the experiment and again one month later - in order to assess the effect of the cryoprotectant.

This report presents the results of item (d) above (measurement of salty matter on the interior walls of the tunnel). The other measurements represent the initial data for use in tracking studies. The data will be collected on an ongoing basis to assess changes over time.

Table 1　Comparison items

Item	Objective
(a) Check appearance	Assess current state of tunnel walls
(b) Extract samples	Obtain samples for future salt content analysis
(c) Carbonation depth testing	Assess current extent of carbonation
(d) Measurement of salty matter	Assess impact on tunnel interior
(e) Water testing at plumbing fixtures	Measure salt content in outflow
(f) Basic compression strength testing	Assess tunnel body and strength

6. RESULTS

6.1. Salty matter on tunnel interior

Inariyama Tunnel

Dispersion of acetic acid based cryoprotectant commenced on February 11. Conventional sodium chloride de-icing agent had been applied 18 times prior to that date. Salt levels were measured on February 9, directly prior to commencement, and again one month later at the same three locations. The three locations were the tunnel entrance and exit, and a point in the center. Measurements were taken on perpendicular surfaces of the tunnel structure.

The quantity of salty matter measured in the vicinity of the Yamashina entrance to the Inariyama Tunnel prior to commencement was 0.55 mg/m^2. After one month using the new acetic acid cryoprotectant, this figure had fallen to 0.04 mg/m^2, a reduction of around 90%.

Table 2 Measurement of salty matter on interior of Inariyama tunnel

Jujo side	Inbound lanes→ Salty matter (mg/m^2)			Yamashina side
Sodium chloride	Tunnel interior	Entrance	Middle	Exit	CAMAG
	Pre trial	0.01	below 0.01	below 0.01	
	After 1 month	0.02	below 0.01	below 0.01	

Jujo side	←Outbound lanes Salty matter (mg/m^2)			Yamashina side
Sodium chloride	Tunnel interior	Exit	Middle	Entrance	CAMAG
	Pre trial	below 0.01	below 0.01	0.55	
	After 1 month	below 0.01	below 0.01	0.04	

(Inariyama Tunnel: 2,537 m, opened to traffic June 2008)

Measurements of salty matter were also taken in the Aina, Shin-Karato and Arima-Kita tunnels on the Kita-Kobe branch of the Hanshin Expressway, where conventional de-icing agent is employed. Notwithstanding differences between the tunnels, the measured values tended to be higher in the center section of the tunnels. This can be attributed to the salt being carried by vehicles and deposited in the tunnel, from where it has less chance of escaping.

Table 3 Salty matter in tunnels on the Kita-Kobe branch (mg/m^2)

Aina Tunnel (1,171m, opened 1982)			
Tunnel interior	Entrance	Middle	Exit
Inbound lanes →	0.01	0.05	0.01
←Outbound lanes	–	0.04	–
Shin-Karato Tunnel (2,071 m, opened 1998)			
Tunnel interior	Entrance	Middle	Exit
Inbound lanes →	0.05	0.06	0.04
←Outbound lanes	0.03	0.015	0.05
Arima-Kita Tunnel (1,810 m, opened 2002)			
Tunnel interior	Entrance	Middle	Exit
Inbound lanes →	0.04	0.05	0.06
←Outbound lanes	0.03	0.05	0.03

7. CONCLUSIONS AND FUTURE CONSIDERATIONS

7.1. Benefits of the automated dispersion system

1) The automated system operated faultlessly and produced the required outcome
The automated system operated on 14 days during the winter season. There were no faults or problems, and the system achieved the required outcome of preventing icing of the road surface.

2) Automated timing linked to temperature sensor
Whereas conventional de-icing operations rely on supervisors issuing instructions based on weather forecasts, the automated system regulates cryoprotectant spraying based on real-time on-site monitoring using temperature sensors. This eliminates the human labor involved in checking the weather and issuing instructions.

3) Cost savings
The automated system eliminates many of the ongoing labor expenses associated with conventional de-icing operations, particularly the preparation, loading and transportation of de-icing agent. Over a number of years, the labor savings will offset the initial cost of installing the automated system.

4) Support for remote control functionality
In the future, the system could be expanded to provide remote-control functionality to enable operators to modify temperature settings, check log reports and monitor storage tank levels (for refilling schedules) from a central control facility. Remote control functionality would further enhance the benefits of the system.

5) Installation points on the Hanshin Expressway
Conventional de-icing operations require the de-icing agent to be dispersed over the entire usable road surface, including the main carriageway as well as entry and exit ramps, and this requires careful coordination and scheduling. As an elevated expressway passing through an urban area, the Hanshin Expressway has relatively few locations suitable for installation of an automated dispersion system. One potential solution is to install automated systems on entry and exit ramps and restrict conventional de-icing operations to the main carriageway only. This would substantially reduce the time and labor involved in de-icing operations. It is hoped that automated systems will be installed at more locations in the future, based on further evaluation of the operational status and benefits of the pilot system at the Inariyama Tunnel.

6) Snow melting performance
In the absence of any accumulated snow cover after the commencement date, we were unable to evaluate the performance of the pilot system with respect to melting snow. Further investigation is required in this area, subject to the foremost priority of ensuring the safety of vehicle traffic.

7.2. Initial observations of internal tunnel structures and fittings

1) Importance of chloride monitoring during internal tunnel maintenance
De-icing agent is not normally applied inside tunnels. However chloride compound applied near tunnel entrances is inevitably carried by vehicle traffic into the tunnel, where it accumulates as deposits. Chloride deposits in the center section of tunnels are particularly difficult to remove. For this reason, monitoring of chloride buildup is a particularly important consideration in maintenance of internal tunnel structures, facilities and associated fittings.

2) Ongoing research on acetic acid cryoprotectant agents

The measurements obtained in this study are considered initial observations. Although no significant improvements were identified, the study provides a valuable reference point for similar studies in the future. A combination of further research and more automated dispersion systems in use will enable environmental impact studies on acetic acid cryoprotectant agents in the future.

7.3. Future outlook

In the era of environmentalism, the lifespan of buildings and structures is an increasingly important issue in Japan. The ability of the CAMAG product to minimize structural deterioration in road tunnels is surely in line with the needs of our times.

We believe that the automated dispersion system represents an advanced new form of technology that will prove cost-effective in the long term, with automation of de-icing procedures and more timely application leading to improved traffic safety.