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Analysis of effect of road sprinkling system for heat island reduction

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ABSTRACT

An effective management plan for rainwater use is being prepared in Korea to secure alternative water resource and propose urban heat island reduction policy. This study evaluated the effects of road sprinkling system installed in an apartment housing complex to improve the effectiveness of rainwater use, first in Korea. The efficiency of the application mechanism and probable effects of the road sprinkling system using collected rainwater were investigated. A system for effective use of rainwater was designed through hydrologic analysis performed by monitoring and conducting surveys such as citizens' satisfaction rate. Road sprinkling system installed can be used for dust and temperature reduction wherein the equipment automatically sprinkles water on the road after collecting rainwater through a general collector on the rooftop. In doing so, road surface temperature, water quality analysis, microclimate forecast before and after sprinkling, and maximum wind speed immediately after sprinkling were under the comfortable condition as suggested by the citizen's survey results. Evaporative latent heat effect of road surface lasted until 40 min after sprinkling. The road surface temperature was lowered by approximately 5°C after sprinkling. This shows that road sprinkling system can contribute to the reduction of heat islands. Furthermore, there was no significant reduction rate for the water quality analysis. However, since turbidity and SS concentrations were about 0 mg/L after 10 min of sprinkling, improvement of water quality was observed. For micropollutants in water quality, traces of Cu, Zn, and Ni, which are generally present in rainwater, were found. Since the observed concentrations were low, the rainwater sprinkling system will have no significant environmental effect. The result of this study may be used as a reference for the installation of rainwater-use facilities such as road sprinkling system for apartment housing complex in other urban areas and detailed design guidelines.

Keywords: Climate change; Heat island reduction; Rainwater reuse; Sprinkling system; Water quality improvement

1. Introduction

The energy problem is closely related to the effective use of limited resources humankind can utilize therefore different countermeasures regarding water resource scarcity are being considered. Even in urban and architecture sector, active review about rainwater use along with existing greywater facility, and reuse of treated wastewater is being conducted. The Ministry of Land, Transport and Maritime Affairs, on May 2008, launched the "Mood Variation Reaction Comprehensive Countermeasure in Land, Transport and Maritime Sector" and selected "Introduction of dispersal rainwater management system that includes penetration of rainwater, undercurrent, and use" as detailed assignment in order to cope with climate change according to environmental aggravation [1]. Moreover, the revised "Sustainable New Town Plan Standard" released last January 2010 allows effective use plan of water resource for the construction of

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a new town [2]. The Ministry of Environment is in considering planning the expansion of rainwater use such as rainwater-use facility installation and strengthening the related system. As of December 2009, a total of 659 rainwater-use facilities were fully operational in Korea, and the percentage of apartment housing and school building using this kind of facilities exceeded half. Landscaping, fire-fighting, and water used for cleaning are the main uses of rainwater as well as for developing surrounding space such as streamlet for microclimate improvement in an apartment complex and securing landscape [3,4].

Road sprinkling system using rainwater is considered as an active rainwater-use system as it saves rainwater through mechanical facilities and can be utilized in a given time and place. Furthermore, the utilization of active rainwater use (e.g., application to large-scale complex from existing road oriented installation) may yield to road temperature reduction, easing non-point pollutant load, and influence dispersion effect.

According to researches, road cleaning through sprinkling systems has a significant effect to the removal of relatively big organic substance and inorganic substance road deposited sediments on street of industrial district and resident district [5]. Moreover, studies regarding heavy metal distribution and pollution source accumulation of stacked sediment particle on road are being reported [6–8].

As a result of this study, it was proven that vegetation waterway installed on streets, through the measurement of suspended solids (SS) of road runoff, heavy metals (copper, lead, and zinc), may be used as a road runoff pollutant load reduction facility as it reduces pollution at peak load [9].

Regarding microclimate improvement plan in the city through sprinkling and storage of water, various researches have been performed for recent heat island effect and securement of the comfort of residents. Especially, study for temperature reduction effect of water-retentive surfacing due to evaporation and the cooling effect of the building are main, and it was found out that securement of moisture-content and sprinkling face may increase sprinkling and storage of water. This study may check temperature distribution due to sprinkling effect in three-dimensional point of view, however, the experimental place was limited [10,11]. The data that is required to verify this sprinkling effect differs according to purpose. It measures evaporative latent heat and reviews substantiality of surface temperature by basically measuring insolation, watering amount, evaporating amount, and the open-air state and using heat balance equation.

In this study, changes in the microclimate and water quality condition after the installation of a road sprinkler system using collected rainwater were analyzed. A survey was also performed to measure the residents' satisfaction rate.

2. Materials and methods

2.1. Present condition of installation of road surface sprinkling system on subject district

Fig. 1 shows the present installation condition of road sprinkling system and measuring place. The study area where the surface sprinkling system was installed includes 477 households and executes sprinkling after saving rainwater in a water tank complex through general collector installed in the rooftop. The system is designed along a section 100 m from the entrance of the apartments wherein 15 nozzles are installed every 5 m distance on central dividing line. It also sprinkles 20 L/min with the 3 kW level pump in terms of operation.

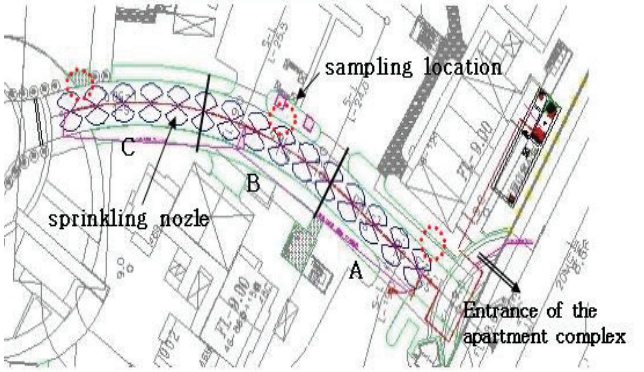

Fig. 1. Plan view of road surface sprinkling system and sampling locations at study area.

The designed capacity of subject road surface sprinkling system is 115 m^3/d, and it was constructed to collect rainwater from the rooftop of one building. Rainwater collected are stored in a rainwater settling tank and gets stored in a freshwater tank after purifying with mobile phase up-flow filter.

Roof rainwater generated amount was calculated by using the following rational formula:

$$Q = \frac{1}{360}\text{CIA} \tag{1}$$

Here, Q is rainwater runoff volume (m^3/s), C is the coefficient of runoff, and A is basin area (ha). Area of rooftop (A) of the general collection building is 0.082 ha. In terms of the coefficient of runoff (C) by construction type, with reference to rooftop type, 0.9 was applied (sustainable securing technology development business of water resource). Runoff amount of rooftop rainwater of one building was about 237.6 m^3/h (rainfall intensity 319.53 mm/h). Inlet ventilation pipe of rainwater-use facility (D) was calculated as 306 m^3/h by considering runoff amount of inlet, and runoff time is designed to secure 115 ton of planned capacity of rainwater-use facility within 0.4 h by considering generated amount per hour of design capacity and inlet.

2.2. Road surface temperature and analysis of microclimate change

The temperature distribution along the entire span of the road section is the major focus when using the thermographic camera. With reference from the marked place with red circle shown in Fig. 1, the thermographic camera was used to measure microclimate change by measuring temperature–humidity and wind speed of weather station and five stations.

Measurement list and humidity data are presented in Table 1, and sprinkling was done for 5 min and measured humidity along the road surface, insolation, and speed including 60 min before and after the experiment by every 1 min.

Table 1
Experimental overview

Date of experiment		August 5, August 18, September 1, 2012	
Time		14:00–16:00	
Weather		Fair and clear	Relative humidity ±60%
Segment		Survey items	Contents
Division	Target	Measurement content	Equipment or tool
Temperature	Surface temperature	Taken every 5 min	Thermal imaging camera
Microclimate	Outside temperature Wind speed Humidity	Data measured at 1 min interval, including 30 min before and after the experiment	Weather station
Road surface state	Degree of drying	Taken every 10 min	Digital camera
Water sprinkler status	Water temperature of sprinkler	25°C	Thermometer
	Flow rate of sprinkler	20 L/min·unit	1,500 L
	Pump capacity	3 kW	Technical data

Fig. 2. Status of field measurements.

With thermographic camera and digital camera (Fig. 2), data were collected every 10 min to review sustainable time according to dry condition of road and sprinkling. Also, it figured out expectation effectiveness and satisfaction according to the operation of road sprinkling system for total 210 people in the complex as the subject.

2.3. Road surface sprinkling outflow water quality analysis

In order to find out change of outflow water by road surface sprinkling, a total of five sprinkling experiment were conducted focusing on analysis of 12 parameters: pH, turbidity, SS, organic substance, total nitrogen, total phosphorus, and total colon bacillus in accordance with standard method after sampling water from inlet of excellent collecting pipe of three stations (A, B, and C). Eight more parameters were considered, Cd, Cu, Pb, As, Hg, Cr^{6+}, Zn, and Ni, in order to figure out sustainable environmental stability.

3. Results and discussion

3.1. Temperature of road surface and analysis result of microclimate change

3.1.1. Temperature change of road surface

Fig. 3 is a part of the results taken on August 18 among 3 d experiment, which is shot appearance for road surface by using the thermographic camera and digital camera. The weather situation on that day was clear with a small amount of cloud in around 33°C and 0.15 m/s of average gentle wind speed of measuring period. Sprinkling has been executed in a part of the road surface in the structure of road sprinkling system, and it may confirm that most rainwater is flowing down to drain hole when the moisture content of asphalt is considered.

The maximum temperature recorded on the road surface before sprinkling is about around 50°C that is considered high temperature, but the temperature of the road portion where sprinkling directly occurred is about 34°C, and it may observe that the sections that are not influenced were lowered about 5°C. On the other hand, the temperature of the road surface after 20 min of sprinkling has a reduction effect and it was analyzed that temperature is constantly lowered even though many parts of the road surface is dried. Although most parts of sprinkling area are dried after 40 min, sprinkling part compared with final road surface temperature is about 16°C, and it may confirm temperature reduction effect of roughly 8°C on the part that is not sprinkled.

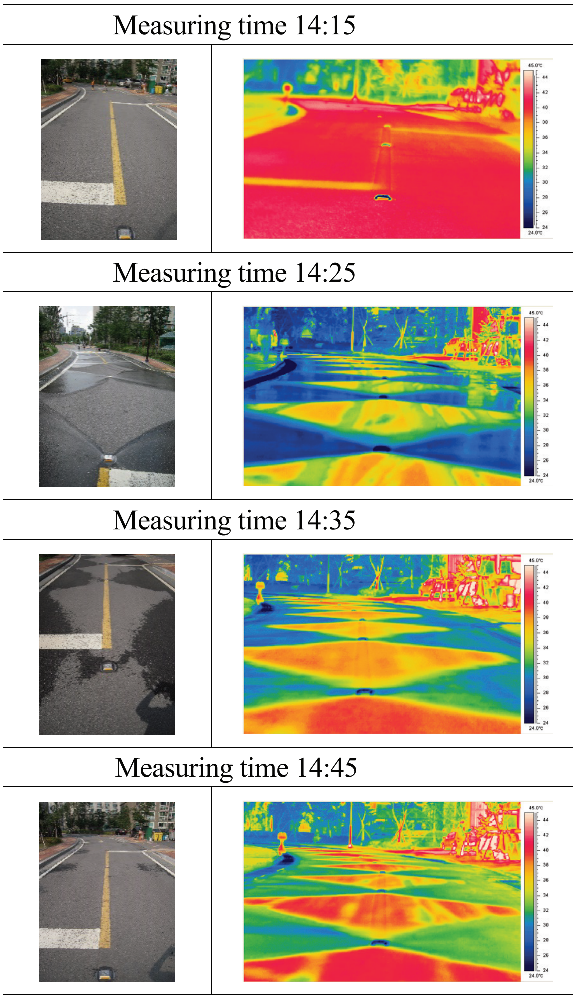

Fig. 3. Monitor the temperature change of road (August 18, 2012).

3.1.2. Analysis of evaporation effect

It calculates evaporative latent heat by using the average of the air during experiment period and road surface temperature and checks relation with a temperature of the road. Generally, heat balance equation is based on elements such as insolation, wind, and outside air temperature increased road surface temperature and the thing that identical heat amount is delivered to stratum or atmosphere. In this study, it tries to check evaporative latent heat by using equation considering a sprinkling of rainwater on heat balance equation [12–14]. Temperature reduction effect according to sprinkling is deeply related to moisture content on an asphalt surface, and it is expected that increasing coefficient of wettability of surface with a method such as installing bump on road surface because the moisture content of surface may influence on evapotranspiration and others.

Heat balance equation:

$$\begin{aligned}\alpha I(n) + \ \varepsilon q_{es} + h_o(T_\alpha(n) - T_\alpha(n) + c_{pw}\rho_w V_{win}(n)(T_w(n) - T_\alpha(n)) \\ =_{so} \rho C_1(T_{so}(n) - T_1(n)) + \gamma(T_{so}(n-1)M(n-1) \\ + c_{pw}(\rho_w V_{win}(n) - M(n-1)(T_{so}(n) - (T_\alpha(n))\end{aligned} \quad (2)$$

where $\gamma(T_{so}(n)) = (2{,}500 - 2.34T_{so}(n)) \times 1{,}000$.

Evaporation amount:

$$M(n) \ = \ W(n)k_x(X_{so}(n) - X_\alpha(n)) \quad (3)$$

$$M(n) \ = \frac{W(n)\alpha_c(X_{so}(n) - X_\alpha(n))}{c_{pa} + c_{pv}\dfrac{(X_{so}(n) - X_\alpha(n))}{2}} \quad (4)$$

Table 2 sets absorption factor of solar radiation, absorption factor of long wavelength, and others as various input condition to calculate evaporative latent heat through asphalt

Table 2
Conditions for estimating latent heat of vaporization

Segment	Items		Remarks
Ambient conditions	Solar radiation absorption	90%	Fair and clear
	Surface long-wavelength absorption	90%	
	Surface temperature	0.023 (kg′/kg)	Relative humidity: 60%
	Absolute humidity		Surface temperature: 49.8°C
	Outside temperature	0.018 (kg′/kg)	Outside temperature: 33.0°C
	Absolute humidity		
	(kg′/kg)		
	Dry air	1,005 (J/kg K)	
	Water vapor	1,846 (J/kg K)	
	Outside temperature	33.0°C	
	Surface temperature	49.8°C	
Water supply conditions	Flow rate	1,500 L	20 L/min unit
	Water supply temperature	25.0°C	
	Coefficient of wettability	10%	Water content assumed to be 10%
	Water sprinkling area	400 m^2	

literature, and it sets by using technical data of survey data and sprinkling system. As a result of calculation, evaporative latent heat that is gained through 1,500 L of sprinkling for 5 min was calculated as 855 kWh, and it was analyzed that it reduces displeasure according to radiant heat as it reduces the surrounding temperature.

3.1.3. Change of wind speed

Fig. 4 shows a change of wind speed by viewpoint before and after sprinkling. During the overall measurement period, wind speed is observed about 0–5.6 m/s, and it was observed that gentle wind was generated in 0.15, 1.17, 1.1 m/s, respectively, for average wind speed. As a result of measurement, increase of wind speed as much as it may regulate clearly, wind speed of before and after wind speed change was not observed, but it could check generation of strong wind speed according to evaporation from the road surface during sprinkling or after sprinkling. It is hypothesized that this is a result according to rapid generation of evaporation heat according to sprinkling, and it may feel that significant wind is actually generated on the road surface during sprinkling. Although it may show the clear relation of temperature according to increase and decrease of wind speed, it may be analyzed that effect on surrounding climate according to change in wind speed actually is small because heat capacity itself of road composed of asphalt is big.

3.1.4. Change of wind speed

Fig. 5 is the measured humidity change of surrounding surface change according to sprinkling. It may be observed that humidity is gradually increasing after sprinkling except

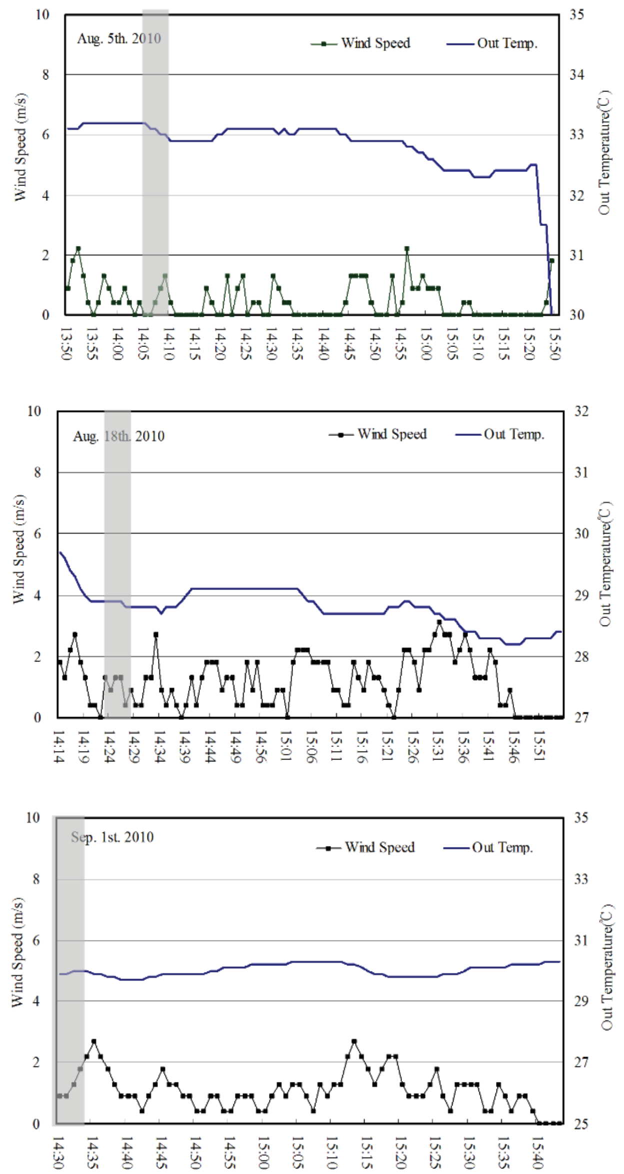

Fig. 4. Change of wind speed and outside temperature after runoff road surface sprinkling system.

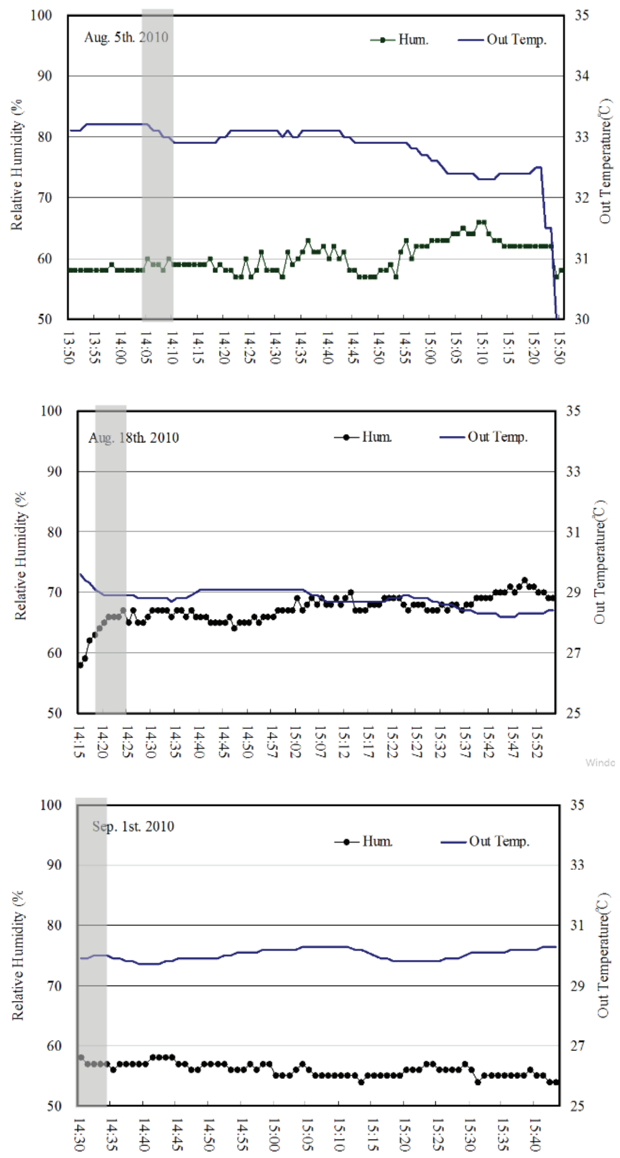

Fig. 5. Change of humidity and outside temperature after runoff road surface sprinkling system.

for September 1. In existing study, the analysis that increases of humidity may apply as the cause of displeasure of pedestrian and others is also suggested, but it was confirmed that displeasure according to an increase of humidity is not largely generated on this road sprinkling system when it analogizes with a survey result. As seen in results from August 5, relative humidity before sprinkling was about 58% that is not high, but humidity after sprinkling for 5 min was 60%, and it measured that humidity increased as about 65%–68% level at before and after 15:10 that was an hour passed after sprinkling. Also, along with evaporation phenomenon, it may be observed that temperature of surrounding road drops about 0.5°C–1°C. Overall, the increasing trend of relative humidity was confirmed due to evaporation effect due to sprinkling, but it is confirmed that it is not the level that brings displeasure to pedestrian of the surrounding road.

3.1.5. Survey result of satisfaction of residents in complex

As a result of surveying expectation effectiveness and satisfaction according to the operation of road surface sprinkling system about 210 people of residents in the housing complex, as shown in Fig. 6, the highest expected effect of this system is the reduction in road surface temperature (58.6%) followed by road cleaning in the complex (31.9%). This means to reduce thermal discomfort in walking as it eases radiant heat through road sprinkling, and it suggests that road sprinkling system may be used effectively as a countermeasure for dust scattering of the road surface.

Fig. 7 depicts satisfaction survey result about microclimate change after road surface sprinkling, it showed that 53.2% were satisfied while 30.5% responded normally. Only 3.5% of the respondents responded "very unsatisfied" therefore it can be considered that the respondents reacted positively regarding the effect of temperature reduction. This result offers fresh feeling visually even though the big change was not observed in the microclimate of the surrounding road surface, and it is analyzed as a result that radiant heat road is reduced. Also, regarding the removal effect of dust scattered after sprinkling, 52% of the residents are responded that this is effective to remove dust scattering, and it is expected that the road surface sprinkling system plays effective role for removing yellow dust in not only summer but also in spring and fall that yellow dust is severe.

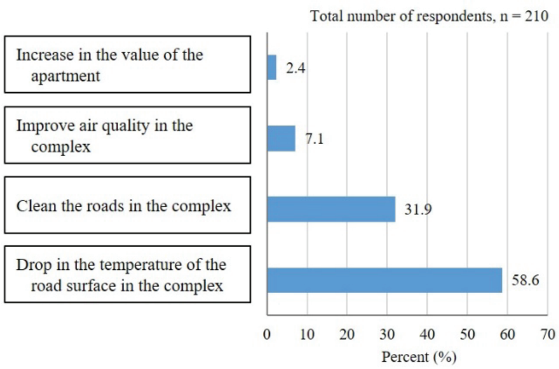

Fig. 6. Expected effects of rainwater utilization system (first priority).

3.2. Analysis result of water quality of road sprinkling runoff

The analysis was conducted by sampling first runoff after sprinkling for 10 min (R1), runoff after 5 min (R2), and runoff after 10 min (R3), and it calculated average pollutant load reduction rate by using concentration change of early runoff and final runoff. Fig. 8 shows pH change according to runoff time, average pH is considered alkalescent condition when it falls between 7.5 and 8.5, which rarely has changed according to runoff time and season. In other words, it seems that pH of road surface sprinkling runoff by using rainwater from the rooftop will not affect the surrounding water. It is also considered that operation is available even if vegetation gutter is substituted for a concrete drainage gutter.

In Figs. 9 and 10, comparison of early runoff and final runoff concentrations due to sprinkling showed that SS resulted in definite reduction effect (80%–100%). Organic matter (CODcr) also showed about 20%–60% reduction in concentration in final runoff compared with early runoff, therefore road surface sprinkling by using only rainwater in complex meant that there is cleaning effect of deposited materials on the road as well as microclimate effect. Moreover, nitrogen (TN) and phosphorus (TP), materials leading to eutrophication of stream or lake, also reduced about 20%–40% through road surface sprinkling.

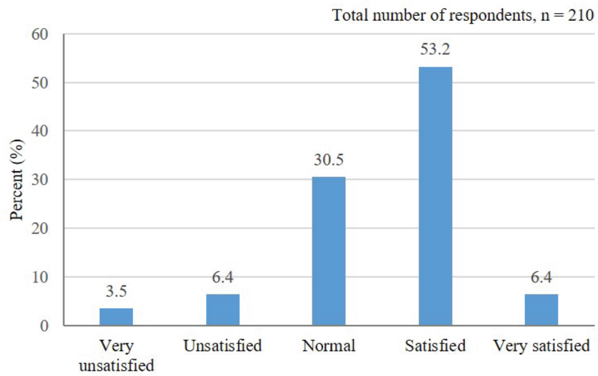

Fig. 7. The temperature reduction effect of a cool feeling.

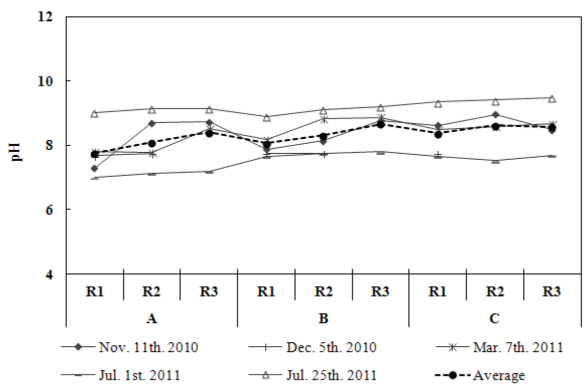

Fig. 8. pH variation of road runoff with installed surface sprinkling system measured between November 11, 2010 and July 7, 2011.

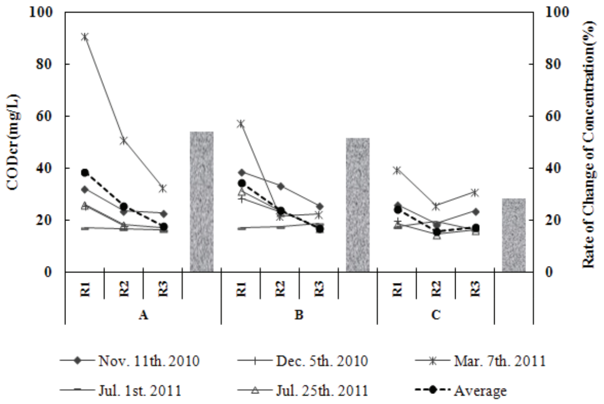

Fig. 9. CODcr (mg/L) variation of road runoff with installed road surface sprinkling system measured between November 11, 2010 and July 25, 2011.

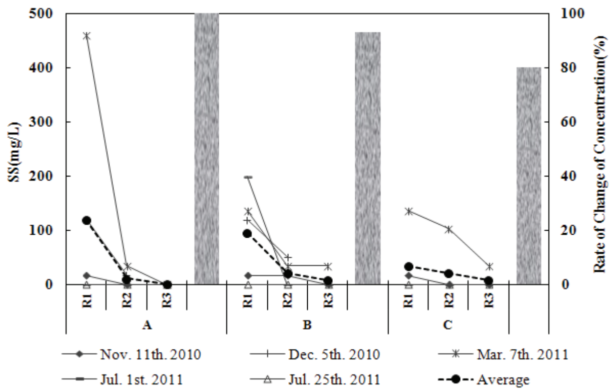

Fig. 10. SS (mg/L) variation of road runoff by runoff time using road surface sprinkling system, as measured between November 11, 2010 and July 7, 2011.

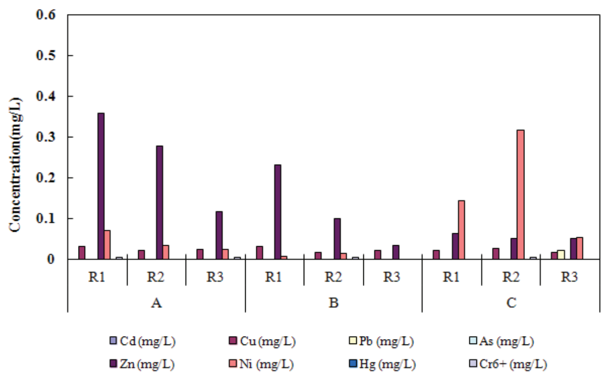

Fig. 11. Concentration variation of metals in road runoff with installed road surface sprinkling system.

If heavy rain occurs, solid matter, organic matter, nitrogen, and phosphorus deposited on road are washed off into surrounding stream, may affect the stream. It is judged that it may be controlled through periodical cleaning of non-point pollutant load through rainwater-use road surface sprinkling system in the complex. As a result of measuring heavy metal for environmental stability of road runoff in complex, the measured value is very low so reduction degree due to the difference of early runoff and final runoff due to sprinkling does not have huge significance. However, high concentrations of zinc were detected; nickel and copper had low concentrations while lead was rarely detected. Also, the existence of mercury, arsenic, and cadmium, and hexavalent chrome were not detected.

4. Conclusion

This study focused on microclimate change, resident satisfaction, and change in water quality after the installation of road surface sprinkling system in a housing complex for expansion of rainwater use.

- It was determined that sprinkling 1,500 L of rainwater for 5 min on the road surface lowers the temperature from 50°C to 30°C for about 40 min. There was a minimal change in air temperature of the surrounding road but increasing trend of instantaneous wind speed and relative humidity was observed. Similar to findings of existing studies, increase in humidity does not cause discomfort to pedestrians, furthermore, it was surveyed that they are satisfied with the effectiveness of sprinkling system due to reduced displeasure about radiant heat from the road surface and the comfort due to the removal of dust scattering. Also, dust removal effect of road surface sprinkling system is expected to create comfort complex environment even not only in summer but also in spring and fall that is severe in the yellow wind through the periodical operation.
- pH of road surface runoff that used rainwater of rooftop in complex showed neutral and alkalescency so there will be no effect to surrounding waters. It was also observed that vegetation gutter process of road surface runoff will improve the landscape of complex. Comparing water quality of early runoff and final runoff of road surface runoff by using rainwater, SS is reducing clearly. Organic matter, nitrogen, and phosphorus (about 0.5–2 mg/L) reduction phenomenon is also observed. Sprinkling system by using rainwater of rooftop of apartment housing complex means that it may control non-point pollutant load in complex properly. In other words, as it operates in the dry season by spacing out sprinkling system, it seems that it may be operated sufficiently as a shocking absorber that eases or disperses as it gives the effect that deposited pollution source on road affects to surrounding stream with sudden runoff in heavy rain.

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Symbols

α	—	Asphalt surface solar absorption
ε	—	Asphalt surface long wavelength absorption
I	—	Global insolation, W/m^2
q_{es}	—	Effective emission
h_o	—	Total heat transfer coefficient of asphalt surface, W/m^2
C	—	Thermal conductance of the material point k, W/m^2
c	—	Static pressure specific heat, J/(kg K); water, pw: 41,866 J/(kg K); dried air, pa: 1,056 J/(kg K); vapor, pw: 4,186 J/(kg K)
P	—	Density of water, 1,000 kg/m^3
V	—	^{ply}Quantity, m^3/m^2 s
T	—	^{ply}Water temperature
so	—	Soil
X_{so}	—	Latent heat of evaporation of water at the same water temperature as T_{so}, kg/kg′
$\gamma(T_{so})$	—	Latent heat of evaporation of water temperature, J/kg
M	—	Evaporation amount, kg/s
α_c	—	Convective heat transfer coefficient
W	—	Depth

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