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Effects of a Cool Roof System on the Mitigation of Building Temperature: Empirical Evidence from a Field Experiment

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Abstract: This study aimed to examine the effects of a cool roof system on the building temperature mitigation using a field experiment under current climate conditions in Seoul, Korea. Particularly, this study analyzed which meteorological factors affect the performance of the cool roof system based on the results of a field experiment during four seasons at the study site with real-time changes in various urban meteorological variables. This study also examined the extent to which each meteorological variable affects a cool roof system. Automatic temperature data loggers were installed on the roof of a Dobong eco-class building with reduced experimental models that included both conventional and cool roofs. A multiple regression analysis showed that when applying the cool roof system with other explanatory variables being controlled, the surface temperature of the building roof decreased by approximately 5.6 °C, and the indoor air temperature of the experimental model decreased by approximately 0.56 °C. These temperature reduction effects are meaningful, as the annual average reduction effects include nighttime and daytime. In addition, the most influential weather condition variable for roof surface or indoor temperature is external temperature, followed by insolation and humidity. Finally, the surface temperature reduction values in the actual roof of the study site and those of the roof surface of the experimental model were different. This suggests that the effect of temperature change on cool roofs is related to environmental factors as well as roofing materials. Therefore, the study suggests that cool roof policies should consider not only solar reflectivity but also other building environmental conditions and roofing materials.

Keywords: climate change; urban thermal environment; urban heat island effect; cool roof system

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1. Introduction

In the Korea Meteorological Administration's (KMA) publication of the "Korean Climate Change Prediction Report" in December 2012, it analyzed climate change in the Korean Peninsula by exploring two different scenarios [1]. The KMA predicted that the number of heatwave days (7.3 days per year, based on the current climate value) would increase to 30.2 days in the second half of the 21st century [1]. Such predictions by the KMA became a reality in the Korean Peninsula in the summer of 2018, after only six years. On 1 August 2018, the temperature soared to 41 °C in Hongcheon, Gangwon-do and to 39.6 °C in Seoul. The nationwide average number of heatwave days was 31.4, the highest number observed since 1973, exceeding the number of heatwave days predicted by the KMA in 2012. This development confirms that climate change on the Korean Peninsula is an urgent reality.

The urban heat island effect is emerging as a significant issue that threatens a pleasant urban environment in addition to climate change. The relationship between the spatial distribution of the urban heat island effect and temperature shows a tendency for the temperature to decrease from the city center to the outskirts [2]. In Seoul, the distribution of heat islands is dispersed to the east and west due to local topography, with the Han

River passing through the city center, the location of commercial and industrial areas, and the form of land use [3]. Therefore, special efforts to reduce the heat island effect should be made in areas where residential and commercial facilities are concentrated and where actual land use occurs.

The cool roof system has recently been highlighted as an effective method among the various heat management methods in cities. The Korean Ministry of Environment and local governments are also promoting climate change mitigation by designing policies, including cool roof policies, that support the reduction of both greenhouse gas and building energy, responding to heatwaves. However, there is still insufficient research on the temperature reduction effects of cool roof systems.

This study aimed to analyze the temperature reduction effect of a cool roof system based on empirical data observed for one year in a public building located in Dobong-gu, Seoul, Korea. Specifically, a cool roof system was installed on the roof of a Dobong eco-class building in Seoul along with two experimental models. In addition to the actual temperature changes of the roofs observed over one year with real-time weather changes, this study analyzed how the applied cool roof system changed the surface temperature and internal temperature of the roof of the test model and provided policy implications for improving the urban thermal environment.

2. Literature Review

The cool roof system has attracted considerable attention because, unlike existing roofs, they not only protect the roof from moisture but also save cooling energy owing to the high reflectivity effect of the cool roof [4]. When widely applied to urban areas, it also contributes to urban thermal management, including the creation of urban heat islands [5–9]. Recently, attempts to reduce the city's internal temperature by utilizing cool roofs in smart city plans and green remodeling projects have been drawing attention. In developed countries, including the United States, cool roof system verification has been completed, and the cool roof system is already being applied in various ways. In addition to the most common method of installing simple cool roofs, various attempts have been made to apply cool wall systems to the exterior walls of buildings, cool pavement systems to roads and parking lots, and cool car coatings to vehicles [10].

Various studies on cool roof systems have been conducted in Korea for many years [11–15], and the Ministry of Environment has been leading the application of cool roof systems to respond to climate change and heatwaves based on these studies. However, unlike in developed countries, due to various limited conditions, a study that completely proves the effect of the cool roof system in the domestic environment through extensive empirical research at the national level has not yet been conducted, and only limited studies have been conducted by individual researchers in each region.

2.1. Research Using Cool Roof Experimental Model

An early study [11] examined the impact of cool roof systems on building temperatures in Korea. Three rectangular experimental models measuring $1400 \times 1400 \times 1400$ mm^3 were created, and conventional, cool, and green roofs were applied. The surface temperature, back surface temperature, and indoor temperature of the model were analyzed, and the indoor temperature was compared based on the highest temperature rise according to the roof material. The highest temperatures for a roof with a general finish, a cool roof finish, and for the test model with a green roof were 45.7 °C, 37.8 °C, and 37.8 °C, respectively. The results showed that for the test models with the cool roof finish and the green roof finish, the difference in indoor temperature was lowered by up to 8 °C, implying that the heat island effect inside the city could be reduced.

In a related context, one study [13] evaluated a temperature comparison based on different roof colors. Producing four models similar to the previous study, the surface temperature, back surface temperature, and indoor temperature of each model finished in black, green, and blue, commonly seen in Korea, and white, commonly used when applying a cool roof, respectively, were observed to study the trend of seasonal temperature changes based on the color of the roof. The results demonstrated the effect of reducing the temperature by applying a cool roof.

A similar study [12] analyzed a cool roof system by preparing two container boxes measuring 5899 × 2348 × 2390 mm^3 instead of a small model made of sandwich panels used in a previous study [11]. According to the analysis, energy consumption in the domestic environment decreased by approximately 8% in the summer season, whereas the building energy consumption increased because of the high reflectivity effect of the cool roof in the winter season.

Meanwhile, one study [16] introduced a cool roof system technology that simultaneously exhibits waterproof and highly reflective thermal barrier effects, unlike the conventional reflective paints used in cool roof projects conducted by local governments in Korea. In this study, three experimental models were created: one model with urethane waterproofing finishing, which is widely used in Korea, a polyurea waterproofing coating, and a vacuum ceramic cool roof. The study found that the model finished with the vacuum ceramic thermal-waterproof coating had the best effect in reducing the temperature compared to the results of the models finished with polyurethane and polyurea coatings.

As such, few studies using experimental models have been conducted in Korea. However, as most buildings in Korea do not have a container structure with steel plates on the front, there are some differences from actual buildings, which are mainly insulated with concrete structures. Furthermore, because there is a difference between the actual environment and the model experimental environment, it is necessary to evaluate the cool roof system based on the domestic climatic conditions that change by season.

2.2. Empirical Studies on the Temperature Reduction Effect of Cool Roof through Application to Actual Buildings

Applying the cool roof system to an office building of Brunel University in London, UK, empirical and simulation studies were conducted using the TRNSYS software [17]. The results suggest that the ideal roof reflectance that can contribute to energy savings is about 0.6 to 0.7. In addition, while the cool roof effect can contribute to savings in cooling demand, it was found that an additional heating load may be generated depending on the region.

Another experimental study [18] applied a cool roof system to a 700 m^2-scale school roof in Trapani, Sicily and analyzed the temperature change and building energy consumption using TRNSYS. The surface temperature was reduced by a maximum of 20 °C and the indoor temperature was reduced by 2.3 °C on average during the cooling demand period.

In a study in Korea, a cool roof waterproofing system was applied to Changwon City Hall in 2014 [14]. An empirical analysis was conducted by observing the temperature change on the roof of Changwon City Hall, a public office building currently in use. The study found that the application of the cool roof system reduced the surface temperature by up to 9 °C and the indoor temperature by approximately 1–2 °C compared with the existing roof surface.

One of the main concerns for cool roof systems is that the heat source can be blocked due to the high reflective performance of the cool roof system in the winter, which leads to an increase in heating demand. In this regard, a previous study [19] applied a cool roof system to approximately 34% of the rooftop area of the Gangnam Public Health Center and observed the seasonal temperature change for comparison with the existing roof surface. After applying the cool roof system, the surface temperature decreased by up to 12.9 °C, 7.1 °C, and 8.2 °C in the summer, spring, and autumn seasons, respectively, thus indicating the high reflective performance of the cool roof system.

Similarly, a study [20] selected two engineering college buildings at Changwon University located in Changwon, Gyeongsangnam-do. This study investigated whether the application of a cool roof system blocks solar energy entering from the roof and reduces the temperature rise. According to an empirical study, the internal room temperature of the building studied decreased by approximately 2 °C. Another empirical study [21] was conducted by applying the cool roof system to a building located in the research institute for two days, from 28 to 29 June 2017. The performance of the cool roof system showed that the surface temperature difference in the summer was more than 10 °C with a temperature reduction effect. There was little difference in temperature during winter.

Domestic empirical studies are limited, as their application to actual buildings is conducted on only one or two target sites selected by researchers in each region. Even in Korea, which is a relatively small region, there are differences in the climate environment depending on the region. Therefore, to objectively study the effects of differences in temperature, insolation, and sunlight of the cool roof system, additional empirical studies are needed using data accumulated over a long period of time by region.

2.3. Simulation Studies on the Effect of a Cool Roof Application

As mentioned above, empirical studies applied to actual buildings are subject to many restrictions and economic and physical difficulties. Therefore, research on cool roof systems using various simulation tools is being conducted as an alternative. Representative simulation tools include Energy Plus, TRNSYS, Visual DOE 4.1, and Roof Saving Calculator [22].

One study [23] compared cool roof and green roof systems using the urban canopy model (UCM), which is specialized for urban areas in the weather research and forecasting (WRF) version 3.8.1 model for 16 cities around the Yangtze River, which represents the Yangtze River Delta region in China. According to the comparison results, the green roof approach showed a significant effect on daytime reduction, with a slowed reduction effect for the nighttime temperature. However, the cool roof showed a strong temperature reduction effect during the day, and a significant temperature reduction effect even at night.

Another study [24] conducted a simulation study by analyzing a meteorological model based in Guangzhou, China, and confirmed that the average urban temperature in summer could be reduced by about 1 °C through the application of a cool roof. Similarly, one study [25] analyzed a cool roof system using a WRF model and UCM in Baltimore, Maryland, located near Washington DC, in the eastern part of North America. It found that to reduce the urban surface temperature of Baltimore and Maryland by 1 °C, approximately 30% of urban roofs need to be replaced with green roofs or cool roof systems with an albedo of 0.7 or higher.

Modeling simulation studies have also been performed in Korea. One study [26] analyzed a cool roof system using the WRF meteorological model (WRF-ARW). It was composed of a WRF preprocessing system (WPS) for pre-processing and a WPF model for simulation, and the analysis results were visualized using GIS S/W. In total, 96.3% of the total rooftop area in Seoul could be used for a cool roof system, indicating that the application environment was very good.

Simulation research was used to overcome and replace empirical research on a wide scale, subject to various practical and possible difficulties, such as the economic and physical burden associated with implementation. However, while simulation analysis studies can be effective in representing a wide range of urban scales or overall climate and a country's environmental characteristics, there is a limitation in that it is difficult to specifically consider a region's micro-climate. There are also many limitations in accurately predicting and deriving meaningful results that can represent the real world because changes in the climate environment of each region occur rapidly over time and are continuously changing variables.

2.4. Limitations of Previous Studies and the Motivation of This Study

Table 1 summarizes the primary previous studies, including the methods used, contributions, and limitations. As various domestic and foreign studies related to cool roof systems have been conducted, the effect of temperature reduction owing to the application of the cool roof system has been proven [27]. However, the introduction of the cool roof system, which has a highly reflective temperature reduction effect, has not been empirically examined to identify the mitigation effects of building temperature during the entire year, which includes four seasons in Seoul, Korea. Therefore, more empirical studies are required to apply it to actual buildings in domestic environments. This study aims to analyze the effect of a cool roof system based on temperature and meteorological data on the actual roof layer observed and grouped by season and to estimate the policy implications of improving the urban thermal environment.

Table 1. Summary of previous studies.

Ref.	Methods	Contributions	Limitations
[17]	The field study and simulation were analyzed in parallel, and predictions and measurements for the calibrated model were compared.	The temperature reduction of avg. 2 °C was founded on roof surfaces. Solar reflectivity of 0.6–0.7 was confirmed as an optimum value to achieve energy savings.	The results are limited due to the difference in simulated prediction and variation of free-floating BLDG under real-time changes in building environmental conditions.
[28]	Computational analysis was carried out to estimate the direct energy savings from 11 different cool roofs applied to building cases.	By increasing the albedo of houses by 0.2, the cooling energy use can be reduced 30–40%.	The results are limited to the natural environment of North America.
[29]	The meteorological simulation of WRF v.3.6 was used to explore a neighborhood scale (~1 km^2) demonstration of cool roofs.	This study found observable temperature signals from ~1 km^2 scale based on both idealized and modeled analysis.	The results are limited to the summer (June and July) environment of the Guangzhou area.
[30]	MFCR, a single-story prefabricated building, is simulated with EnergyPlus in five different cities in different climate zone of China.	MFCR cool roof is feasible for the prefabricated BLDGs in China as the SSP for BLDGs located in all five locations is less than three years.	The results are limited to five cities in China. There will be an environmental difference compared to the Korean peninsula.
[31]	Nine experimental chambers were prepared to measure temperature changes in Shanghai. Measured data were validated using the THERB simulation model.	Both cool roofs and green roofs can reduce cooling loads significantly. However, a cool roof increases the heating load while a green roof reduces it.	The performance of green and cool roofs both face degradation over time. (vegetation density, dirt pickup, etc.)
[11]	This study was based on the descriptive analysis of roof temperature data collected from three experimental models (Cool roof, Green roof, and conventional Roof).	Evaluate the solar reflective performance of cool roofs compared to both green and conventional roofs.	The study was limited to an experimental test result. There will be a difference in the actual building roof case.

Table 1. *Cont.*

Ref.	Methods	Contributions	Limitations
[14]	This study conducted a descriptive analysis of roof temperature data after the actual application of a cool roof system on the roof of Changwon City Hall.	It was confirmed that the roof surface temperature was reduced by up to 9 °C, and the indoor temperature was decreased by about 1–2 °C.	This study needs to consider the differences in locational, meteorological, building environment and roofing materials used in the study site.
[16]	This study monitored the temperature difference of three different experimental models placed in Busan, Korea (Polyurethane, Polyura, and vacuum ceramic cool roof-coated).	This study defined current issues in the roof coating industry in Korea and evaluated the most popular roof coating methods along with the ceramic cool roof system.	The study was limited to a single located experimental test result. There will be a significant difference in different types of buildings in various locations.
[26]	This study evaluates the adaptation of cool roof and green roof effects in terms of the air temperature of Seoul Metropolitan City using WRF quantitative modeling analysis.	96.3% of the total roof area of Seoul can be adopted by cool roofs. The cool roof was more effective during day time, while the green roof was more effective at night.	This study needs to consider various weather conditions and climatic factors operating the numerical model with a lengthy analysis time.

3. Methodology

3.1. Selection of Case Study Site and Research Questions

This study examined how the cool roof system offers alternatives to the conventional general roof in the climatic and environmental conditions of Dobong-gu, Seoul, Korea, and how the system is affected by real-time changes in the climate environment. The study site, the Dobong eco-class building, is in northeast Seoul at the latitude and longitude coordinates of 37°39′34.6″ N and 127°01′46.5″ E, respectively (see Figure 1).

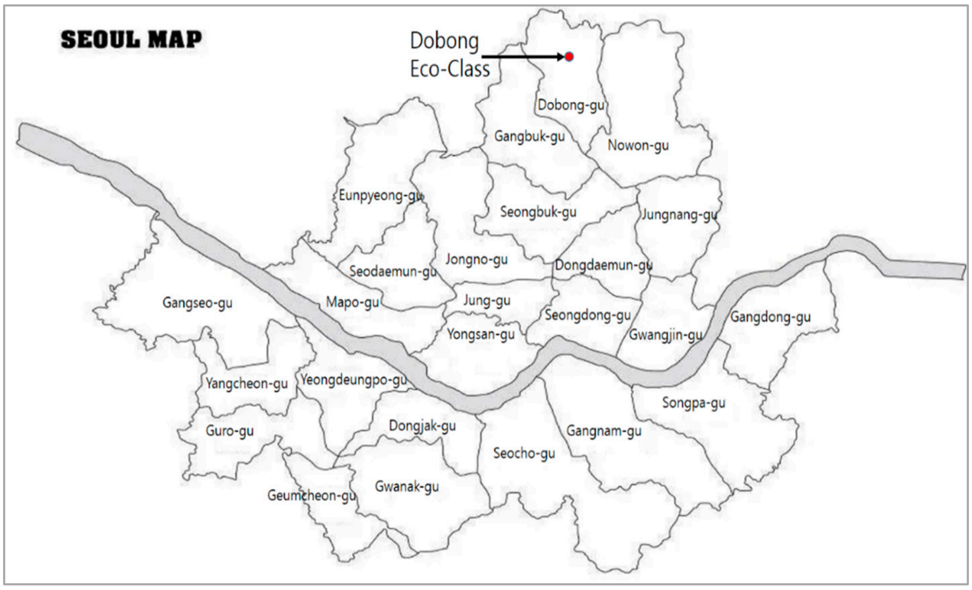


Figure 1. Location of the case study site.

The Dobong eco-class building, selected as a case study site, is a public building with an area of 238 m^2; it is a one-storey building suitable for conducting empirical studies, and was built with reinforced concrete with a red brick wall (see Figure 2). The roof of the building has a structure where 80 mm of insulation is inserted between a 12-mm thick gypsum board, 5-mm thick plywood, and 12-mm thick waterproofed plywood board, and it is covered with a galvanized steel panel that is exposed to the outside.

Figure 2. Bird's-eye view of the case study site (image source: authors). ① Experimental model (cool roof) ② Experimental model (Conv. Roof) ③ Actual Roof (Cool Roof) ④ Actual Roof (Conv. Roof).

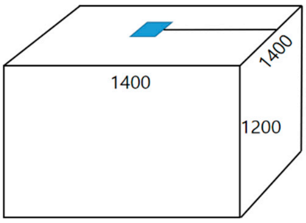
A cool roof system with a total area of 155 m^2 was installed on top of galvanized steel roofs exposed to outside air and partially on top of flat concrete roof surfaces. The rest of the roof area was left unchanged as the control group for further comparative analysis. Above all, because it is not used at night as an educational facility and has relatively good access to rooftops and access control for outsiders owing to the nature of public buildings, it is easy to protect and manage the temperature data measured on the roof. It also has the advantage of securing research reliability better than a private building.

This study focused on two research questions. First, what are the mitigation effects of a cool roof system on the building temperature? This question identifies the difference in temperature mitigation effects between cool and conventional roofs. Second, what meteorological factors affected the performance of the cool roof system during the four seasons at the study site? This question identifies the key meteorological factors that affect the performance of cool roof systems.

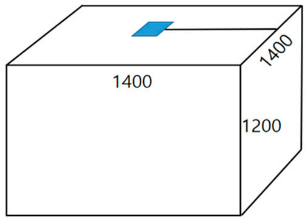
3.2. Experiment Overview

3.2.1. Field Condition and Suggestion of Alternatives

An empirical study was conducted on actual buildings in cooperation with the Environmental Policy Division of the Dobong-gu office. As the target site of this study was a public building and part of the roof layer could not be perforated or damaged, the surface temperature measurement was carried out in an actual building, and the indoor and back surface temperature measurements were replaced by additionally manufacturing an experimental model. For the production of the experimental model, this study used the same specifications in terms of the materials, surface structure, and internal and external structures because each specification might show different emissivity when manufactured with different specifications and materials. To supplement the cool roof and control group experiments, two experimental models of the same size and standard as a sandwich panel with 10 mm thick insulation material were fabricated and placed side by side on the top of the roof panel and included in the empirical experiment. Two experimental models were fabricated and placed on the upper part of the concrete slab of the Dobong Eco-class (see Figure 3).



(1400 mm × 1400 mm × 200 mm)
Cool roof system applied experimental model



(1400 mm × 1400 mm × 1200 mm)
Conventional waterproofing experimental model

Figure 3. Experimental building model design.

To conduct a smooth comparative experiment, a cool roof system was installed in one of the two locations, and the urethane-based waterproofing material (green), the most widely used material in Korea, was purchased and applied to the roof of the experimental model. Subsequently, an automatic temperature data logger was attached to the roof surface, back surface, and indoors, and an experimental model to which a cool roof system was applied was compared and analyzed with a control group and finished with the most popular roof waterproofing material in Korea (see Figure 3).

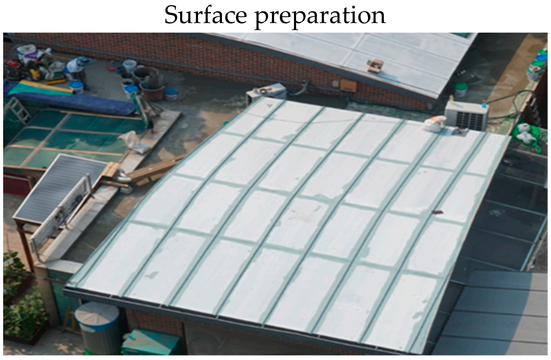
3.2.2. Installation Process of Cool Roof System at the Case Study Site

The roof of the Dobong eco-class was divided into two main types. First, the concrete flat roof part was a flat roof made of concrete slabs with a structure that connected two separate buildings. However, before the cool roof was applied, the concrete spherical surface was damaged because of the aging of the existing waterproofing layer, and the neutralization of the concrete progressed as rainwater entered through the cracks in the damaged waterproofing layer.

Therefore, for the application of the cool roof system, all the waterproofing layers of the urethane coating were removed, the damage due to the aging of the waterproofing layer was removed first, and the concrete spherical surface whose strength was lost by the neutralization of the concrete was ground and polished (see Figure 4).

Surface preparation

Stich-bonded fabric reinforcement



Reinforcement of vulnerable areas

Application of cool roof coating

Figure 4. The application process of the cool roof system (image source: authors).

A part of the Dobong Eco-Class building comprises a flat concrete roof, but the concrete flat roof surface is weakened owing to aging. Therefore, we first reinforced the vulnerable roof surface using specially designed hydration-solidifying composite waterproofing materials with stitch-bonded reinforcing roof fabrics. A high-solar reflective (solar reflectance of 0.88) CHMA silicon acrylic cool roof waterproofing material with a VOCs content of 50 g/L or less, which conforms to the international paradigm, was impregnated into the stich-bonded reinforcing roofing fabric to strengthen the tensile performance of the cool roof waterproofing membrane.

To analyze the cool roof system that meets the international paradigm, it was adopted as a product that qualifies eco-friendliness in both the manufacturing and post-application stages. Therefore, based on water-based products with VOCs $\leq$ 50 g/L, products that passed all categories of the KS F 3211 standard for waterproofing coatings for construction were selected in accordance with the Cool Roof Guideline presented by the Seoul Metropolitan Government [32].

The joints and corners within the roof surface are typically the most vulnerable areas of the building roof. To reinforce the vulnerable areas, a full fabric application method was used by embedding stitch-bonded reinforcing fabrics between the layers of high solar reflective roof coating materials based on the manufacturer's method.

3.2.3. Measuring the Temperature Data of the Research Site

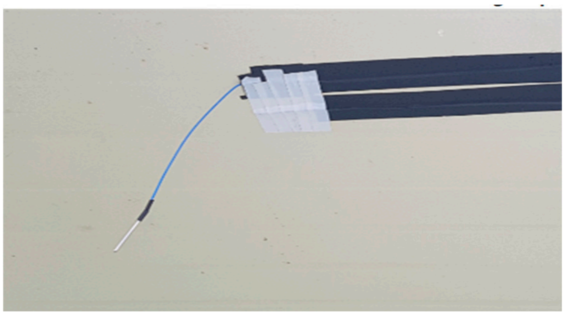
To effectively measure the actual temperature data accumulated through this study, 10 automatic temperature sensors were installed at the study site using two Testo 176 T4 temperature data loggers, which are four-channel high-precision measuring devices in the centigrade accuracy range of $\pm$ 0.3 °C $\pm$ 0.5% and manufactured by Testo, Germany, and an additional Testo 175 T3 two-channel high-precision automatic temperature measuring device that was placed in order to prepare possible data lost by a lightning strike.

Specifically, sensors were installed on the actual roof surface of the Dobong eco-class building, approximately 7.6 m from the center of the roof of the classroom building and 2 m from the center of the roof of the women's restroom building (see Figure 5). Two additional sensors were installed. For the experimental models, the area was divided into two parts; a cool roof was applied to one, and urethane waterproofing material was applied to the other. The latter is most widely used in Korea.

Sensor attached to the cool roof surface

Sensor attached to the conventional roof surface

Sensor attached to experimental model



Sensor attached inside of experimental model

Figure 5. Temperature sensor installations at the case study site (image source: authors).

Both the reduced experimental models were equipped with an automatic temperature sensor to detect the indoor temperature inside the model by extending the connecting line approximately 70 cm from the center of the roof surface, 70 cm from the center of the back surface of the roof, and 20 cm from the center of the roof inside the model.

3.3. Analysis Model

Based on data accumulated every hour by 10 temperature sensors installed at the study site for one year from 1 May 2018, to 30 April 2019, an integrated model and a distinction model were constructed, and the influencing factors of the cool roof system were examined through multiple regression analysis.

The dependent and independent variables were continuous data, and multiple regression analysis was used to analyze the causal relationship between two or more independent and dependent variables. First, the effect of the cool roof system was confirmed in the integrated model by deciding whether the cool roof system was to be applied as a dummy variable without distinguishing the analysis variables from the model to which the cool roof system was applied and the control model without the cool roof system. Thereafter, a multiple regression analysis was performed again with a model that divided the experimental model to which the cool roof system was applied and the conventional experimental model to which the cool roof system was not applied.

4. Analysis

4.1. Variables and Data Sources

The main dependent and independent variables used in this study are shown in Table 2. The dependent variables used in this study were data collected on the temperature (°C) of the roof of the site detected every hour at the research site for one year from 1 May 2018, to 30 April 2019. The descriptions of the variables are listed in Table 2.

Table 2. Descriptions of variables.

Category	Variable	Description	Source
Dependent variable	Actual roof surface (conventional)	The surface temperature of the actual roof of the study site (conventional)	Direct measurement
	Actual roof surface (cool roof)	The surface temperature of the actual roof of the study site (cool roof)	
	Experimental surface (conventional)	Surface temperature of the experimental model roof (conventional)	
	Experimental surface (cool roof)	Surface temperature of the experimental model roof (cool roof)	
	Back surface of the experimental model roof (conventional)	Back surface temperature of the experimental model roof (conventional)	
	Back surface of the experimental model roof (cool roof)	Back surface temperature of the experimental model roof (cool roof)	
	Experimental indoor (conventional)	Indoor temperature of the experimental model (conventional)	
	Experimental indoor (cool roof)	Indoor temperature of the experimental model (cool roof)	

Table 2. *Cont.*

Category	Variable	Description	Source
Independent variable	Temperature(°C) Wind speed (m/s) Precipitation (mm) Humidity (%)	Observation area: Dobong-gu	Open MET data portal
	Insolation (MJ/m^2) Snowfall (cm)	Observation area: Seoul (Songwol-dong) (ASOS)	
	Total cloud amount (decile)	Observation area: Seoul (Songwol-dong) Sunny (scale 0–5), cloudy (scale 6–8), cloudy (scale 9–10) (ASOS)	

The main dependent variables in this study were drawn from approximately 86,000 cases, including those from the roof surface temperature measured on the actual roof of the research site and the roof surface temperature, back surface temperature of the roof, and indoor temperature data measured from the experimental model installed at the same site for one year from 1 May 2018, to 30 April 2019. Eight automatic temperature sensors were attached to each experimental location to observe the temperature change for one year over the four seasons. Two additional preliminary measuring sensors were placed to prevent data loss because the measuring equipment could be damaged by natural influences, such as lightning accidents or heavy rains, during the one-year experimental period.

This study determined the extent to which the dependent variable responded to the natural environmental change of the site, which changed in real time during the same period, through the independent variable. As for the explanatory variables, data from the Automatic Weather Stations (AWS) of Dobong-gu were used as independent variables for temperature, wind direction, wind speed, precipitation, and humidity according to the regional observation method of the KMA, whereas data from the Automated Synoptic Observing System (ASOS) in Songwol-dong, Seoul were used for insolation, snowfall, and total cloud amount [33,34].

To perform a multiple regression analysis, each explanatory variable was first defined and a basic statistical analysis was performed, as summarized in Table 3. Measurements were carried out every hour for the cool roof and the conventional roof, resulting in 8766 observations. The data obtained in this manner were grouped and applied to two models. First, an integrated model was built without distinguishing between the 8766 observations obtained from the cool roof and the 8766 observations obtained from the conventional roof (control group). Subsequently, a distinction model to classify whether a cool roof was applied was reconstructed, and the factors affecting the cool roof performance were explored. The multi-collinearity of independent variables was reviewed for all analysis models, which confirmed that there was no multicollinearity problem, as the VIF values of all independent variables were five or less.

4.2. Summary of Temperature Differences between Cool Roof and Conventional Roof

Before performing the multiple regression analysis, Table 4 summarizes the actual temperature differences at each observation point for the two different types of roofs. The temperature differences were divided into three categories (minimum, maximum, and average difference in temperature).

Based on the results summarized in Table 4, the minimum temperature difference varies from 0.1 °C to 1.2 °C, the maximum temperature difference distributed from 3.5 °C to 21.4 °C and the average temperature difference varies from 0.6 °C to 5.6 °C depending on the substrate. There is a relatively small difference in the minimum temperature compared to the maximum temperature, which implies that the cool roof system is much more effective during summer, and there is not much difference in terms of temperature reduction during the winter season.

Table 3. Variables and basic statistical analysis.

	Variable	Obs.	Mean	S.D.	Min.	Max.
Dependent variables (temp.)	Actual roof surface (conventional)	8766	17.435	18.808	−18.2	76.9
	Actual roof surface (cool roof)	8766	11.846	14.280	−19.2	55.5
	Experimental model surface (conventional)	8766	15.668	19.094	−21.8	81.2
	Experimental model surface (cool roof)	8766	13.216	16.004	−21.9	64.3
	Experimental model back surface (conventional)	8766	15.359	12.958	−13.5	53.9
	Experimental model back surface (cool roof)	8766	14.582	12.184	−14.7	49.7
	Experimental model indoor (conventional)	8766	15.267	12.765	−13.2	52.6
	Experimental model indoor (cool roof)	8766	14.709	12.125	−14.1	49.1
Indepen. variables	Temperature (°C)	8766	12.675	0.118	−14.1	39.1
	Wind speed (m/s)	8766	1.125	0.009	0	5.4
	Precipitation (mm)	8766	0.186	0.019	0	76
	Humidity (%)	8766	67.066	0.239	12.7	97.4
	Insolation (MJ/m^2)	8766	1.076	0.013	0	3.52
	Snowfall (cm)	8766	1.288	0.142	0	8.8
	Cloud amount (decile)	8766	4.756	0.045	0	10

It should be noted that the temperature difference summarized in Table 4 is a comprehensive result, including all weather and time variables, such as day and night, outside temperatures, insolation, amount of rainfall, humidity levels, and wind speed.

Table 4. Summary of temperature differences between cool roof and conventional roof.

	Minimum Temperature (°C)			Maximum Temperature (°C)			Average Temperature (°C)		
	Cool Roof	Conv. Roof	Temp. Δ	Cool Roof	Conv. Roof	Temp. Δ	Cool Roof	Conv. Roof	Temp. Δ
Temp. of actual roof surface	−19.2	−18.2	1.0	55.5	76.9	21.4	11.9	17.4	5.6
Roof surface temp. of exp. model	−21.9	−21.8	0.1	64.3	81.2	16.9	13.2	15.7	2.5
Back surface temp. of exp. model	−14.7	−13.5	1.2	49.7	53.9	4.2	14.6	15.4	0.8
Indoor temp. of exp. model	−14.1	−13.2	0.9	49.1	52.6	3.5	14.7	15.3	0.6

4.3. Multiple Regression Analysis through Constructing an Integrated Model

First, the influence of the overall cool roof system was identified based on the integrated model built by applying the cool roof system as a dummy variable without first dividing the model to which the cool roof system was applied and the general test model to which the cool roof system was not applied. Table 5 summarizes the results of the multiple regression analysis on the surface temperature of the actual roof and the roof surface of the experimental model after setting the dummy variables for the cool roof application.

The multiple regression analysis found that by applying the cool roof system when all other explanatory variables were controlled, the roof surface temperature decreased by approximately 5.6 °C, and the explanatory power of the analysis model was also high at 91%. The influence of significant variables through the standardized regression coefficient (beta), which shows the influence of explanatory variables on response variables, was found to be a temperature of 0.729, followed by insolation at 0.367, total cloud amount of 0.055, wind speed of 0.015, and humidity of 0.006.

The results of the multiple regression analysis of the surface of the experimental model showed that by applying a cool roof system when all other explanatory variables were controlled, the roof surface temperature decreased by approximately 2.5 °C, which shows that the linear model estimate based on the high explanatory power of approximately 91% explained the given data well. As for the effect of the significant variables, a temperature of 0.650, insolation of 0.484, total cloud amount of 0.077, humidity of 0.031, and wind speed of 0.011 were measured.

Table 6 summarizes the results of multiple regression analysis based on the data observed on the back surface and indoors of the experimental model after setting the independent variable for the cool roof application. The multiple regression analysis found that by applying a cool roof system when all other explanatory variables were controlled, the back surface temperature of the experimental model's roof dropped by approximately 0.8 °C, and the effect of significant variables was a temperature of 0.971, followed by a humidity of −0.078, insolation of 0.036, and total cloud amount of −0.018.

Table 5. Multiple regression analysis of surface temperatures (actual roof vs. experimental model roof).

	Actual Roof						Experimental Model Roof				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	***p***	**Beta**
Constant	−2.595	***	−13.49	0.000	-	Constant	−6.653	***	−33.45	0.000	-
Cool roof	–5.589	***	–72.67	0.000	–0.165	Cool roof	–2.451	***	–30.82	0.000	–0.069
Temperature	1.119	***	256.63	0.000	0.729	Temperature	1.042	***	231.01	0.000	0.650
Wind speed	0.294	***	5.28	0.000	0.015	Wind speed	0.219	***	3.80	0.000	0.011
Precipitation	−0.001		−0.02	0.981	−0.000	Precipitation	0.042	*	1.80	0.072	0.004
Humidity	0.004	*	1.80	0.073	0.006	Humidity	0.024	***	9.55	0.000	0.031
Insolation	7.121	***	116.48	0.000	0.367	Insolation	9.776	***	154.65	0.000	0.484
Snowfall	−0.093		−0.62	0.532	−0.001	Snowfall	−0.349	**	−2.28	0.023	−0.005
Cloud amount	0.227	***	22.86	0.000	0.055	Cloud amount	0.332	***	32.30	0.000	0.077
Obs.	17,532					Obs.	17,532				
F	22,030	***				F	22,458.1	***			
R-sq.	0.910					R-sq.	0.911				

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 6. Multiple regression analysis of the back surface and indoor temperatures of the experimental model.

	Back Surface Temperature						Indoor Temperature				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	***p***	**Beta**
Constant	4.057	***	35.84	0.000		Constant	4.224	***	39.73	0.000	
Cool roof	–0.777	***	–17.16	0.000	–0.031	Cool roof	–0.558	***	–13.12	0.000	–0.022
Temperature	1.109	***	431.97	0.000	0.971	Temperature	1.107	***	459.35	0.000	0.980
Wind speed	0.107	***	3.27	0.001	0.007	Wind speed	0.124	***	4.03	0.000	0.008
Precipitation	−0.010		−0.76	0.447	−0.001	Precipitation	−0.01		−0.76	0.445	−0.001
Humidity	−0.044	***	−30.55	0.000	−0.078	Humidity	−0.045	***	−33.75	0.000	−0.082
Insolation	0.523	***	14.54	0.000	0.036	Insolation	0.353	***	10.45	0.000	0.025
Snowfall	0.264	**	3.02	0.003	0.006	Snowfall	0.297	***	3.62	0.000	0.006
Cloud amount	−0.055	***	−9.41	0.006	−0.018	Cloud amount	−0.066	***	−12.10	0.000	−0.022
Obs.	17,532					Obs.	17,532				
F	36,444.0	***				F	40,695.8	***			
R-sq.	0.943					R-sq.	0.949				

Notes: ** $p < 0.05$; *** $p < 0.01$.

Finally, the indoor temperature analysis of the experimental model found that when all explanatory variables were controlled, the indoor temperature decreased by approximately 0.56 °C, and the effect of significant variables was a temperature of 0.980, humidity of −0.082, and insolation of 0.025. For the integrated model, the effect of the explanatory variables was analyzed by reflecting the relationship between the temperature change of the roof to which the cool roof system was applied and the temperature change of the conventional roof to which the cool roof system was not applied in the integrated model. It showed the effect of reducing the surface temperature by approximately 5.6 °C on the actual roof of the Dobong eco-class to which the cool roof system was applied and about 2.5 °C of the surface temperature of the experimental model.

4.4. Multiple Regression Analysis by Roof Type

Table 7 shows the results of multiple regression analyses of the model that divided the cool roof system and the conventional roof with respect to the surface temperatures of the actual roof and the experimental model.

Table 7. Multiple regression analysis of the surface temperatures of the actual roof (cool roof vs. conventional roof).

	Cool Roof						Conventional Roof				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	**p**	**Beta**
Constant	−7.431	***	−44.58	0.000		Constant	−3.348	***	−13.08	0.000	
Temperature	1.079	***	279.83	0.000	0.833	Temperature	1.159	***	195.18	0.000	0.680
Wind speed	0.463	***	9.39	0.000	0.027	Wind speed	0.125	**	1.66	0.097	0.006
Precipitation	0.032		1.58	0.115	0.004	Precipitation	−0.033		−1.06	0.288	−0.003
Humidity	0.022	***	10.42	0.000	0.035	Humidity	−0.014	***	−4.15	0.000	−0.016
Insolation	4.076	***	75.38	0.000	0.249	Insolation	10.166	***	122.48	0.000	0.472
Snowfall	0.062		0.47	0.636	0.001	Snowfall	−0.247		−1.23	0.219	−0.003
Cloud amount	0.256	***	29.17	0.000	0.073	Cloud amount	0.197	***	14.67	0.000	0.043
Obs.	8766					Obs.	8766				
F	23,923.4	***				F	17,282.6	***			
R-sq.	0.950					R-sq.	0.932				

Notes: ** $p < 0.05$; *** $p < 0.01$.

The results of the analysis confirmed that the test results of the conventional roof, to which the cool roof system was not applied, reacted more in all areas of the surface temperature of the actual roof, the surface temperature and the back surface temperature, and the indoor temperature of the experimental model. The results of the experiment on the actual roof surface of the study site showed that when the outside temperature increased by one unit, the increase in the surface temperature of the conventional roof to which the cool roof system was not applied was greater than that of the roof surface to which it was applied.

During the surface temperature test of the actual roof of the target site, to which the cool roof system was applied, the outside temperature had the most significant effect and was less affected by other weather variables. The order of strength among the significant explanatory variables for the roof to which the cool roof was applied was the temperature (0.833), insolation (0.249), total cloud amount (0.073), humidity (0.035), and wind speed (0.027) (see beta values in Table 7). In the case of the conventional roof, among the significant explanatory variables, strength was determined by a temperature(0.680), insolation (0.472), total cloud amount (0.043), humidity(−0.016), and wind speed (0.006) (see beta values in Table 7).

Similar results were found in the case of the roof surface temperature of the experimental model. The surface temperature of the experimental model confirmed that the model in which the cool roof system was applied was less affected by temperature and insolation, which are the main factors, than the conventional experimental model in which the cool roof system was not applied.

When the external temperature and insolation increased by one unit, the conventional experimental model, to which the cool roof system was not applied, reacted more to the change. When the cool roof system was applied, the strength was confirmed in the order of temperature (0.712), insolation (0.419), total cloud amount (0.080), humidity (0.041), and wind speed (0.017) among the significant explanatory variables, as well as in the order of temperature (0.607), insolation (0.543), total cloud amount (0.075), and humidity (0.022) for the conventional roof (see beta values in Table 8).

Table 8. Multiple regression analysis of the surface temperatures of the experimental model roof (cool roof vs. conventional roof).

	Cool Roof						Conventional Roof				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	***p***	**Beta**
Constant	−8.123	***	−36.37	0.000		Constant	−7.635	***	−26.57	0.000	
Temperature	1.033	***	199.84	0.000	0.712	Temperature	1.050	***	157.94	0.000	0.607
Wind speed	0.313	***	4.74	0.000	0.017	Wind speed	0.125		1.47	0.142	0.006
Precipitation	0.044		1.63	0.103	0.005	Precipitation	0.041		1.18	0.239	0.004
Humidity	0.029	***	10.06	0.000	0.041	Humidity	0.019	***	5.13	0.000	0.022
Insolation	7.675	***	105.91	0.000	0.419	Insolation	11.878	***	127.39	0.000	0.543
Snowfall	−0.259		−1.47	0.141	−0.004	Snowfall	−0.443	*	−1.94	0.052	−0.006
Cloud amount	0.315	***	26.74	0.000	0.080	Cloud amount	0.349	***	23.02	0.000	0.075
Obs.	8766					Obs.	8766				
F	16,358.5	***				F	13,886.7	***			
R-sq.	0.929					R-sq.	0.917				

Notes: * $p < 0.1$; *** $p < 0.01$.

As for the experimental results of the back surface temperature of the experimental model in Table 9, unlike the surface temperature, the main factors were temperature and humidity. When the external temperature increased by one unit, the conventional experimental model in which the cool roof system was not applied reacted more than the experimental model in which the cool roof system was applied.

Table 9. Multiple regression analysis of the back surface temperature of the experimental model (cool roof vs. conventional roof).

	Cool Roof						Conventional Roof				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	***p***	**Beta**
Constant	3.404	***	24.72	0.000		Constant	3.933	***	22.83	0.000	
Temperature	1.078	***	338.16	0.000	0.975	Temperature	1.140	***	285.89	0.000	0.970
Wind speed	0.113		2.79	0.005	0.008	Wind speed	0.101	**	1.99	0.047	0.006
Precipitation	0.004	*	0.26	0.797	0.001	Precipitation	−0.025		−1.18	0.236	−0.003
Humidity	−0.041	***	−23.04	0.000	−0.075	Humidity	−0.047		−20.92	0.000	−0.081
Insolation	0.535	***	11.98	0.000	0.038	Insolation	0.511		9.14	0.000	0.034
Snowfall	0.252	*	2.33	0.020	0.005	Snowfall	0.275		2.03	0.043	0.006
Cloud amount	−0.040	***	−5.57	0.000	−0.014	Cloud amount	−0.070		−7.67	0.000	−0.022
Obs.	8766					Obs.	8766				
F	25,602.9	***				F	18,157.7	***			
R-sq.	0.953					R-sq.	0.934				

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

In the analysis of the back surface temperature of the experimental model, the back surface of the roof layer of the experimental model to which the cool roof system was applied showed the influence of temperature (0.975), followed by humidity (−0.075), insolation (0.038), and total cloud amount (−0.014) among the significant variables. Meanwhile, there was a temperature of 0.970, humidity of −0.081 and insolation of 0.034 for the conventional experimental model to which the cool roof system was not applied (see beta values in Table 9).

The indoor temperature of the experimental model to which the cool roof system was applied was affected by temperature (0.983), insolation (0.242), humidity (−0.084), and total cloud amount of (−0.019), among the significant explanatory variables. The data for the roof with the cool roof system were less affected by temperature and humidity, which are the main factors, than the data for the conventional roof without the cool roof system. The indoor temperature of the experimental model in which the cool roof system was not applied was also affected by temperature (0.979), humidity (−0.080), insolation (0.025), total cloud amount (−0.025), and wind speed (0.007) among the significant explanatory variables (see beta values in Table 10).

Table 10. Multiple regression analysis of the indoor temperature of the experimental model (cool roof vs. conventional roof).

	Cool Roof						Conventional Roof				
Variable	**Coef.**		**t**	***p***	**Beta**	**Variable**	**Coef.**		**t**	***p***	**Beta**
Constant	3.927	***	28.88	0.000		Constant	3.962	***	25.33	0.000	
Temperature	1.081	***	343.59	0.000	0.983	Temperature	1.133	***	313.07	0.000	0.979
Wind speed	0.146	***	3.64	0.000	0.010	Wind speed	0.102	**	2.20	0.028	0.007
Precipitation	0.005		0.30	0.763	0.001	Precipitation	−0.024		−1.28	0.201	−0.003
Humidity	−0.045	***	−25.84	0.000	−0.084	Humidity	−0.046	***	−22.49	0.000	−0.080
Insolation	0.335	***	7.60	0.000	0.242	Insolation	0.371	***	7.31	0.000	0.025
Snowfall	0.290	***	2.71	0.007	0.006	Snowfall	0.303	**	−2.46	0.014	0.006
Cloud amount	−0.055	***	−7.67	0.000	−0.019	Cloud amount	−0.078	***	−9.45	0.000	−0.025
Obs.	8766					Obs.	8766				
F	26,023.4	***				F	21,581	***			
R-sq.	0.954					R-sq.	0.945				

Notes: ** $p < 0.05$; *** $p < 0.01$.

5. Discussions and Conclusions

5.1. Discussions

Roofs are a primary component of the building envelope and are directly related to the total energy consumption of the building [11]. Based on the experimental study in a Dobong eco-class building in Seoul, Korea, it was confirmed that a cool roof system (solar reflectance of 0.88) reduces the peak roof temperature by 21.4 °C on actual roof surfaces, by 16.9 °C on the roof surface of the experimental model, by 4.2 °C on back surfaces of the roof, and by 3.5 °C in indoor temperature of the experimental model (see Table 4).

The peak roof temperature reduction on the roof surface of the experimental model placed in the Dobong eco-class was in line with previous studies [17,35,36]. The study [17] conducted at Brunel University in London, UK, found that the maximum internal air temperature was reduced by 1.3 °C. In comparison, the peak indoor temperature difference of the experimental model in Dobong eco-class was at 3.5 °C (see Table 4). London has a relatively unfavorable climate for a cool roof system because of its cloudy and wet climate and the low amount of insolation.

A previous study was conducted in Singapore with the development of a simulated model based on the cool roof heat transfer (CRHT) mechanism [35]. Two identically configured, side-by-side, unoccupied apartments located on the top floor in Singapore were analyzed using the CRHT model. The model predicted that the peak roof temperature reduction of 14.1 °C was determined through the concrete roof when solar reflectance of 0.74 was applied [35]. However, there is a meaningful difference when a comparison is made with the surface temperature of the actual roof of the Dobong eco-class. The main cause can be found in the different materials used to construct the roof and the different climatic conditions between Seoul and Singapore.

Another study [36] carried out in Perugia, Italy, indicated that the proposed cool roof system reduces the peak overheating by approximately 15 °C to 18 °C on roof surfaces. Also, the study indicated that the proposed cool roof system reduces indoor temperature by 2 °C. Meanwhile, this study indicates that the maximum temperature difference of the experimental model resulted in 16.9 °C on roof surfaces and 3.5 °C in indoor temperature. Perugia will be relatively close to the climate conditions of South Korea compared with the previous study sites described above.

One of the empirical studies was conducted in Korea on the roof of Changwon City Hall, and it was confirmed that the roof surface temperature decreased by up to 9 °C and the indoor temperature decreased by 1–2 °C [14]. Another empirical study conducted in Seoul was carried out on the roof of the Gangnam public health center, and the maximum temperature reduction after the cool roof application resulted in 12.9 °C, while indoor temperature ranges from 0.34 °C to 1.12 °C in reduction were measured [19].

As a result of the comparison with previous studies, the roof temperature reduction effect found in the Dobong eco-class building was in a similar context to that of previous studies. However, there are small and large differences in the roofing materials and geographic location of the target sites. This means that additional follow-up studies on cool roof systems for various types of roofing materials widely used in Korea are needed to estimate the potential benefits of implementing cool roof systems in Korea.

Tables 5 and 6 show the influence of each meteorological variable on the standardized regression coefficient, which indicates the degree of influence of each meteorological variable that has been affected in real-time. The results in Tables 6 and 7 show that outside temperature, followed by insolation and humidity, were identified as dominant meteorological variables that exhibited the greatest influence on the cool roof system.

The Korean Climate Change Assessment Report in 2020 by KMA projected that the average annual temperature of South Korea is expected to rise by more than 2 °C (based on the RCP 4.5), and by more than 4 °C (based on the RCP 8.5) by the end of the 21st century [37]. According to current knowledge, the increasing impact of climate change has been continuously detected even after the Paris Agreement was signed in 2016, and the assessment results show that climate change attributions, such as the severe increase in temperature and sea level and abnormal climate events, have also been on the rise [38].

As previously mentioned, insolation and humidity are other important meteorological variables that must be considered based on the standard regression coefficient (beta). Moreover, roof coating projects usually occur before and after the rainy season in the summer. Therefore, most roof coating applications in Korea must consider wet and humid conditions. Currently, cool roof requirements have not been developed in Korea [39].

5.2. Conclusions

This study derived the factors affecting the performance of a cool roof system by conducting an empirical analysis of the effects of the cool roof system for each season in year-round weather conditions in Korea. The main results of this study are as follows: First, it was confirmed that the average annual roof surface temperature of approximately 5.6 °C could be reduced through the application of the cool roof system to the roof of the study site. This is a meaningful temperature reduction effect, as it is an annual average reduction effect that includes both the nighttime when the sun sets and cooling occurs and the daytime when the sun is rising.

Second, as an environmental factor affecting the cool roof system, the outside temperature had the most significant influence, and insolation and humidity were identified as the vital weather conditions that mainly affected the cool roof system. The temperature of the Korean Peninsula has been rising rapidly in recent years, and a report released in 2020 by the KMA predicted that the temperature would rise by more than 2 °C based on the RCP 4.5 scenario and by more than 4 °C based on the RCP 8.5 [37]. Therefore, as global warming continues to intensify, the adoption of cool roof systems will be more beneficial for overcoming climate change issues.

Third, the most influential meteorological variable was outside temperature, followed by insolation and humidity. In addition, the rainy season on the Korean Peninsula is gradually increasing [40], and the main performance requirement of cool roof systems should not be defined based on high solar reflectivity as well as other weather variables.

Although this study is meaningful in that it empirically analyzed the performance of a cool roof system using experimental models targeting actual case areas, it has some limitations. For example, this study did not consider the long-term evaluation of a cool roof system. In Korea, unlike developed nations (such as the United States) the air quality in the urban environment is much lower. Recently, the air quality has rapidly deteriorated owing to yellow dust from China [19]. Additional considerations of a cool roof system, such as dirt pick-up resistance, are required to maintain enough solar reflectivity over a long time.

Another limitation of this study was that the thermophysical properties of various types of roofing materials used in Korea have not been widely considered. For example, most of the buildings that make up cities in Korea are concrete structures [41], and there is a trend in the demand for urban regeneration projects or remodeling that encourages the repair of existing buildings rather than new constructions. Moreover, many roofing materials can be installed on top of concrete structures. This means that when the official requirement for a cool roof system is developed, there are many other characteristics besides the high solar reflectivity of the cool roof system. It suggests adhesiveness on wet surfaces, damp-proofing capabilities, fungal resistance, etc. Therefore, it is thought that a follow-up study considering the physical characteristics of various kinds of roofing materials distributed in Korea will be necessary, and this needs to be considered to maintain the appropriate long-term performance of a cool roof system.

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