Analysis Methodology to Mitigate the Urban Heat Island Effect in the City of Cuenca with Emphasis on Concrete Pavements

Trotsky Narváez 1, Cristian Contreras 2, Julio Pintado Farfán 2

1 Catholic University of Cuenca, Master's Program in Construction with a major in Sustainable Construction management, camino a Patamarca y Cojimíes – Uncovía, Cuenca, Ecuador
2 Catholic University of Cuenca, Academic Unit of Engineering, Industry and Construction, Av. De las Américas y General Torres esquina s/n, Cuenca, Ecuador
trotsky.narvaez.50@est.ucacue.edu.ec

Abstract. It is evident that the consequence generated by the Urban Heat Island (UHI) in medium-sized cities with a population of more than 600,000 inhabitants generates a decrease in comfort for the user of the road network due to the increase in temperature and the difficulty of dissipating it. In the city of Cuenca there is a large number of urban roads that are rigid pavement and currently construction and maintenance projects are being generated for them, so it is necessary to seek solutions in the execution of concrete to reduce the UHI effect. The research comprehensively has two approaches: qualitative and quantitative-experimental. In the qualitative approach, the method of systematic review supported by meta-analysis of data is used to contrast information from secondary sources of case studies worldwide in Urban Heat Island, and through an outline the most common methods will be exposed. appropriate to reduce the effects of the object of study. Subsequently, this defined methodology will be put to the consideration of an expert judgment so that through its evaluation we can justify the proposed methodology. The expected result is a method of analysis and experimentation to be applied in the context of the city of Cuenca, which allows determining the effects of radiation on the construction materials of rigid pavements, defining construction strategies and types of concrete to reduce the UHI effect. The city of Cuenca accumulates large amounts of heat during the day and has difficulty dissipating it during the night, so this research seeks to propose construction alternatives and possible mitigation solutions to avoid or counteract the impact produced by the heat island through the most appropriate method.

1. Introduction
The increase in urban population worldwide has led to a drastic increase in anthropogenic activities and modifications of the urban surface. This contributes to the increase of urban temperature above the temperature of the surrounding rural areas. When this happens, the city is said to experience the Heat Island Effect (UHI). For a long time, the phenomenon has been studied throughout the world, in developed, underdeveloped and developing countries, analysing various factors such as its causes, effects, evaluation and mitigation measures, which has given us a clearer idea of what this phenomenon implies for society, environment and urbanization of our surroundings.
In addition to the implementation of green roofs and vegetation coverings, cool pavements have been recommended for urban temperature reduction [1] [2]. These strategies minimize the high rate of heat absorption by road pavements. Implementation of these strategies has been attempted in many cities in both developed and developing countries. Developed countries have made more progress in the development and design of cool pavements [3]. The implementation of cold pavements for UHI mitigation and the inclusion of cold pavements in urban development policies are subject to the level of awareness and interest of stakeholders [4].

There is predominantly a very poor representation and implementation of UHI mitigation strategies in urban planning policies in developing countries. It was assumed that some policy makers and engineers in such countries do not have adequate information and understanding about the UHI phenomenon [5]. In addition, understanding and evaluating regional geographic and atmospheric peculiarities is critical to assessing the effects and potential solutions of UHI in a region [6] [7]. In this regard, [8] reported that some mitigation strategies that were effective in summer may accelerate the UHI effect during winter. This shows that countries located within different climate regions may need to adopt mitigation strategies that can be effective in their locations.

On the other hand, the identification of the UHI has been limited by the fact that urban heat is evaluated with respect to only one point or rural area, when the reality in some places suggests a greater inclusion of measurement sites, as in the case of Cuenca where a greater number of rural stations can complete the study, in addition to considering its varied topography. In addition, climate studies have been based on flows over flat and homogeneous terrain, similar to linear scenarios, when in reality the scales of study in each territory can be heterogeneous, as in mountain contexts where the altitude varies, so that these analyses must be refined [9].

Specifically, the climatic context of the Andes is characterized by being one of the most important mountain systems in the world, with one of the most marked east-west climatic gradients globally [10], whose climatic modification is conditioned by the Andean topography [11] characterized by its variation in altitude and slope [12] [13]. Thus, one hypothesis to describe the behavior of the UHI in Andean cities suggests the "heat sink effect" (Figure 1) associated with the strong breeze from the Andes Mountains, which sweeps the UHI and displaces it to the west of the city [14].

In addition to the previous Andean delimitation, Ecuador is a tropical zone, since environments close to the equator are warmer than those near the equator [15] and that, at the same time, within this territory there are different UHI situations for coastal [16] and saw. In the context of the canton of Cuenca (Ecuador), if a cut is made in an east-west direction (Figure 1), it can be seen that it is located within the Andes Mountains and is bounded by the Cordillera del Cajas to the west and to the east by the mountains that border the Province of Morona Santiago. This valley-like configuration, that is, a geometry with a depression in the land surface in the central part where the city is located, is very common in Andean cities or in the case of Ecuador, where cities in the highlands have a similar pattern because the Andes mountain range crosses the entire territory from north to south.

Particularly, in Cuenca, while the existence of heat island has been characterized and verified for the year of 2014 showing an ICU of 2 ºC in the night period (16 h to 24 h) for ambient temperature, while surface temperature differences exceeds ambient temperature in the peripheral areas with a difference ranging from 5 to 15 ºC and between 2 to 13.5 ºC in the urban area. In addition, a more recent experimental study focuses on the warmest week of November for 2017 that compares the urban center with the rural Llacao station of similar altitude and identifies an UHI of 5 ºC in the daytime and an ICU of 3 ºC for the night-time.
Given this background, it is necessary to mention that according to the bibliography reviewed and that have as reference a case study of the city of Cuenca, most of the studies conducted in relation to the phenomenon of Urban Heat Island, determine quantitatively and qualitatively the effect itself, how to measure it but do not relate directly and in detail a study of the effects produced by concrete pavements or flexible pavements, even worse, a methodology of deeper analysis of how pavements behave in the face of this Urban Heat Island effect.

Figure 1. Andean Basin-Ecuador Schematic Diagram [17]

That is why the object of this research comprehensively has two approaches: qualitative and quantitative-experimental. In the qualitative approach, the method of systematic review supported by meta-analysis of data is used to contrast information from secondary sources of case studies around the world on urban heat island, and through an outline the most common and appropriate methods to reduce the effects of the object of study will be exposed.

2. Conceptual Framework and Research Methodology

2.1. Conceptual Framework

Heat Island the Urban Heat Island (UHI) phenomenon explains the undesirable situation whereby temperatures in urban areas become higher than those in the surrounding suburban and rural areas [18] [19].

Pavements Next, we can observe the characteristics of a pavement as in the case of Figure 2, where the thermal behaviour of a pavement can be observed.

Figure 2. Thermal behavior of a pavement [20] [21]

While it is true that there are several relevant factors that could be taken into account to develop construction alternatives in order to mitigate the effect of the urban heat island in the city of Cuenca, one of them that has been emphasized in this research is undoubtedly the type of concrete used in the road, sidewalks, buildings, their construction materials and their thermophysical properties; from the literature reviewed has been summarized in the following table.
Table 1. Thermophysical properties of pavements

| Properties | Description | Improvement measures | Effects |
|------------|-------------|----------------------|---------|
| Albedo     | Albedo is the proportion of incident solar ratio reflected by a surface. Pavement albedo is the ratio of the radiation reflected from the environment to the radiation received by the pavement surface. Pavements with lower albedo have higher temperatures. It ranges from 0-1 | Surface pavements with smooth textured, light-colored materials | Smooth, light-colored tiles were found to be cooler than rougher materials |
| Emissivity | Emissivity is the ratio between the solar radiation emitted by the pavement surface and the ratio emitted by a black body at the same temperature. It is the most important factor affecting the surface temperature of pavements at night. It ranges from 0-1 | Painting the pavement surfaces with light-colored paints | Unpainted pavements with albedo 0.15 were found to be 11k warmer than painted pavements with albedo 0.55 |
| Absorption | Absorptivity is the ratio of absorbed radiation to the ratio received by the pavement surface, ideally, the sum of albedo and absorptivity should be unity | Placement of a reflective coating on the pavement surface | 45k cooler than black coated pavements with an albedo of 0.08 |
| Conductivity | Thermal conductivity is a measure of the ability of a material to transfer heat. It is the amount of thermal energy transferred at a given time per unit area, per unit temperature gradient (W/mk) | Addition of conductive or insulating mastics to a pavement | The conductivity of asphalt mixes can be increased from 1.5 to 2.0 W/mk by adding 20% of insulating fillers |

2.2. Research Methodology

This study is divided into two main stages: The bibliographic review of primary and secondary sources; and the evaluation of the judgment of experts in this discipline.

Stage 1: For this stage we proceeded to the systematic review of the existing bibliography of secondary sources related to heat island worldwide, with the criterion of specifically reviewing research articles on the subject published in the last 15 years, giving priority in their selection to the most recent ones. In addition, we selected specific articles related to the measurement processes of the heat island effect, the influence of pavements on this phenomenon, possible mitigation methodologies based on the constructive variability of pavements. In addition, the VOSviewer software was used as a tool, which allowed us to have another search criteria and the importance of the articles, such as the citations of the documents and their reference articles. This review and its characteristics allowed us to obtain methodological results and a variety of solutions around the characteristics of the pavements from which we have been able to identify their convergent points and put together a possible methodology and solution for our environment based on the criteria of reliability and validity that will then allow our experts to evaluate under these concepts in the next stage.

Stage 2: The main objective of this stage is to evaluate the contents of the conceptual framework developed by assessing the levels of reliability and validity according to the established indicators.

Validity and reliability are the two quality criteria that any measurement instrument must meet after being submitted to consultation and expert judgment so that researchers can use it in their studies. Given this background as a small preamble to a conceptual framework, a group of professional experts in the field was chosen to conduct an evaluation under these criteria established as indicators in relation to a methodology and possible mitigation solutions to address the urban heat island effect based on the construction of cold pavements in the environment of the city of Cuenca. The evaluation of the experts will be based on 4 categories which are Sufficiency, Clarity, Coherence and Relevance, each one of these indicators will be evaluated by levels of reliability and validity, each category has a particular valuation, being able to be between 1 and 4, being 1 the lowest level and 4 the highest.

3. Results and discussions

Likewise, based on the methodology of the applied research, which was developed in two stages, in the same way we will develop the results of this research, dividing it into two stages in accordance with the methodology, thus obtaining the following results:
Stage 1: As a result of having applied the search methodology described in the previous point and managing a systematic review of the documentation found, we obtained a first screening of documents that were related to the proposed topic, which based on a search by keywords such as heat island, concrete pavements, mitigation, we obtained a first result of 173 articles that were directly related to the topic to be studied. Then a deeper sifting was performed by reviewing each document and selecting only those articles that in their content were directly related to cold pavements and their properties to mitigate heat island in different parts of the world with different methodologies of analysis and that the results have been satisfactory, as a result of this analysis of the review of this documentation, we were left with 10 articles that in their content, analysis, methodologies and results gave us greater clarity to determine our object of study. And finally a selection was made based on eliminating those documents that are not directly related to concrete pavements, in addition a comparison of the methods of analysis was made and we looked for those coincidences and convergences, thus summarizing the result as shown in the following table:

**Table 2. Summary of systematic research**

| References          | Cold Pavement Type. | Study location | Analysis method | Results                                                                 |
|---------------------|---------------------|----------------|-----------------|------------------------------------------------------------------------|
| [25]                | Utilization of albedo enhanced concrete pavement. | Tehran, Iran | ENVI-met simulation software | It resulted in lower surface temperatures of 5.32°C and 6.96°C than conventional concrete and asphalt pavements respectively |
| [26]                | Use of albedo concrete pavement to replace asphalt pavements. | Toronto Canada | ENVI-met simulation software | Reduction in surface temperature achieved to 7.9 °C |
| [27]                | Improve pavement reflectivity through the use of lighter colors and street vegetation. | Changwon, South Korea | Field observation and analysis with simulation software | Reduced the pavement surface temperature by an average of 3.4°C in June and 4.4°C in August |
| Li & col, 2013      | Combined permeable and reflective pavements. | California, EEUU | Field observation using thermocouple sensors embedded in pavement layers | A reduction of the surface temperature of 2 to 7 °C was achieved |

Table of own content.

Then based on the types of pavements that can be used in the city of Cuenca and that had greater convergence in the analysis as shown in the table above we can see that if we analyse the result based on the type of pavement we have a convergence to use pavements with improved albedo, reflective pavements or pavements with light colours and the combination of these. In addition, something that was taken into account to determine a methodology and that has also been agreed upon by several authors is the need to combine cold pavements with the accompaniment of vegetation in the streets. The analysis methods found to be common in this research, as shown in the summary table, and which are quite practical and accessible to our environment, are: the use of a simulation software ENVI-met, the use of infrared cameras and thermocouple sensors embedded in the pavement.

### 3.1. Proposed Methodology

The methodology of analysis to mitigate the Urban Heat Island in the city of Cuenca that is proposed below has been determined as a result of the review of a significant amount of information regarding experiences in different cities around the world, for this we had to perform a process of selection and classification of information, resulting in what is shown in Table 2. After this, a combination of the information contained in this table was made under a criterion of including within the methodology to be proposed that it be applicable to the environment of the city of Cuenca, that it consider types of concrete pavements, also the combination of road structures and buildings accompanied by vegetation,
as well as the use of a software calculation tool easy to handle, effective and accessible; Based on these criteria, the proposed methodology is developed below.

3.2. Methodology by Planned Simulation

This methodology by planned simulation is based on the simulation through a software, of an optimal scenario within the planning of roads, buildings and green areas in the urban area of our city that when compared with a traditional base scenario allows me to determine types of concrete pavements, amount of vegetation, rotation of our buildings in the most optimal way to reduce the effect of the heat island in our city. The software to be used in this methodology will be ENVI-met (version 4.3.0).

This model has already been successfully used in UHI and urban warming studies [28][29]. This software calculates the urban climate in direct relation, diffuse, reflected and longwave radiation fluxes from buildings and vegetation, including the simulation of all physical parameters of plants. The minimum simulation time is usually 6 h and the best time to start the simulation is at night or at dawn, so that the software can follow the solar radiation. ENVI-met requires a dimensional tree area input file and a configuration file containing input parameters [26]. The steps to be followed for the development of this methodology are as follows:

1. Determination of the place or area to be planned and where the simulation will be carried out.

2. Compilation of the necessary input data for the execution of the ENVI-met software for the simulation, parameters that are within reach of our needs in meteorological zones located in several points of our city, these input parameters are detailed in Table 3.

### Table 3. ENVI-met input parameters for simulation

| Parameters                        | Unit          |
|-----------------------------------|---------------|
| Time to start                     | hour          |
| Simulation period                 | Greater than 6 hours |
| Initial air temperature           | °C            |
| Wind speed at 10m                 | m/s           |
| Wind direction                    | ° (north south east west) |
| Specific humidity 2500m           | g/kg          |
| Relative humidity at 2m.          | %             |

3. The input scenarios for our simulation software will be determined, first starting from a base model, i.e. the characteristics of the materials based on the amount of albedo and % vegetation cover.

### Table 4. Scenario input parameters

| Parameters                        | Roof albedo. | Street Pavement. | Vegetation cover. | Vegetation cover. |
|-----------------------------------|--------------|------------------|-------------------|-------------------|
|                                   |              | Various Types.   | Tree              | Lawn              |
| Base Model                        | 0-1          | 0-1              | %                 | %                 |
| Green model                       | 0-1          | 0-1              | %                 | %                 |
| Fresh roof model                  | 0-1          | 0-1              | %                 | %                 |
| Fresh Floor Model                 | 0-1          | 0-1              | %                 | %                 |
| Rotation Model                    | 0-1          | 0-1              | %                 | %                 |

The values to be entered will be those determined from the materials to be used and the model to be followed
4. The types of concrete to be used in our simulation will be determined based on a base model and a model of a fresh pavement, determining in each of them the amount of albedo, thermal capacity and conductivity.

Table 5. Details of pavement materials in streets

|                          | Albedo | Thermal capacity | Thermal conductivity |
|--------------------------|--------|------------------|----------------------|
| **Base Model**           |        |                  |                      |
| Used or dirty concrete   | 0-1    | -                | -                    |
| Asphalt                  | 0-1    | -                | -                    |
| Light concrete           | 0-1    | -                | -                    |
| **Fresh floor mode**     |        |                  |                      |
| Gray concrete            | 0-1    | -                | -                    |

The values to be entered will be determined by the materials to be used and the model to be followed

3. Once the data have been entered into the software, the simulation will be carried out in the field for at least 6 hours, it is recommended to do it at night or at dawn so that the software can follow the solar radiation.

4. Evaluation of the results, the same will allow us to compare the variation of the temperature between the base models and the optimal models proposed in our simulation, so that with these results we can determine the pavements that have behaved better, as well as the amount of vegetation necessary to combine in our areas to plan the orientation of the buildings, which tomorrow will allow us to mitigate the effect of the heat island in our city.

3.3. Validación de ENVI-met

En muchos estudios anteriores, la validación de los resultados de ENVI-met se ha realizado comparando los resultados de la simulación y de medición de campo. Los resultados de estas investigaciones indican que el software simula las condiciones ambientales con la debida precisión. Como se puede observar en la gráfica a continuación se observa que los resultados de la simulación con los resultados medidos en campo son fiables y por lo tanto la metodología planteada para aplicar este software nos darían resultados bastante precisos.

![Figure 3. Comparison of simulation and field measurement results](25)

Well, this methodology has been applied in several countries around the world and has given very good results when comparing the software applied with the measurements made in the field, having a low level of inaccuracy, thus ensuring a reliable result to evaluate the possible solutions to the heat island effect, considering all the aspects mentioned such as the types of pavements to be built in the city,
the amount of vegetation to be simulated and the meteorological conditions of the city of Cuenca, being very useful for further studies which are the most appropriate materials based on this methodology.

Stage 1 in this stage of the study was made known to several experts in the subject of the research and to an expert who is currently working in the planning and construction of rigid pavement roads in the city of Cuenca the proposed methodology, so that under their perspectives they could evaluate this methodology, obtaining the following results:

Table 6. Results of the expert evaluation

| Dimension                        | About                               | Categories to be evaluated | Expert master in bioclimatic design (Mexico) | Master expert in environment and bioclimatic architecture | Master expert in geology, director of the project executing unit of the municipality of Cuenca |
|----------------------------------|-------------------------------------|-----------------------------|-------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Purpose of the methodology       | Sufficiency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 4                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 3                           | 4                                         | 4                                                        |                                                                                                                                                |
| The software as a tool for the methodology | Sufficiency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 4                           | 4                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 4                           | 4                                         | 4                                                        |                                                                                                                                                |
| The content and sequence of the steps of the methodology | Sufficiency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
| The collection of input data     | Relevance                           |                              |                                            |                                                          |                                                                                                                                                |
|                                  | Sufficiency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 2                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
| PROPOSED METHODOLOGY: "Planned Simulation Methodology" | The planning and simulation of the scenarios | Sufficiency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
| Classification of pavements      | Sufficiency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
| The execution procedure          | Sufficiency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
| The simulation results           | Sufficiency                         | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 4                           | 3                                         | 4                                                        |                                                                                                                                                |
| The results of the methodology   | Sufficiency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Clarity                             | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Consistency                         | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
|                                  | Relevance                           | 3                           | 3                                         | 4                                                        |                                                                                                                                                |
According to the table of results of the experts who evaluated this proposed methodology and its procedures, it is observed that the analysed parameters comply with a moderate and high level of validity and reliability to be applied to justify the objects of the research. In addition, one of our experts suggests that it would be necessary and interesting to apply it in the urban planning of our city, providing that there are 75% of roads in the city built with rigid pavement and that there is still a significant percentage of roads to be built and that this methodology could be very useful for the interests of the Municipality, as shown in Figure 4.

![Road map of Cuenca](image)

**Figure 4.** Road map of Cuenca.

4. Conclusions
Based on the results obtained in this research and justifying the proposed objectives, we can conclude that:

The methodology proposed is viable and applicable in our environment as a tool in the Planning of the urban area of the city of Cuenca.

The cold concrete pavements, having a significant percentage in the road planning of the city of Cuenca, could be used to replace the common gray pavement and, making a cost-benefit analysis for the city, would mitigate the effect of the urban heat island and improve the thermal comfort of the citizens.

The combination of cold pavements and vegetation would be an efficient alternative to mitigate the heat island effect in the city of Cuenca.

It is appropriate in future research to apply this methodology and the ENVI-met software tool as an experimental study and to give continuity to the object of this study.

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