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Optimization of Pavement Albedo on Surface Heating Reduction in Urban Canyons in Hot and Humid Climate of Nepal

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Abstract

Climate change is unavoidable and the most affected area by climate change is urban outdoor areas as indoor spaces can be conditioned through mechanical means. Low albedo materials like asphalt have a tendency to absorb and radiate more heat, which contributes to the urban heat island effect. In hot, humid conditions, this impact worsens the discomfort felt by pedestrians. The study aims to determine the optimum value of pavement albedo in the street that can balance the thermal structure within a canyon. The study adopted quantitative approach incorporating on site measurement of air and surface temperature of two streets followed by a thermal comfort questionnaire survey and simulation as research methods to fulfill its objective.The survey was conducted on two selected streets in Birgunj Metropolitan City with a random sample of 30 respondents each. Results showed that the physical characteristics of the canyon, such as albedo, aspect ratio, sky view factor and the orientation of the street impacted highly on the pedestrian thermal comfort.The difference in the average air temperature in asphalt (albedo 0.10) and the concrete (albedo 0.45) street was found to be 1.94℃. Similarly, the difference in maximum average hourly air and surface temperature between the streets were found to be 5.33℃ and 6.13℃ respectively. The respondents felt lesser heat from the pavement in Concrete Street rather than the Asphalt Street. Simulation results concludes that the optimum value of albedo is 0.3 for street with aspect ratio 2 and above, and 0.5 for aspect ratio 1 and below for both North South and East West oriented streets. The optimum albedo values reduced the air temperature of studied street by 3.9℃ and surface temperature by 10.33℃. However the mean radiant temperature increased by 6.68℃ due to the increased reflectivity.

Keywords

Urban canyon, Albedo, Air temperature, Surface temperature, Pedestrian, Thermal comfort

1. Introduction

With the rapid urbanization and alarming effect of climate change, significant challenges has been created in to urban areas, particularly in regions with hot and humid climates. In Nepal, the effects of the urban heat island (UHI) have been addressed time and again, resulting in elevated surface temperatures, reduced thermal comfort, and compromised urban livability. A small roadway or urban setting that is marked by tall buildings or other structures on both sides, producing a "canyon-like" effect, is referred to as an urban canyon. The aggregation of urban canyon units determines the thermal response for bigger sections of a metropolis [1]. Canyon material absorbs and stores 30% of solar thermal energy, which is then released at night to raise the ambient temperature [2].Due to anthropogenic heat and the usage of heat-absorbing materials, a high intensity of the heat island was discovered with a nighttime increase in air temperature of 13°C around the canyon [2]. The local physical characteristics of the sites: Sky View Factor (SVF), tree shade, ground surface cover, and canyon effect, can affect human exposure to potentially uncomfortable thermal conditions during a typical summer [3].Due to the varying thermal characteristics of urban construction materials and the three-dimensional geometry of built-up surfaces, which together alter nearby air temperatures, the UHI measured at the canopy layer may show substantial spatial and temporal fluctuation [4].

The energy balance of urban canyons is significantly influenced by pavement albedo, also known as surface reflectivity. Low albedo is a characteristic of traditional dark-colored asphalt pavements, which causes substantial solar radiation absorption and subsequent surface heating. Contrarily, reflecting or light-colored pavements have higher albedo, allowing for increased solar radiation reflection and lowering surface temperatures. The urban heat island effect can be reduced and thermally comfortable streets can be created by adjusting pavement albedo, which benefits both local businesses and pedestrians.

Albedo is the most crucial of these material characteristics in terms of how pavements interact thermally with their surroundings when exposed to sunlight [5]. The materials' specific heat capacity, thermal emittance, and thermal conductivity are second order factors. Due to the restricted amount of direct sunlight and the presence of dark, low-albedo pavement materials, surface heating is exacerbated, which is uncomfortable for pedestrians and hinders business operations, especially during the hot summer months. Therefore, in Nepal's hot and humid climate, it is imperative to address the problem of surface heating in urban canyons and look for practical methods to reduce UHIs.

A possible approach to reduce surface heating and improve thermal comfort in urban canyons is the optimization of pavement albedo. Albedo is the term used to describe surface reflectivity; materials with higher albedo reflect more solar energy and retain less heat. By choosing pavement materials with higher albedo or applying surface treatments that increase reflectivity, the absorption of solar radiation can be reduced, which ultimately lowers surface temperatures.

Since, the temperature ranges between 22°C to 41°C in Subtropical region of Nepal, it is difficult to carry out outdoor activities during daytime. In the context of Nepal, there are limited research done to reduce the surface temperature to make the streets walkable in hot summer days. The pavement type selection process, as stated by the Ministry of Physical Infrastructure and Transport Department of Roads, on Flexible Pavement Design Guideline (2nd Revision, 2021), includes primary and the secondary factors. Both the factors do not cover the area of heat reflectance property of the pavement material and pedestrian level thermal comfort. Thus it is of utmost importance to have a thorough study of the pavement properties in order to create a thermally comfortable streets in the hot and humid climate of Nepal.

Street design is an important issue in bioclimatic urban development to mitigate thermal discomfort in pedestrian level. The research aims to investigate the potential of manipulating pavement albedo of urban canyons to reduce surface temperatures and mitigate the adverse effects of UHIs that ultimately provides a thermally comfortable street to the pedestrians.

2. Literature Review

The albedo rates a surface's ability to reflect light on a scale from 0 to 1. In urban climatology, the albedo may be measured at various scales, including the local-urban scale for the entire urban surface (i.e., urban fabric) and the scale of specific aspects (i.e., roads, façades, and roofs) [1]. Albedo only comes into effect under the solar radiation. High temperatures and high humidity levels already make it challenging for people to remain comfortable in hot and humid environments. Urban canyons make these problems worse by trapping heat and lessening the efficiency of the environment's cooling mechanisms. The tall structures serve as barriers, obstructing the free passage of air and reducing heat dissipation. As a result, heat builds up inside the canyon, producing a microclimate that is significantly hotter than the surroundings. In urban canyons, the combination of constrained airflow, increased solar radiation absorption, and decreased natural ventilation can lead to uncomfortable temperatures for walkers. The construction materials for urban canyons are also very important for pedestrian thermal comfort.

Several studies that measured PET values and street temperature have reported a clear correlation between pedestrian thermal comfort and pavement material. The surface and the air temperature reduction is not affected by the orientation of the street but is affected by the albedo of the pavement surfaces [6]. Cool pavements could reduce the peak ambient air temperature by up to 1.9 °C, and the ground surface temperature could be reduced by 12 °C[7]. The reduction of peak air temperature is estimated at 0.57–2.3 °C for every 0.1 increase in urban albedo, equivalent to a total effect of 1–3.5 °C [8]. The effect of changing albedo on the pedestrian thermal comfort was also studied. Studies showed that the increment in the reflectance of the pavement materials can cause a discomfort due to increased interreflections between surfaces. Although the air temperature may be lowered by using high-albedo materials on canyon surfaces, the drop is insufficient to compensate for higher radiant loads. As a result, pedestrian thermal comfort might actually be negatively impacted [9]. Reflective pavements can be used only if an urban canyon has an aspect ratio no greater than 1.0 [10].

Various cool pavement paints have been developed that has been successfully experimented and shown to have reduced the surface temperature. The efficiency and applicability of a dark-colored, high-albedo pavement coating, called PerfectCool was developed recently in Japan by NIPPO Corporation Co. According to on-site testing, the coating may reduce asphalt surface temperatures by up to 17°C when compared to a typical asphalt surface without the coating [11]. The cool asphalt technologies includes various measures to prevent heat from entering the pavement such as Light-colored aggregate technology, Chip seals technology and sand seals technology, Shot-blasting technology, and Colored asphalt technology [12]. Replacing black asphalt with Yellow, beige, green, and red asphalt with albedo values 0.26, 0.31, 0.10, and 0.11respectively could lower down the surface temperature by 9.0, 7.0, 5.0, and 4.0°C respectively [13]. The research under consideration had used a range of methods, including computer modeling and simulation, experimental method, and calculation methods.

3. Research Setting

The streets studied are located in Birgunj Metropolitan City that lies in the Madhesh Province of southern Nepal. The climatic condition is sub-tropical monsoon with a very hot and humid summer. According to Meteoblue, the temperature remains more than 30°C from July to October and above 35°C from April to June which may exceed to above 40°C during April to June. According to Climate Consultant, the Relative humidity is between 60-80 % throughout the year at some part of the day. The region receives rainfall between 2-5mm rainfall per day during July, else the region remains dry most of the year. The wind is calm to light breeze (less that 5 mph) throughout the year providing less air flow. The first ever recorded tornado in Nepal had affected Parsa district in 2019 due to the regional weather and climate change in South Asia. Given the context of the streets and its bio-climatic value, pedestrian-friendly comfortable streets are essential in Birgunj.

The streets selected were local roads as categorized by Nepal Urban Road Standard 2076. The streets were analysed on the basis of their pavement material and aspect ratio. A preliminary study of four streets (concrete shallow canyon, concrete deep canyon, asphalt shallow canyon and asphalt deep canyon) was done on 8th July, 2023 between 2 to 2:30 p.m.Thus for a comparative study of two streets of highest and lowest air and surface temperature, i.e., asphalt shallow canyon and concrete deep canyon were taken for research.

The asphalt street (albedo 0.12) lies at the coordinates 27°01'00.9"N 84°53'09.5"E which is 124m away from the Birgunj Bypass road on the east and around 500m from Tribhuvan highway on the west. The street consists of

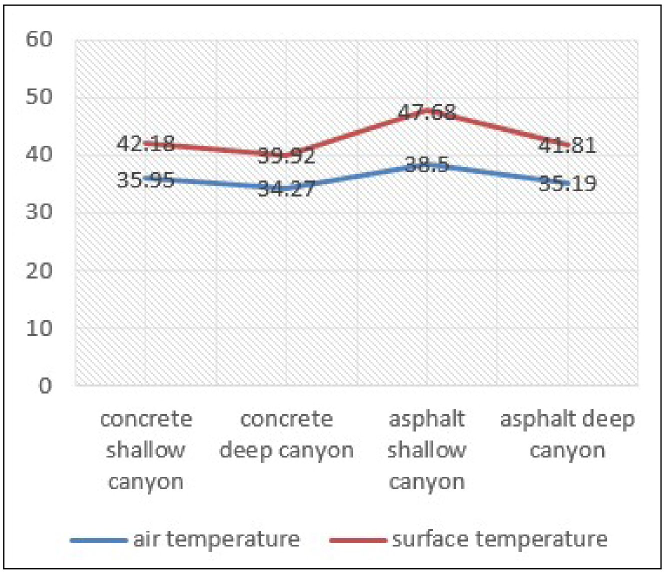

Figure 1: Air and surface temperature of various streets

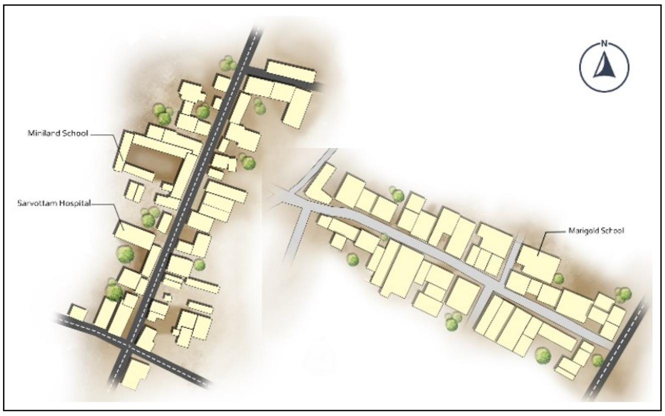

Figure 2: Plan of selected Asphalt and Concrete Street

residential buildings, a school and a few commercial buildings. The street width is 8.58m (28'), with a 1.5m (5') pedestrian sidewalk, while the surrounding buildings have 1 to 2.5 storeys. Because the average height of a one-story structure is 3.3m (10'-10"), the maximum height of a building on the street is 8.25m (27') making the street a shallow canyon. The aspect ratio in the street is fairly low and the SVF is fairly high.

The concrete street (albedo 0.45) lies at the coordinates 27°00'25.9"N 84°52'47.5"E which is connected to the Birgunj Bypass road on the east and around 575.92 m from Tribhuvan highway on the west. The street consists of residential buildings, a school and a few commercial buildings. The street width is 6m (19'), without any pedestrian sidewalk, while the surrounding buildings have 2 to 5 storeys. Because the average height of a one-story structure is 3.3m (10'-10"), the maximum height of a building on the street is 16.5m (54') making the street a deep canyon. The aspect ratio in the street is fairly high and the SVF is fairly low.

4. Methodology

The methodology employed in this thesis combines a literature review, survey research, and simulation research. The literature review included identifying relevant databases, such as academic journals, conference proceedings, and online repositories, which were then screened based on their relevance to the research topic. This thesis's survey research component used field measurements to get quantitative information on air and surface temperatures. The instruments used were a data logger for monitoring and recording air temperature over time, a digital thermos-Hygrometer for measuring the relative humidity and air temperature next to every respondent an infrared thermometer and wire thermometer for measuring the thermal radiation emitted by the pavement surface and a laser measuring tape for measuring the dimension of urban canyon (width of the street, height of the building).

Questionnaire survey research for thermal comfort assessment was performed to gather subjective data from individuals to understand their perceptions and satisfaction regarding thermal conditions. The questionnaire was organized into sections that address different aspects of thermal comfort, such as thermal sensation assessment, outdoor environment assessment, Adaptation Strategies/Clothing/Acclimatization strategies and Pavement Albedo Perception. The questionnaire began with introductory questions to gather demographic information (e.g., age, gender, occupation) that may influence thermal comfort perception. The questionnaires were generated using KoBoCollect v2023.1.2 and results were analyzed using IBM SPSS statistics 27.

The precise site conditions were recreated to ascertain the findings using ENVI-met headquarters 5.5.1(Summer 23) student version. Analyzing climate conditions and the site's recorded temperature and humidity data allowed for the determination of the simulation date and time. Different scenarios were developed and simulated in accordance with them for the enhanced outcomes. To assure accuracy, the simulation was repeated numerous times.

5. Findings and data Analysis

The climatic parameters air temperature and relative humidity were measured with Hobo data logger for 14 days starting from 9th July 2023 to 22nd July 2023. The surface temperature was measured manually from 6am to 6pm for same time period.

5.1 Thermal structure analysis

The highest average hourly air temperature recorded on Asphalt Street was 40.92°C at 2 p.m. and the highest average hourly air temperature recorded on Concrete Street was 35.29°C at 2 p.m. The difference on average hourly temperature between two streets was found to be 5.33°C. Similarly, the highest average hourly surface temperature recorded on Asphalt Street was 47.26°C at 1 p.m. and the highest average hourly surface temperature recorded on Concrete Street was 41.13°C at 4 p.m. The difference on average hourly temperature between two streets was found to be 6.13°C.

The maximum hourly average relative humidity recorded in Concrete Street was 79.97% at 7 p.m. and the minimum hourly average relative humidity recorded was 68.1% at 4 p.m. The

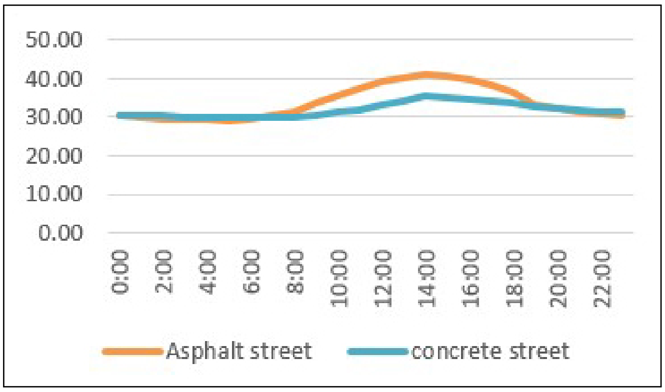

Figure 3: Average hourly air and surface temperature

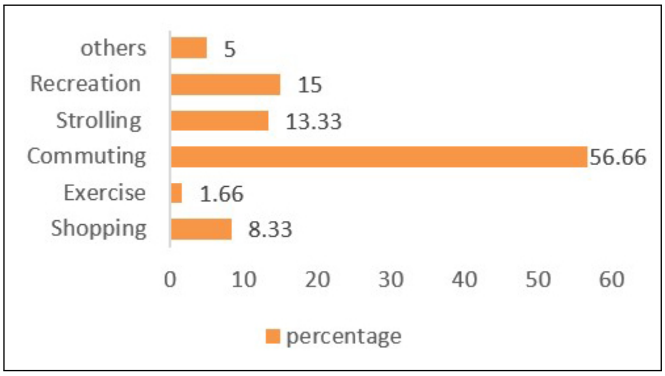

Figure 6: Reason for visiting the street

difference was found to be 11.86% throughout the day.

The maximum hourly average relative humidity in both the street remain similar whereas there is a difference of 18% in the minimum hourly average relative humidity which makes the pedestrian thermally uncomfortable in both dry and humid streets.

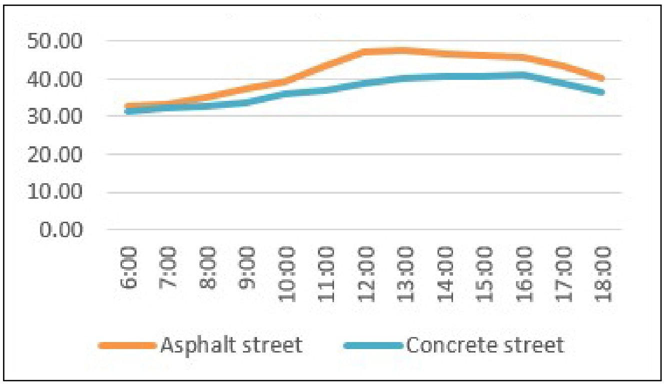

Figure 4: Average hourly surface temperature

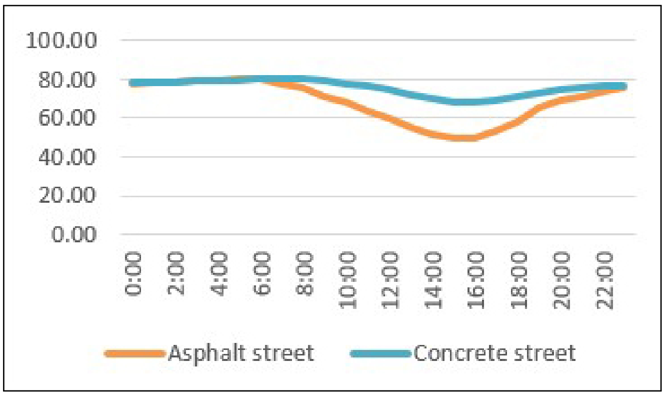

Figure 5: Average hourly Relative Humidity

5.2 Questionnaire Survey

The questionnaire survey was conducted for 6 days from 10th July 2023 to 15th July, 2023. A total number of 386 and 319 number of pedestrian were found to be present on each of the streets observed at a span of 15 minutes throughout the day. For the questionnaire survey, 10% of the total number of observed pedestrian was taken. For uniformity, 30 samples each were taken for the survey

5.2.1 Weather Information

The sky conditions during the survey were clear sky/mostly sunny, few days were partly cloudy and very few days were rainy and overcast. The air speed conditions during the survey were mostly light breeze and calm. A very few days had moderate air breeze. The frequency of people surveyed during these sky conditions and air speed are presented the table 1.

Sky Condition	Frequency	Air Speed	Frequency
Clear sky/Sunny	38 (63%)	calm	20 (40%)
Partly cloudy	16 (27%)	Light breeze	24 (33%)
mostly cloudy	4 (7%)	Moderate breeze	16 (27%)
Rainy	2 (3%)	-	-

Table 1: Weather condition during survey

5.2.2 Personal Information

The primary target group for this survey were pedestrians, however guards, shopkeepers and street vendors who spend the most time on the street were also included.38 number of the respondents were male and 22 number of the respondents were female.

People often visit the street for commuting, strolling and recreation purposes. Maximum number of people used the street for commuting while least people used for morning walks.

Type of respondent	frequency	Age group	frequency
Pedestrians	37 (62%)	0-20	8 (10%)
Street vendors	9 (15%)	20-30	16 (27%)
Shop keepers	12 (20%)	30-40	14 (23%)
Guards	2 (3%)	40-50	14 (23%)
-	-	50-60	6 (10%)
-	-	>60	2 (3%)

Table 2: Personal information of the respondents

5.2.3 Thermal sensation Assessment

When asked how they felt at that very moment, those who responded in the asphalt street in the morning between 6 am to 8 am felt slightly cool and cool, those who responded between 8 am to 10 am felt neutral, between 10 am to 4pm they felt very hot, while between 4 to 6 pm, they responded to feel warm and very hot.

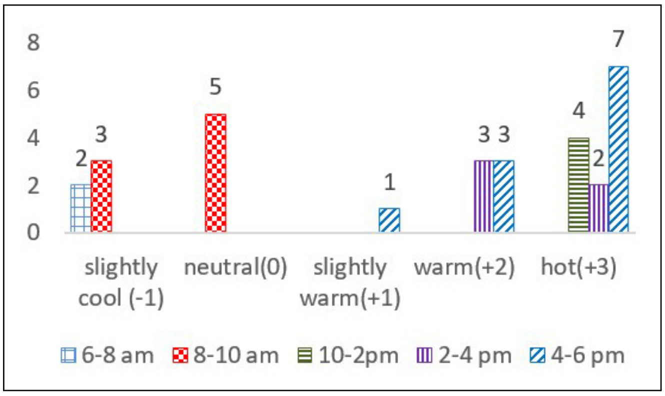

Figure 7: Thermal sensation-Asphalt street

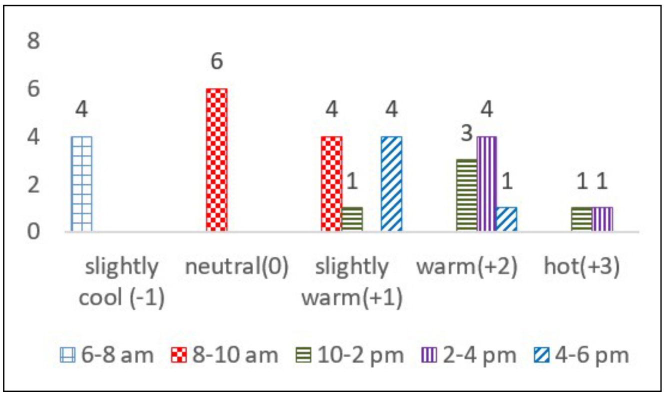

Figure 8: Thermal sensation-Concrete street

Similarly, those who responded in the concrete street in the morning between 6 am to 8 am felt slightly cool and warm, those who responded between 8 am to 10 am felt neutral and warm, between 10 am to 2 pm they felt warm, hot and very hot, between 2 to 4 pm they reported to feel hot to very hot while between 4 to 6 pm, they responded to feel warm and hot. The respondents felt warm and hot even after 6pm.

Combining the total preference of visiting the street, 21 respondents preferred in the morning time between 6am to 11 am, 15 respondents preferred in the evening between 6pm to 8pm and 24 respondents preferred at night after 8 pm.

The respondents felt thermally comfortable in the early morning and morning time, slightly uncomfortable in the late morning when the sun is heading up, uncomfortable in the noon and mid-day and very uncomfortable in day time and in the afternoon.The thermal acceptance is denoted by very uncomfortable (-2), uncomfortable (-1), neutral(0), comfortable (+1) and very comfortable(+2).

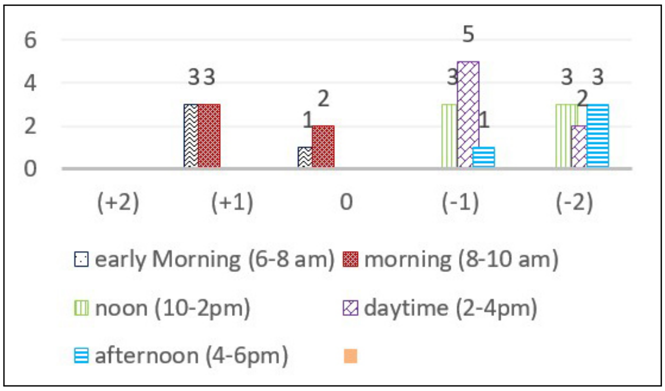

Figure 10: Thermal Acceptance-Concrete street

5.2.4 Outdoor Environment Assessment

The outdoor environment was assessed through the perception on ambient temperature, relative humidity, sun exposure and air movement. The respondent felt uncomfortable ambient temperature, low relative humidity, moderate to high sun exposure and no air movement in Concrete Street. Whereas in case of asphalt street, they felt extremely uncomfortable ambient temperature, high relative humidity, intense direct sunlight and very little air movement. The overall outdoor environment remains uncomfortable in both the streets.

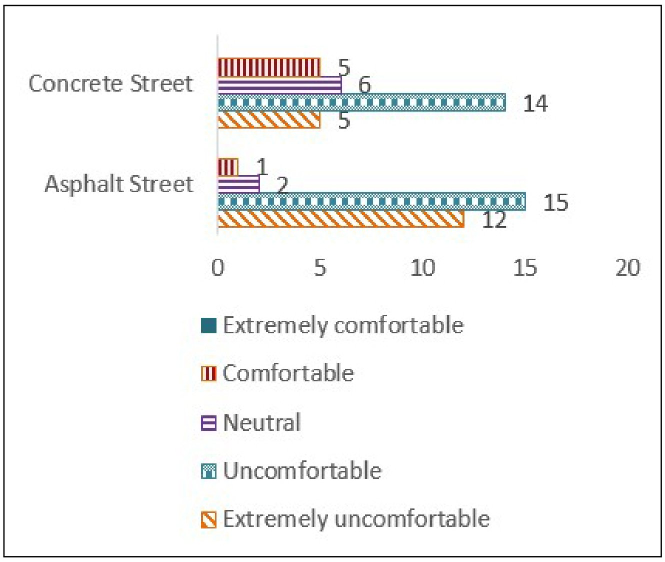

Figure 11: Ambient Temperature

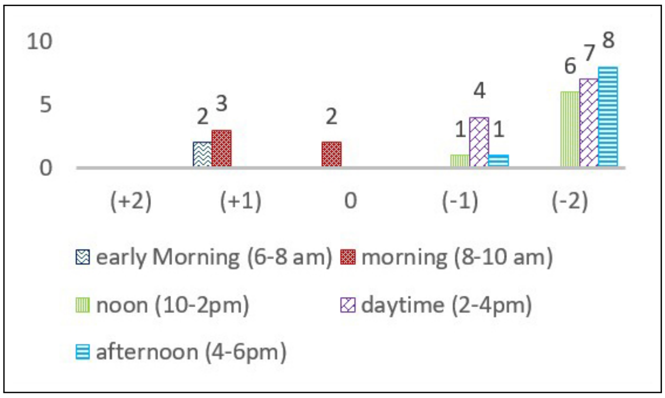

Figure 9: Thermal Acceptance-Asphalt street

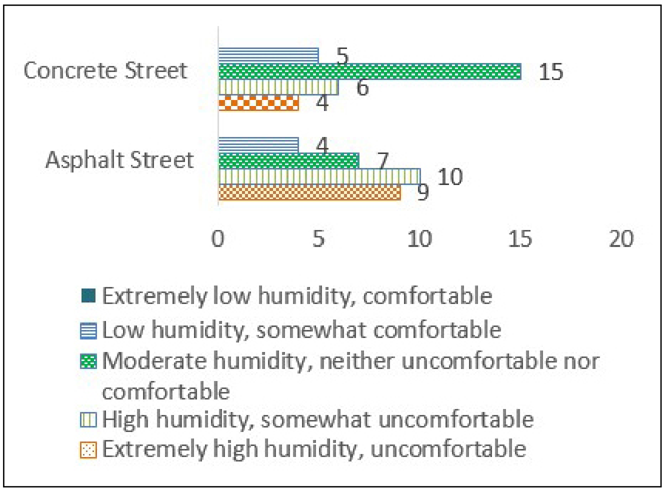

Figure 12: Relative humidity

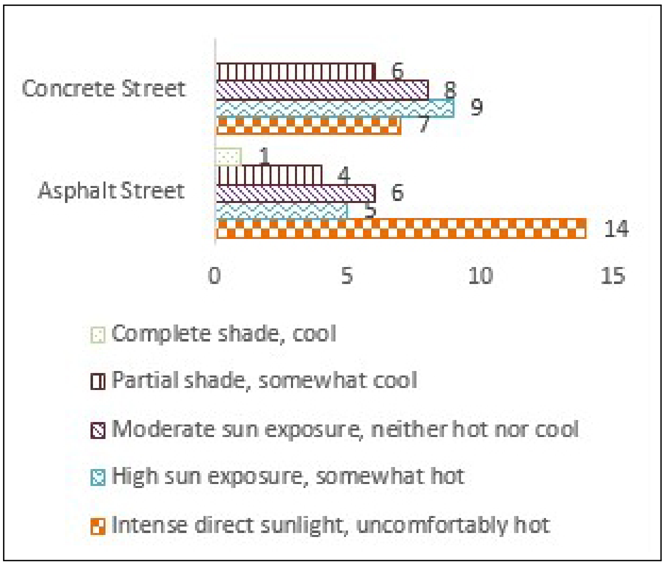

Figure 13: Sun Exposure

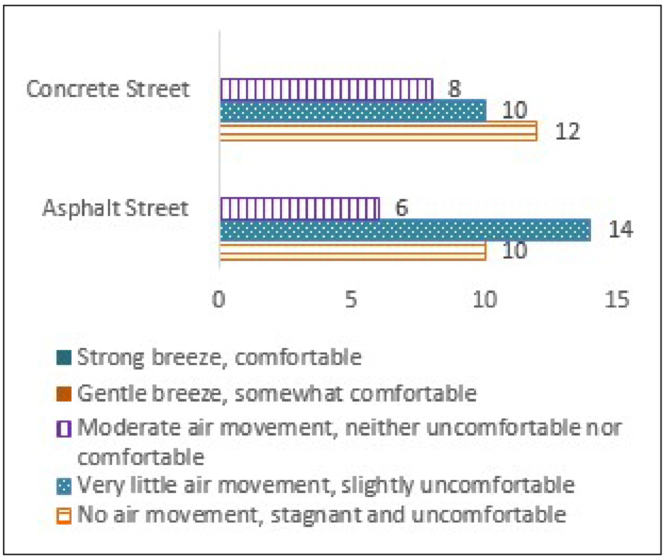

Figure 14: Air Movement

Majority of the respondents in asphalt street felt uncomfortable ambient temperature with intense direct sunlight. They reported to have felt high to extremely high relative humidity and very little air movement. All these microclimatic features made them extremely uncomfortable during the daytime. Whereas in case of concrete street, the respondents felt high sun exposure, uncomfortable ambient temperature, moderate relative humidity and no air movement at all. This implies both the streets as well as the respondents are highly impacted upon the macroclimate of the entire city.

5.2.5 Acclimatization/Adaptation strategy

In order to study the acclimatization and adaptation strategies adopted by the respondents, it was necessary to understand the relation of the respondents to the microclimatic condition. The people who were born and raised in the neighborhood had completely adapted the microclimate while those who are temporary residents had moderately adapted. Those who have recently moved there and who were the visitors had not adapted at all and still use acclimatization strategies like scheduling outdoor activities and adjusting clothing choices clothing such as wearing lighter and loose fabrics.

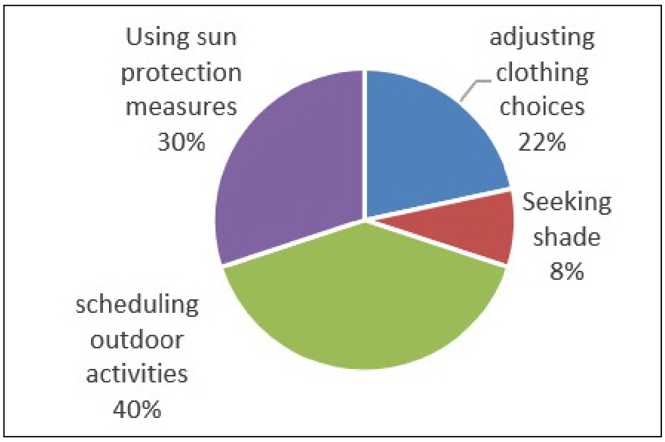

Figure 15: Adaptation strategies

5.2.6 Pavement Albedo Perception

Identifying whether individuals experience heat coming from the pavement is necessary to understand pavement perception. It was possible to gain a thorough understanding of thermal comfort and environmental interactions by collecting information on how people experience pavement heat. 26 people felt heat emission from the pavement on asphalt while4 people did not feel the heat. In case of Concrete Street, 19 people felt the heat emission from the pavement and 11 people did not feel the heat at all.

When asked if increasing the albedo value (surface reflectivity) of pavements would help in reducing surface heating in the area, 35% of the people were not sure at all, 32% said there would be no apparent temperature variation, 20% said there might be a slight temperature disparity, 8% felt there could be noticeable temperature contrast and only 5% reported to have significant temperature difference. The results were similar to pavement temperature perception. Therefore, this shows the lack of awareness about the relation between pavement material reflectivity, surface heating and outdoor thermal comfort.

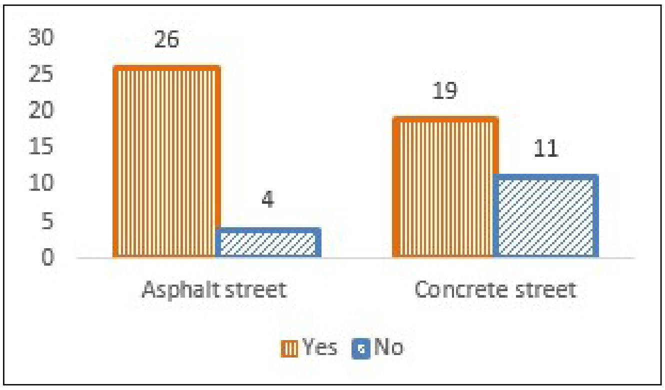

Figure 16: Heat from the pavement

6. Simulation Results

The exact representation of existing asphalt street was created using ENVI-met and was named as base case. The aspect ratio of the street was changed to 1, 2 and 3 and each aspect ratio was simulated with asphalt, concrete dark pavement, concrete dark pavement and concrete light pavement with albedo values of 0.12, 0.2, 0.3 and 0.5 respectively. The simulation was done in NS orientation of the street and later all scenarios were changed to EW orientation creating a total of 32 scenarios.

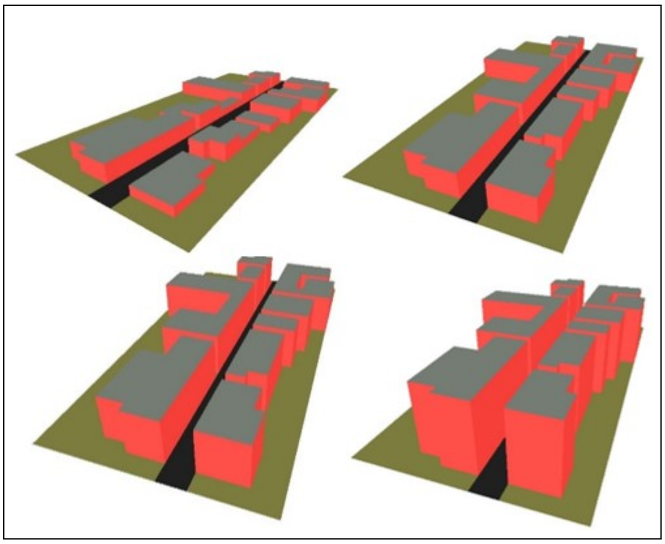

Figure 17: 3d model of base case, AR1, AR2 AND AR3

The computed variables were air temperature, surface temperature and mean radiant temperature. The obtained results are shown below.

Air Temperature (°c)								
Pavement Albedo	BASE CASE		AR1		AR2		AR3	
	20°N	110°N	NS	EW	NS	EW	NS	EW
0.12	42.91	42.02	41.94	42.04	40.44	41.52	39.74	40.78
0.2	-0.42	-0.16	-1.29	-0.43	-1.02	-0.15	-0.08	-0.11
0.3	-2.87	-1.5	-2.67	-1.63	-1.43	-0.69	-0.47	-0.2
0.5	-3.9	-1.57	-3.27	-2	-2.16	-1	-1.5	-0.59

Figure 18: Potential air temperature predicted by ENVI-met

Mean Radiant Temperature (°c)								
Pavement Albedo	BASE CASE		AR1		AR2		AR3	
	20°N	110°N	NS	EW	NS	EW	NS	EW
0.12	71.50	68.41	66.78	68.03	59.97	63.55	57.79	62.84
0.2	+0.51	+3.12	+1.53	+1.64	+1.51	+2	+1.97	+1.99
0.3	+1.91	+5.09	+3.2	+3.94	+5.12	+4.08	+5.26	+5.63
0.5	+6.68	+11.66	+5.18	+6.38	+13.73	+11.73	+11.24	+11.72

Figure 20: Mean radiant Temperature predicted by ENVI-met

Surface Temperature (°c)								
Pavement Albedo	BASE CASE		AR1		AR2		AR3	
	20°N	110°N	NS	EW	NS	EW	NS	EW
0.12	59.65	56.47	58.27	56.22	54.74	53.78	55.12	49.26
0.2	-3.34	-0.85	-0.89	-2.26	-5.18	-1.77	-4.95	-2.4
0.3	-5.31	-3.39	-4.56	-3.96	-4.26	-3.59	-8.81	-3.66
0.5	-10.33	-7.62	-9.21	-8.76	-9.44	-6.48	-10.89	-4.96

Figure 19: Surface temperature predicted by ENVI-met

Increment in pavement albedo decreased the potential air temperature in all the scenarios and the significance increased gradually on increasing the albedo values. The air temperature was decreased by 3.9°C, 3.27°C, 2.16°C and 1.5°C in base case, AR1, AR2 and AR3 respectively.

Similarly, the surface temperature reduction was found to be 10.33 °C,9.21 °C, 9.44 °C and 10.89 °C in base case, AR1, AR2 and AR3 respectively. The street performed best on North South orientation than East west oriented streets.

The mean radiant temperature was found to be increased in all the scenarios. In base case and AR1, the increment was by 6.68°C and 5.18°C whereas in AR2 and AR3 it further increased up to 13.73°C and 11.24°C than the scenarios with albedo value 0.12. This was due to the increased radiant loads as the aspect ratio was increased.

7. Conclusion and Recommendation

The field measurement showed a difference in the average air temperature in asphalt (albedo 0.12) and the concrete (albedo 0.45) street was found to be 1.94°C. Similarly, the difference in maximum average hourly air and surface temperature between the streets were found to be 5.33°C and 6.13°C respectively. The simulation concludes that the optimum value of albedo is 0.3 for AR2 and above, and 0.5 for AR1 and below for both North South and East west oriented streets. For base case and AR1, the albedo value could be limited to 0.5 or can be increased provided enough green spaces, tree cover that creates shade and evaporative cooling to prevent the mean radiant temperature from increasing. This implies there can be a huge decrement in the overall ambient temperature if only the albedo value is altered which can create changes in the overall macroclimate of the Birgunj City. The use of high-albedo materials in urban design, such as concrete, is a component of a larger heat mitigation approach. To further minimize heat absorption and improve comfort, other techniques can include adding shade trees, setting up cool roofs, making green areas, and adopting urban vegetation.

Pavement materials' albedo values may change over time as a result normal wear and tear, weathering, and the settling of dirt and pollutants. By repairing and maintaining the reflectivity of the pavement, reflective coatings can assist in preventing this natural loss. They contribute to the comfort of pedestrians and the general cooling of the city by directly influencing the temperature of the pavement and the adjacent surroundings.

The increasing temperature anomaly of the city shows the slow formation of the Urban heat Island. Therefore to address such climate change in the near future, optimizing the streets reflectivity may appear as a promising measure for the heat mitigation. Exploring the development, testing, and manufacture of reflective paints in Nepal is an excellent way to address the challenges brought on by the urban heat island effect. The lack of specific policies and guidelines regarding pavement albedo in Nepal poses a significant challenge. It is essential to consult a variety of stakeholders, including government agencies, urban planners, architects, engineers, environmental specialists, and community representatives, in order to effectively change and revise building regulations while taking into account the unique requirements of Nepal's sub-tropical urban environment.

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