Emerging Trends in Overcoming the Weather Barrier to Sustainable Mobility in Gulf and Tropical Cities

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Abstract. Several studies predicted that in case of the continuous rising concentrations of anthropogenic greenhouse gases (GHGs), the gulf region might experience intolerable temperatures to humans. Such terrible weather may have a severe consequence on different vital activities in different Gulf countries, such as the Muslim rites of Hajj in Mecca city. However, supporting the global mitigation efforts would significantly minimize the seriousness of the expected impacts. With that in mind, hot weather was reported as the significant barrier to sustainable mobility in those countries. Their current mobility is heavily dependent on privately-owned fossil-fueled vehicles rather than other sustainable transport choices. This paper reviewed the most recent innovative and solutions to overcome the problems associated with the hot climate. The review focused on the new techniques concerned with reducing the pavement surface temperature and the corresponding decreases in the ambient air temperature, aiming to promote sustainable mobility modes in hot climate cities. The paper also identified future research needs to fulfill each proposed solution's scientific and practical gap and overcome the weather barrier.

Keywords: Climate change, Global Warming, Asphalt Pavement, Reduce ambient Temperature.

1. Introduction

Climate change represents a severe threat to creatures' lives on the planet (Wang, et al., 2021; and Salimi and Ghamdi, 2020 [1-2]). In 2021, clear indications of climate change were substantiated by many unconventional weather events. The deadly flood in Germany, unexpected rainfall in Riyadh during summertime, wildfires in Canada, and many other cases prove that climate is really changing. With that in mind, mobility choices of today could be one of the major reasons for contamination and CO2 emissions either be the pass for sustainable opportunities and climate respect. Unfortunately, the current mobility in almost all Gulf cities is unsustainable (Shaaban, 2020; and Sultan et al., 2021 [3-4]). It is heavily dependent on privately-owned fossil-fueled vehicles rather than other sustainable transport choices, such as cycling, walking, and public transportation.

Recently, several countries realized the importance of reducing CO2 emissions. Saudi Arabia, for instance, shifted its policies toward more sustainable mobility options, raising the quality of pedestrian’s environment, encouraging cycling, and walking as a healthy lifestyle following the global Sustainable Development Goals (SDGs) [5]. In conjunction with the official launch of the new public transportation projects, the transformation to sustainable mobility could be expected shortly. In addition to the willingness of the community to switching to more sustainable mobility modes. The assessment study (Sultan, et al., 2021 [4]) concluded that about 60% of the study’s sample expressed their willingness to shift to more sustainable mobility modes. Despite that, sustainable mobility in the gulf and tropical cities still faces many barriers. The weather conditions were reported as the most significant barrier to utilizing active and public transport modes in many different cities (Jain and Singh, 2021; Shannon, et al., 2006; Limanond, et al., 2011; Smith and Henriquez, 2019; Shooshtarian, et al., 2018; Rayan, et al., 2021; Taleghani and Berardi, 2018; and Ribeiro, et al., 2020 [6-13]).
Several studies (Herath, et al., 2021; and Pal and Eltahir, 2015 [14-15]) concluded that climate change might occasionally in summer conditions threatens human survival in some hot climate regions such as Riyadh, Abu Dhabi, Doha, Dubai, Manama, Kuala Lumpur, and many others. In normal conditions, the human body is masterful at managing its temperature. The human body is sweating and increasing blood flow to the skin to help in dissipating the heat and cool down itself when exposed to hot weather conditions. Despite that, the human body may struggle to get rid of heat if the air is heavily laden with water vapor, as in this case, sweat will not evaporate. That’s why a threshold wet-bulb temperature of 35°C was specified by different studies (e.g., Sherwood and Huber, 2010 [16]). Even healthy and fit people would not be tolerable any length of time in a temperature above the threshold wet-bulb. Gupton, 2002 [17] defined the Wet-bulb temperature (WBT) as a joint measurement of both humidity and temperature, in the way that considering the cooling effect by evaporation. Thus, it will always be less than the traditional dry-bulb temperature that is given by the weather forecast authorities.

In North America or, Europe wet bulb temperature might reach 23°C in humid summer conditions. However, WBT may exceed over 31°C in the Gulf region and its coastal neighborhoods. Pal and Eltahir, 2015 [15] reported that the WBT threshold is achieved in various locations, although it was not exceeded anywhere in the Gulf until 2005. Conversely, the ensemble average of the major temperature events (Tmax) achieved values exceeding 50°C in many semi-arid interior regions and along with few seaside areas, but relatively less values over the Red Sea and Gulf. However, the study expected that by the end of this century, the threshold WBT might be exceeded in this region considering the high emission scenario.

The temperature of the pavement is influenced and obtained by the ambient temperature, which varies throughout the year in the so-called temperate zone (Hendel and Royon, 2015; Kyriakodis and Santamouris, 2018, Lohmann, et al., 1993 [18-20]). High pavement temperatures during hot weather are known to cause rutting and structural damage (Jesus et al., 2013 [21]). The urban heat island (UHI) effect is also exacerbated by high pavement temperatures during the summer months, resulting in additional problems associated with the high energy usage of air-conditioning systems in metropolises (Golden and Kaloush, 2006 [22]). This may also cause several types of damage to the transport infrastructure, reducing its effectiveness and overloading the energy distribution network. Alongside, it prevents pedestrians from using the most active and public transport modes, pushing them to heavily rely on unsustainable modes such as private fuel cars, which contribute extremely to the CO₂ emission and hierarchy the green gas house problem thus the global warming. With that in mind, prioritize the development objectives becomes one of the urgent needs of the communities towards a more livable, safe, and sustainable environment. Therefore, exceptional and innovative solutions are strongly required to overcome the significant weather barrier and reduce the air ambient temperature that enables pedestrians to utilize the active and public transport modes.

This paper mainly focuses on the weather’s significant barriers to using active and public transport modes in gulf areas and tropical cities. The emerging trends and extraordinary innovative solutions that recently developed to overcome the atmosphere temperatures are introduced. It also critically discusses the mechanism, relative merits, key advances, and disadvantages of the various methods available, aiming to recommend several valid and applicable solutions that can be employed in gulf areas and tropical urban.

2. Future climate in the Gulf and tropical cities

The geological formations of and around the Arabian Gulf in Southwest Asia have significantly contributed to oil and gas production within this region. It is also one of the primary natural etiologies for the hot climate in those areas. The inability of this region to induce deep convection was attributed to persistent regional-scale subsidence, which involves adiabatic and diabatic descent and suppresses deep convection. Besides, the Gulf and coastal neighborhoods’ surface albedo are relatively low, dissimilar to the surrounding deserts. Due to the high absorption of solar radiation in this region, as well as the higher total heat flux and evaporation rate, the humidity and heat retained at the surface are both increased in comparison to other regions.
On the other hand, the produced oil and gas from this region are consumed locally and worldwide and mightily contribute to the earlier and current carbon dioxide (CO₂) emissions. Recently, and because of the continuous rising of greenhouse gases (GHGs) concentrations, it has become expected that the gulf region may experience intolerable temperatures to humans. The Fifth Assessment Report released by the Intergovernmental Panel on Climate Change (IPCC), 2013 [23] highlighted substantial evidence that the considerable increases in manmade greenhouse gas concentrations are the primary cause of the Earth’s warming that has occurred in recent decades.

Using the IPCC’s representative concentration pathway (RCP) trajectories, Pal and Eltahir, 2015 [15] attempted to predict the impacts of future climate change towards the end of the century (2071-2100). Two GHG concentration scenarios are assumed: RCP4.5 (Thomson et al., 2011 [24]) and RCP8.5 (Riahi et al., 2011 [25]). RCP8.5 depicts a situation where businesses continue as usual, but RCP4.5 incorporates mitigation. The study showed that under the RCP8.5 scenario, by the end of the century, the Southwest Asian coastal regions adjacent to the Gulf might experience a high WBT max that could exceed the 35°C, as highlighted in Fig.1. Also, the annual T max is expected to increase dramatically in the different locations surrounding the Gulf.

Gulf cities such as Dubai, Dhahran, Abu Dhabi, and Jeddah could, in the upcoming 30 years, suffer high annual WBT max exceeding the 35°C threshold several times in the same year. Pal and Eltahir explained that by the frequently blowing warm winds from Turkey and Iraq. These winds are crossing the Gulf coasts and earning moisture which will transport a high WBT to most Gulf metropolises. Also, extreme annual T max events exceeding 45°C may be the normal temperature in most cities located in this region. For instance, the annual T max in Kuwait and Al Ain cities is expected to exceed 60°C during the coming years; although, those cities are somehow protected from extreme WBT max events, as they have low elevations. On the other hand, some cities, such as Doha, will be subjected to both T max and WBT max events. The geographical formation of this city project it to dry warm air from the semi-arid interior desert, along with hot moist air from the western Gulf.

The study (Pal and Eltahir, 2015 [15]) also expected that compared to the Gulf, the Red Sea coast will experience milder conditions but still severe so far. Annual WBT max was forecasted to range from 33°C to 32°C in Mecca’s neighboring and Jeddah. Also, the annual T max is predicted to achieve values as great as 55°C (Fig.1). With that in mind, about two million Muslim pilgrims are praying outdoors from dawn to dusk near Mecca annually. Such terrible weather may have a severe consequence on the Muslim rites of Hajj. According to the lunar calendar, the ritual Hajj date is fixed, and therefore it might happen during the summer session for several successive years. In this case, the mandatory outdoor Muslim rite may harm pilgrims’ health, especially the people. In the same line, due to climate change in Southwest Asia continuing, the rise in annual T max would exacerbate the current harsh desert conditions. With that in mind, the population in those countries is rapidly increasing (World Population Prospects, 2014 [26]), and new urban may emerge to meet. However, the increase in annual WBT max may limit coastal development.
Figure 1. Maps of observed and expected temperatures in the Arabian Gulf and its coastal neighborhoods under the RCP4.5 and RCP8.5 scenarios. [a] Wet-bulb (WBT$_{\text{max}}$). [b] Dry-bulb (Modified from Pal and Eltahir, 2015 [15]).

On the other side, if the Southwest Asia countries tend to support the RCP4.5 scenario (considers global mitigation efforts), this would pointedly minimize the seriousness of the expected influences. As in the RCP4.5 scenario, annual WBT$_{\text{max}}$ does not exceed the threshold of 35°C in any of the sites reflected (Fig.1). Also, T$_{\text{max}}$ is not expected to exceed 55°C, except at few sites where the present temperature is high already. In addition, the good news is under this scenario (RCP4.5), where the rituals of Hajj are taking place, the WBT$_{\text{max}}$ would rise only about 2°C warmer than the current climate in Mecca’s neighboring and Jeddah.

3. Methodology

Recently several solutions were invented to help in overcoming the sustainable mobility problems associated with hot atmospheric temperature. Before discussing those solutions and investigating their reliability, understanding the causes of air ambient temperature rise will be mandatory to align each solution to a certain warming cause. As explained in Fig.2, the air ambient atmosphere is heated in the following three mechanisms: radiation, conduction, and convection.

Radiation is the direct heating of an object caused by the transmission of heat waves (Ganji, et al., 2018 [27]). The atmosphere absorbs only a small amount of incoming solar radiation but absorbs a large amount of outgoing radiation from the earth’s surface. As a result, terrestrial radiation heats the atmosphere more than incoming solar radiation. On the other side, conduction is the heat energy transfer between or within substances by the molecular activities (NOAA NWS, [28]). Since the inferior layer of the atmosphere is in touch with the ground, some of the ground’s absorbed heat is transmitted to the inferior layer of the atmosphere through conduction. As a result, heat particles move from the inferior to the upper layer, and the atmosphere gets heated up through convection, as explained in Fig.2.a. When the air in the lower layer of the atmosphere gets heated, it expands and moves upwards, and the air from different sides comes to take its place. Thus, convection currents are formed by the constant rising of air. Fig.2.b pinpoints that the most significant percentage of the arriving solar energy is absorbed by land (51%). Therefore, the between pavement temperatures relationship with the built-up environment (Fig.2.c) has been studied by numerous studies (Al-Jabri, et al., 2005; Grimmond and Oke, 1999; Fortuniak, 2008; and Qin and Hiller, 2014 [29–32]).
Typically, pavement can be classified as a rigid or flexible structure. Concrete material is used for the rigid pavement, while asphalt mainly refers to the flexible one. Both types of pavement materials are exposed to absorb and store solar radiation (Al-Jabri, et al., 2005; Grimmond and Oke, 1999; Fortuniak, 2008; and Qin and Hiller, 2014 [29–32]). Thus, the solar energy induced by pavements could be represented in the following three components:

\[ E_H = H_S + H_L + H_C \]  

(1)

Where, \( E_H \): the induced solar energy by the pavement (W/m²); \( H_S \): the released sensible heat (W/m²); \( H_L \): the released latent heat (W/m²); \( H_C \): the conductive heat through pavement structure (W/m²).

The thermal equilibrium of pavement can be found through the induced solar radiation budget, also named the net radiation, as expressed in equation (2). This net radiation represents the algebraic difference between the radiation collected by pavement and the terrestrial radiation released (Wang, et al., 2016 [34]).

\[ R_n = R_i - R_r + R_a - R_s \]  

(2)

Where, \( R_n \): the net radiation collected by pavement (W/m²); \( R_i \): the incident radiation (W/m²); \( R_r \): the reflected radiation (W/m²); \( R_a \): the atmospheric radiation (W/m²); \( R_s \): the pavement surface radiation.

The reflected radiation from the pavement (\( R_r \)) can be represented as in equation (3):

\[ R_r = \alpha \times R_i \]  

(3)

where \( \alpha \): the pavement surface’s albedo.

The reflection coefficient (\( \alpha \)), so called the albedo is the incident light fraction that any surface, this coefficient could give an indication about the material surface’s reflectivity (Bobes-Jesus, et al., 2013 [21]; Golden and Kaloush, 2006 [22]; and Sen and Roesler, 2016 [35]). It takes into account the hemispherical reflectance of solar radiation and integrates it over the entire solar spectrum, including the specular components and diffuse.

Fig.2.c summarizes the energy equilibrium relationship on a pavement surface with a typical pavement structure. Accordingly, the governing equation equation (4) can express the energy absorbed by pavement structures.
\[ R_n = R_i - R_r + R_a - R_s = H_S + H_L + H_C \] (4)

This study aims to promote the active and public transport modes in hot climate countries by endorsing and reviewing the efficiency of various methods available to reduce the heat absorbed/transferred by or from the pavement. Unfortunately, in the available space, it is impracticable to discuss comprehensively all of those advances. Nevertheless, an effort has been devoted to discussing the significant advances, presenting a summary about the most employed approaches’ key merits and disadvantages, and providing an inclusive list of references that gives further details for the readers.

4. Solutions

The following section critically discusses several promising techniques recently invented to overcome the weather barrier that obstructs the utilization of active transport modes.

4.1 Geothermal Pavement Systems

Heat exchanging with the soil is the main mechanism of the Ground Source Heat Pumps (GSHP). Robert Webber, first invented this mechanism in 1940. Recently, it has been mainly used in heating or cooling buildings by exchanging thermal energy with shallow soil layers on depths varying from 1m and up to 200m. As explained in Fig.3.a the ground source heat pump or the geothermal heat pump transfers the heat energy from or to the soil through a vapor-compression of a carrier fluid contained in the vertical or horizontal loops of the pipes (Fig.3.b), burdened in the soil.

The underground soil acts in this system as the heat source or heat sink. Since the soil temperature closer to the ground surface is exceptionally dependent on the air ambient temperature, several studies (Alam et al., 2013; Gashti et al., 2014; and Muhammad et al., 2016 [36-38]) showed that the optimum embedded depth should be not less than 4m depth to achieve a constant and reliable underground temperature to be utilized in the heat transfer process. Fig.3.c shows the relationship between soil temperature and depth in Malaysia (Tropical city) on a typical day, as illustrated after about 5m depth underground soil temperature tends to be constant, regardless of the surface ambient temperature among different sessions.

![Diagram](a)
The efficiency of GSHP environmentally-friendly system in reducing the energy consumption for heating/cooling purposes was commended in many cases. For instance, Duffield and Sass, 2003 [40] concluded that using geothermal systems with buildings saved about 75% of the consumed energy compared to the traditional electrical resistance heating systems. However, limited studies (Motamedi et al., 2020; and Habibzadeh-Bigdarvish et al., 2021 [41-42]) discussed the feasibility of using the GSHP with the pavement structures. Ho and Dickson, 2017 [43] indicated that geothermal systems were practically feasible to be utilized as a snow-melting system that invests the shallow geothermal energy in melting the ice on highways and runways.

Motamedi et al., 2020 [41] performed a well-instrumented Insitu test on a 20m×10m pavements segment equipped with a geothermal system. The test was conducted in Adelaide city, Australia, and thermal response testing (TRT) was applied to examine the geothermal pavement. The TRT test results were also utilized to validate a numerical model. This study concluded that the geothermal pavement radius of the influence was close to 0.5m, with a heat exchange rate of 25 W/m per the pipe’s length.

The efficiency of the GSHP system effectively influences the temperature of the pavement surface has been assessed by Chiarelli et al., 2017 [44]. It was found that the geothermal system was able to control the pavement temperature increase or decrease utilizing of natural convection of the warmed air up or down by geothermal resources. A set of experiments were performed using a ground source heat simulator, and the obtained results highlighted the effectiveness of ground heat sources in mitigating pavement temperatures employing air convection. This study concluded that in simulated winter condition, temperature increase ranging from 0.4°C to 2.1°C were obtained. While temperature decreases of between 2°C and 6°C were achieved in simulated summer conditions. In addition, this approach was validated and proved in real-life conditions by comparing the temperature differences between the control slab and the pavement prototype. As shown in Fig.4, the temperature differences ranged from about -6°C to +6°C.
Although the remarkable advantages of the GSHP systems, but the high implementation costs associated with their installation still represent a significant barrier to adopting this system more widely (Motamedi et al., 2020 [41]). With that in mind, very few recent studies from the electrical engineering field addressed that the renewable thermoelectrical energy harvested utilizing the asphalt pavement through the thermoelectric generators (TEG). A field study of asphalt pavement temperature (Zhu, et al., 2019 [45]) proved that the temperature difference between asphalt pavement structures and the underlying subgrades are significant enough to apply the Seebeck effect and harvest electric energy through TEGs. However, this study reported that at present, the generated power through this system is still insufficient enough. The study also concluded that the thermoelectric technology application in the pavement is still in the early stage of development and research. Nevertheless, success in generating sufficient electric power through the asphalt and TEG system may justify the implementation cost of the geothermal with the pavements. Future studies may work on the improvement of the efficiency of those energy harvesting systems by promoting the thermal convection of the TEGs, suggest different configurations for the system, enhance the thermoelectrical pavement properties using the composite material approaches.

4.2 Reflective Passive Cool Pavement

Dissimilar to the regular dark pavement, the cool pavement employs additives to improve the ability of pavement to reflect solar radiation (Fig.5). As explained before, the reflection coefficient or the albedo is the leading property controlling a material's reflectivity. Typically, the higher the albedo coefficient, the lesser absorptivity to solar radiation. Besides, Qin and Hiller, 2014 [32] concluded that albedo also influences the energy equilibrium of pavement surface. Table 1 summarizes the albedo coefficients of the most common pavement materials.

Taha, 1997 [46] confirmed the less solar radiation absorption of the materials with a high albedo, resulting in a relatively lower temperature surface (cooler) and a reduction in the radiation longwave intensity. This study also showed that by improving the albedo of the pavement surface from 0.25 to 0.40, the air temperature was decreased by 4°C. Consistently, Rosenfeld, et al., 1998 [47]) confirmed the air temperature reduction in Los Angeles of about 0.6°C when the albedo of the pavement was raised from 0.05 to 0.30. In the same line, according to Akbari, et al., 2001 [48], raising pavement albedo by 0.25 could pointedly lessen air temperature by 10ºc, which significantly contributes to mitigating the UHI effect. In subsequent research, Akbari and Matthews, 2012 [49] expected that pavement albedo improving by 0.15 in cities globally can lead to a 20 Gt reduction in global CO₂ emissions, saving around $500 billion. Also, Gago, et al., 2013 [50] reported that a direct energy savings of about 20–70% could probably be achieved by increasing the albedo coefficient. Because of this, there is a

![Figure 4. Difference between the control slab and the pavement prototype temperatures, after 90 to 170 hours (After Chiarelli et al., 2017 [44]).](image-url)
substantial increase in the past few years in research and associated technologies in the areas of reflecting pavements paired with high emissivity.

Table 1. Albedos of various common pavement materials (After Xu et al., 2021 [51]).

| Pavement Materials | Reflection coefficient (Albedo) | References |
|--------------------|---------------------------------|------------|
| Asphalt            | 
*New:* 0.04-0.06  
*Aged:* 0.09-0.18 | Santamouris, 2013-a [52]; Santamouris, et al., 2011 [53] |
| Asphalt concrete   | 
*New:* 0.05-0.1 | Santamouris, 2013-b [54]; Akbari and Matthews, 2012 [49]; Grimmond and Oke, 1999 [30]; Pan, et al., 2015 [55]; Bretz, et al., 1998 [56]; Hendel, et al., 2018 [57]; Haselbac, et al., 2011 [58] |
| Aged: 0.10-0.20    |                                      |
| Cement concrete    | 0.21-0.29                        | Li, et al., 2013 [59]; Santamouris, et al, 2012 [60] |
| Light-colored     | 
*New:* 0.35-0.40  
*Aged:* 0.20-0.30 | Akbari and Matthews, 2012 [49]; Pan, et al., 2015 [55] |
| concrete           |                                        |
| Marble             | 0.2-0.4                           | Santamouris, et al., 2011 [53]; Stathopoulou, et al., 2009 [61] |
| Sand               | 0.581                             | Hendel, et al., 2018 [57] |
| Granite            | 0.08-0.3423                       | Santamouris, et al., 2011 [53]; Stathopoulou, et al., 2009 [61]; Hendel, et al., 2018 [57] |

The research efforts in the area of raising the albedo coefficients are directed into two ways. First, some studies investigated the feasibility of using artificial high albedos pavement materials without affecting the structural properties of the pavement. On the other hand, others explored different types of coats and paintings that can be employed with the traditional dark pavement.

![Figure 5](image1.png)  
**Figure 5.** [a] Comparison between light and dark pavement segments using thermal infrared images (Image courtesy of Larry Scofield, APCA, [62]). [b] A new temporary parking with a cool pavement in the National Laboratory of Lawrence Berkeley (After U.S. Department of Energy, [63]).

Pavement roughness and color are affecting the tendency of pavement to absorb solar radiation. Doulos et al., 2004 [64] concluded that less solar radiation is absorbed with light-colored and smooth surfaces compared to dark-colored surfaces and rough surfaces. An interesting experiment was conducted by Synnefa et al., 2011 [65] to assess the effectiveness of color coating on the pavement solar radiation tendency. A thin asphalt layer with different colors, including red, green, beige, yellow, and off-white, was examined under solar radiation by measuring its surface temperature Synnefa et al., 2011 [65]. The results of those experiments are summarized in Table 2. It can be seen from these results that the more lighting the coating color, the more albedo increase and the more reduction in surface temperature.
Table 2. pavement tendency to absorb more solar radiation based on color

| Pavement Color | Reflection coefficient (Albedo) | Reduction in surface temperature | References |
|----------------|---------------------------------|----------------------------------|------------|
| Black          | 0.03                            | The reference                    |            |
| red            | 0.11                            | 4 K                              |            |
| green          | 0.1                             | 5 K                              |            |
| beige          | 0.31                            | 7 K                              |            |
| yellow         | 0.26                            | 9 K                              |            |
| off-white      | 0.45                            | 12 K                             |            |

4.3 Thermochromic pavement

Despite the significant benefits of the cool reflective pavement, as discussed in the previous section, it would successfully reduce the temperature of the pavement surface in the hot climate, particularly during the summer conditions. However, a second unfortunate consequence is that the surface temperature would be reduced in the winter, which raises the heating requirement at this season Karlessi, et al., 2009 [66]. Therefore, several studies recommended using thermochromic materials in the pavement due to their transition process.

As explained in Fig.6, Thermochromic materials have the ability to change their color reversibly upon the change in temperature. This color transition ability is due to the change in the material’s crystalline phase and structure, as explained by Favoino et al., 2015 [67]. Three main components form the organic leuco-dye mixtures of thermochromic materials. Those three components are, respectively, the color former, the color developer, and the solvent. The base color is determined by the color former. The color developer is a mild acid that changes the color. The color transition temperature is affected by the solvent's melting point (Bamfield, 2001 [68]; and Karlessi et al., 2009 [66]).

Figure 6. Chemical structure of thermochromic materials in both cooled and colorless situations, and their transition due to temperature change (After Hu and Yu, 2016 [69]).

Karlessi, et al., 2009 [66] examined the efficiency of the thermochromic material under hot summer conditions by comparing the surface temperature of white concrete tiles coated with common traditional coating materials and with different thermochromic coating. The daily mean surface temperature was measured, and results revealed that thermochromic coating materials were superior to the traditional ones in terms of surface temperature reduction. The temperature of the pavement surface was measured as (36.4–48.5°C) and (31.0–38.4°C) for the common and thermochromic coating, respectively. Furthermore, it was reported that the albedo of the concrete tiles was increased by 43%, when the
thermochromic coating was changed from colored to colorless phase. Those findings are also agreed with Ma et al., 2002; and Hu and Yu, 2013 [70-71] conclusions. In addition, Ma et al. showed that using the thermochromic coating with an outdoor cement sample led to a reduction of the ambient temperature by 4°C. While Hu and Yu examined the thermochromic coating with asphalt binder. It was highlighted that compared to traditional asphalt binder, the thermochromic coated asphalt was 3°C warmer in cold winter and 6°C cooler in hot summer.

As introduced above, the thermochromic pavement could successfully overcome the disadvantage of the cool pavement by its outstanding performance in both hot and cold climates. Despite that, thermochromic might affect the concrete pavement strength negatively, as proven by Bentz and Turpin, 2007; and Ma and Zhu, 2009 [72-73]. Besides, this coating material is associated with some aging and optical degradation problems, as reported by Karlessi and Santamouris, 2015 [74].

4.4 Cloud Seeding & Porous-permeable pavements

Cloud seeding can be defined as a weather modification method that disperses substances into the air to function as cloud condensation or ice nuclei and influence the microphysical processes within clouds (Fig.7). Although this method is being used in different countries but the effectiveness of this technique is still debated. Several studies revealed that it is complicated to clearly prove that cloud seeding substantially affects decreasing air ambient temperature. This is because the relative variation in the rain temperature to air or surface temperature is usually unknown.

On the other side, Pelley, 2016 [75] showed that the most mutual objective of cloud seeding, in many cases, was to increase snow or rain precipitation. As shown in Fig.8, Villegas-Mora et al., 2020 [76] presented a relationship between precipitation and air temperature. It can be seen from this relation that in all the four years records air temperature was decreasing with the increase in the rain precipitation. The specific heat capacity of the water is close to 4.2×10³ J kg⁻¹ K⁻¹, a 1 mm h⁻¹ rainfall precipitation rate is therefore equivalent to a heat flux of 1.2 ΔT W m⁻² approximately, since ΔT is the difference between the absorbing surface and the rain temperatures.

Byers et al., 1949 [77] revealed that at the start of a thunderstorm, rain might be relatively colder than the ambient air but possibly comparable at later stages. Through evaporative cooling and heat transfer, the failing raindrops cooling the unsaturated air. The heat can be transferred from the hot air...
to the relatively cool raindrops, consequently cooling the air. Also, momentum transfer from rain might cause cold convective downdraughts, which transfer cold air from higher levels to the surface (Knupp and Cotton, 1985; and Srivastava, 1987, Kamburova and Ludlam, 1966 [78-80]). However, with the continuity of rain falling, the air becomes saturated, and both rain and air return to the original wet-bulb temperature (Wei et al., 2014 [81]). In addition, Feingold, 1993; and Schlesinger et al., 1988 [82-83] concluded that various thermodynamical factors affecting the effectiveness of the cloud seeding method, such as drop concentration, moisture of the atmosphere, and the temperature profile, drop size, and their distribution.

![Figure 8. Relationship between precipitation and the environmental temperature (After Villegas-Mora et al., 2020 [76])](image)

On the other hand, several studies introduced another class of pavement materials that can be employed to promote the rainfall effect in reducing the air temperature. Haselbach et al., 2011 [58]; Asaeda and Ca, 2000; and Wang et al., 2018 [84-85] defined the porous-permeable evaporative pavement as the pavement with permeable open-graded structure. The existence of the water pores between the aggregate particles enables the pavement to hold moisture into the pores, and thus, surface’s heat could be reduced through the evaporation; as expressed in equation (5), the Latent heat induced by pavement is:

$$H_L = I \times E$$

Where $I$: the water vaporization specific latent heat (2260kJ/kg); $E$: the water’s evaporation rate.

The pavement material’s evaporation rate is mainly affected by the difference between the atmosphere and the pavement’s water content and temperature. The higher the moisture content of the pavement surface, the higher the evaporation rate, hence a much cooler surface. That’s why some studies (e.g., Yamagata, et al., 2008 [86]) revealed that the watering mechanism could enhance the evaporation effect and thus cool the pavement surface by switching much sensible heat into latent heat. This can also eliminate the contribution of sensible heat to the UHI effect.

Fini et al., 2017 [87] performed a series of experiments to compare the permeable and impermeable pavements behaviors. It was found that porous pavements were superior to both pavers and asphalt in terms of infiltration and evaporation of water. Also, the study revealed that inner subgrade soil
temperature was also affected by the pavement type, as the soil under porous pavements was 4°C and 5°C cooler than underlying soil with concrete pavers and asphalt. Thus, permeable pavements could assist in mitigating urban heat islands by enhancing evaporation from paved soil (Cardinali, et al., 2020 [88]). In the same line, porous pavements have shown CO₂ emission rates similar to control.

**Figure 9.** Comparison of permeable pavement and impermeable pavement (After Haselbac et al., 2011 [58], and Xu et al., 2021 [51])

4.5 Cool pavement with Phase change material (PCM)

The phase change materials (PCM) are substances materials able to change their physical state by absorbing or releasing large amounts of latent heat, i.e., from solid to liquid and conversely. Because of their high latent heat capacities, PCMs are suitable for cooling applications utilizing both sensible and latent heat during heat storage and release processes. Available PCMs can be classified as inorganic, organic, or eutectic mixtures. Also, PCM materials include solid to liquid, solid to solid, liquid to gas, and solid to gas. In construction and pavement applications, several studies (Neeper, 2000; Zhang, et al., 2008; Cerón, et al., 2011; and Chen, et al., 2011 [90-93]) recommended the solid-liquid PCMs, because of their volumetric stability.

Integrating the Phase change materials (PCM) into pavement volume increases its heat storage capacity (Karlessi et al., 2011 [94]). As a result, a significant amount of the sensible heat that is supposed to be released into the atmosphere could be translated into latent heat and kept the temperature constant. This decreases the air temperature by keeping the pavement surface temperature lower, and inducing less sensible heat to the environment.
PCMs can be incorporated into the different pavements surfaces, either cement or asphalt pavement, by two means. First, it can be directly integrated into different porous mediums, such as weight and lightweight aggregates (Fig.11.a). However, this would affect the strength of PCM-impregnated concrete negatively, and also cause a negative impact on the cement hydration process, as reported by Snehal et al., 2020; and Snehal and Das, 2020 [95-96]. Secondly, it can be covered by a micro-encapsulation with a metal or polymer exterior core-shell, as shown in Fig.11.b. This PCM’s microencapsulation can reduce the inflammability risk and increase the heat transfer contact area, thus avoid any exposure and unexpected reactivity near the external environment and improving the performance Karlessi et al., 2011 [94].

![Figure 11. Schematic diagram of the PCM’s two typical structures (After Zhang et al., 2016 [97]).](image)

Various experimental studies investigated the effects of PCM on pavement surface and ambient temperature. Karlessi, et al., 2011 [94] employed the PCM with a coating material and compared its behavior with other conventional cool coatings. It was found that the surface temperature of the concrete tiles utilized in these experiments was 3–7.5°C less than the ones coated with the conventional cool materials. The study has also revealed that the released latent heat by PCMs throughout nighttime had not contributed much to the coating surface temperature. Consistently, Anupam et al., 2021 [89] concluded that PCMs were primarily used in lightweight porous aggregates. In service, PCM-integrated asphalt pavements were 4.30°C cooler than standard asphalt pavements. However, the released latent heat during PCM freezing raises the pavement temperature at night, and further research might focus on improving this aspect.

**Conclusions**

This paper reviewed and discussed the most recent innovative and sustainable solutions proposed in the last decade to overcome the problems associated with the hot climate and global warming in general. The study focused on the new techniques concerned with reducing the pavement surface temperature and the corresponding decreases in the air ambient temperature, aiming to promote sustainable mobility modes in hot climate cities by eliminating the effects of the weather barrier. Following are the main findings concluded from the review results.

- The Arabian Gulf’s geological formations in Southwest Asia are the primary natural etiologies for the hot climate in those areas and significantly contributed to oil and gas production within this region. The produced oil and gas from this region are consumed locally and worldwide, significantly contributing to the earlier and current carbon dioxide (CO₂) emissions. Several studies predicted that in case of the continuous rising of the anthropogenic greenhouse gases concentrations (GHGs), the gulf region might experience intolerable temperatures to humans. Such terrible weather may have a severe consequence on different vital activities in different Gulf countries, such as the Muslim rites of Hajj in Mecca city. However, if the Southwest Asia countries tend to support the global mitigation efforts, this would significantly minimize the seriousness of the expected impacts. Both wet bulb (WBTₘₐₓ) and annual maximum (Tₘₐₓ)
temperatures are not expected, in this case, to exceed the human threshold limits in those areas. In addition, under this mitigation scenario, where the rituals of Hajj are taking place, the $WBT_{\text{max}}$ would rise only about 2°C warmer than the current climate in Mecca and near Jeddah.

- Most of the recent solutions invented to overcoming the sustainable mobility problems associated with hot atmospheric temperature have focused on reducing the pavement surface temperature. Whereas the ground and pavement materials are exposed to absorb and store the most significant percentage of the incoming solar radiation (about 51%), also it was found that terrestrial radiation heats the atmosphere more than the direct incoming solar radiation. In addition, the air ambient atmosphere is heated through the radiation, conduction, and convection mechanisms, and the pavement surface temperature directly influences the three mechanisms.

- The geothermal systems represent a promising solution that can control the pavement temperature decrease or increase through natural convection by the warmed air up or down by geothermal resources. Experimental and simulations studies revealed that geothermal systems were able to decrease or increase the pavement temperatures with temperature differences up to -6°C and +6°C in summer, and winter conditions, respectively. Despite that, those systems are associated with high capital costs, which delay implementing those systems on wider scales. Furthermore, some studies proved that the temperature difference between asphalt pavement structures and the underlying subgrades are significant enough to apply the Seebeck effect and harvest electric energy through TEGs. This may justify the high cost of the system by generating electricity from the pavement. However, at present, the generated power through this system is still insufficient enough. Success in generating sufficient electric power through the asphalt and TEG system may justify the implementation cost of the geothermal with the pavements. Future studies may improve the efficiency of those energy harvesting systems by promoting the thermal convection of the TEGs, suggesting different configurations for the system, and enhancing the thermoelectrical pavement properties using the composite material approaches.

- Dissimilar to the regular dark pavement, the cool pavement employs additives to improve the ability of pavement to reflect solar radiation. The low reflection coefficient (albedo) of the regular dark pavement is the significant leading property responsible for the high solar radiation absorption by the pavement surface. Several studies showed that using pavement materials with a high albedo absorbs less solar radiation, resulting in a cooler surface and a reduction in the intensity of longwave radiation. Those studies concluded that improving the albedo of the pavement surface from 0.25 to 0.40 can decrease the air temperature by almost 4°C. Despite the remarkable advantages of the cool reflective pavement in reducing the pavement surface temperature, mainly during the summer conditions, a second unfortunate consequence is that the surface temperature would be reduced in the winter, which raising the heating requirement at this season. Therefore, future research efforts in the area should be directed to overcome this significant concern.

- Several studies recommended using thermochromic materials in the pavement to extinguish the disadvantage of cool pavement during the cold climate. The transition process of the thermochromic materials enables those materials to change their color reversibly according to the temperature change. As a result, these coating materials can increase the pavement albedo by about 43%, efficiently increasing or decreasing the air surface temperature. Experimental studies reported that compared to traditional asphalt binder, the thermochromic coated asphalt was 3°C warmer in cold winter and 6°C cooler in hot summer. On the other side, unfortunately, the thermochromic affects the concrete pavement strength negatively, as reported in several studies. Besides, this coating material is associated with some aging and optical degradation problems.
Cloud seeding can be defined as a weather modification method that disperses substances into the air to function as cloud condensation or ice nuclei and influence the microphysical processes within clouds. Although this method is being used in different countries but the effectiveness of this technique is still debated. Some studies revealed that it is complicated to clearly prove that cloud seeding substantially affects decreasing air ambient temperature as the rain temperature variation relative to air or surface temperature is not well known. On the other hand, some others showed a direct relationship between air temperature and rain precipitation. With that in mind, some studies revealed that inner subgrade soil temperature was also affected by the pavement type, as the soil under porous pavements was 4°C and 5°C cooler than soil covered with concrete pavers and asphalt. Thus, porous pavements could contribute to mitigating urban heat islands by enhancing evaporation from paved soil.

Integrating the Phase change materials (PCM) into pavement volume increase its heat storage capacity. As a result, a significant amount of the sensible heat that is supposed to be released into the atmosphere could be transferred into latent heat and kept the temperature constant. In service, PCM-incorporated asphalt pavements were found to be up to 4.3°C cooler than standard asphalt pavements. However, the latent heat released during PCM freezing raises the pavement temperature at night, and further research might be required in this aspect.

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Declaration of Competing Interest
The authors declare that there is no conflict of interest.

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