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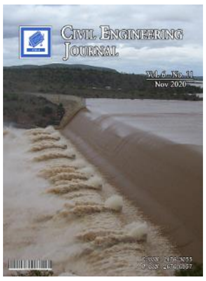

Climate Zones of the Asphalt Binder Performance for the Highway Pavement Design

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Abstract

The asphalt pavement is exposed to the natural environment, which is affected by Climate change such as temperature, rain, ultraviolet, and other environmental conditions. This study aimed to establish the asphalt binder performance of Yemen so that the asphalt pavement can be designed to resist the distresses of rutting and cracking that occurred due to seasonal temperature changes and rainfall. The first step of determining the binder performance is to establish high and low temperatures, as well as rainfall because the asphalt binder is a temperature and rainfall sensitive viscoelastic material. To study the climatic zoning of asphalt pavement in Yemen, the data of temperature and rainfall in 19 provinces of Yemen in the past 10 years were collected and comprehensively analyzed, and the variations laws of them were analyzed. According to the Chinese approach, the climatic zoning of Yemen's asphalt pavement was divided. The moisture temperature coefficient was introduced, and its probability distribution state was also analyzed. The standard of the moisture temperature coefficient was suggested and the asphalt pavement climate zones based on the moisture temperature coefficient were determined. The results indicated that the main influencing factors of asphalt pavement in Yemen were the temperature rise and rainfall, and the climate zones of asphalt pavement were divided into different zones such as 1-2-1, 2-2-2, 1-2-2, and 3-1-2. According to the principle of equal probability, the moisture temperature coefficient was found to be 18, and the asphalt pavement climate zoning map was drawn. The findings of this study are highly significant and provide valuable decision support for pavement management and improve the transportation system.

Keywords: Road Engineering; Asphalt Pavement; Yemen; Climate Division; Moisture Temperature Coefficient.

1. Introduction

The asphalt pavement is exposed to the natural environment for a long time, which is influenced by temperature, rain, ultraviolet, and other environmental conditions, and its pavement performance is constantly attenuated. The continuous high temperature and extreme low temperature, precipitation and strong UV radiation are the most significant environmental conditions which affecting the asphalt pavement performance. Asphalt binder is a temperature-sensitive viscoelastic material, temperature can cause some common distress of asphalt pavement [1]. Due to the viscoelastic property, asphalt pavement is susceptible to rutting at high temperatures and subject to cracking due to shrinkage of the binder at low temperatures [2, 3]. Many countries have designated climate zones for

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the asphalt pavement adapting to their climate conditions, to better guide asphalt selection materials and mixture design and ensure the long service life and high performance of the pavement. According to the high and low-temperature design of asphalt pavement, the United States proposed a program named as the highway strategy research program (SHARP). This program established the Long-Term Pavement Monitoring Program (LTPP) in 1987 to support an extensive pavement performance analysis, thereby improving engineering tools for designing, managing, and constructing pavements [4].

The binder is selected according to the design temperature of the high and low temperature of asphalt pavement, the hottest average temperature within a year is taken as the design temperature of high temperature, and the lowest air temperature is taken as the design temperature of the low temperature of pavement[5]. Based On the SHARP model, many pavement temperature approaches were properly established to select the proper asphalt binder performance PGs [6]. The first study was manually carried out in Saudi Arabia to measure pavement temperatures in various pavement sections. This study showed that the maximum pavement temperatures ranged from 3 to 72 °C in arid environments and from 4 to 65°C in coastal areas. Another study was also conducted for the entire Gulf area and suggested five performance graded binder zones [7]. The second study conducted an extensive two-year study in Oman to develop a temperature model for asphalt pavement. The collected data were analyzed and a linear regression model was obtained to predict high and low pavement temperatures. The study tested the SHARP and LTPP models against actual measurements of air and pavement temperatures and concluded that the LTPP model produced closer results to actual temperatures. Unlike the previous studies, the Chinese approach divides the asphalt pavement climate zoning according to the high and low temperature and precipitation [8]. According to the climatic data of nearly 10 years from 17 meteorological stations in various regions of Laos, the authors divided Laos into five-level natural divisions and put forward the high temperature, the low temperature, and water stability standards for asphalt pavement according to different climatic characteristics [9]. Tang Juan analyzed the main climate data of Hainan Province, such as temperature and rainfall, and carried out zoning on the influence of temperature and humidity on the highway asphalt pavement in Hainan Province according to the high and low temperature, humidity, and dryness [10].

Yemen road construction started late, so far has not developed a corresponding asphalt pavement climate zone, so that makes the Yemeni asphalt pavement has no rules to follow in the design, management, and construction stages. According to the latest survey data, the proportion of asphalt pavement in Yemen's existing pavement structure is 13% (paved road), the gravel pavement 35%, and the earth pavement 52%, that is indicating the current Yemen road level is still very low [11]. With the economic and social development in Yemen and the increasing demand for heavy traffic, the proportion of high-quality asphalt pavement in the future construction is bounded to be increasing. Therefore, according to climatic conditions in Yemen, this article makes scientific and rational asphalt pavement climate division, which is very important to improve the design and service life of the asphalt pavement.

Based on the collected and analyzed temperature and rainfall data, the climate zoning of the asphalt binder performance grades is given. This is included the description of the analyzing of the temperature and rainfall data, which is explained in section 2. In section 3, the results of the analyzed data were presented and the concept of moisture and temperature coefficient is considered. Also, the climate zoning of asphalt pavement is divided and the comparison of the results with the previous studies is also presented. Then, the climate zoning maps of asphalt pavement is drawn. Finally, the summary of the findings is accordingly presented in section 4.

2. Research Methodology

2.1. Study Area

Yemen is a part of the Arabic Peninsula which located in the southern part, the latitude is somewhere in the range of 12 and 20 degrees, while the longitude is about 41 to 54 degrees. Yemen is bordered by Saudi Arabia to the north, Oman to the east, the Arabian Sea, and the Gulf of Aden to the south, and the Red Sea to the west. (See Figure 1).

Yemen has an area of 555.000 Square Kilometres, with an absolute population of 28.26 million and has a population density of 50 persons per Square Kilometres. Naturally, Yemen can be divided into five regions: a mountainous, a plateau, a coastal area, the Rub Khali, and islands [11].

The mountains in Yemen are the result of an upturn in the African continent, while the declining trench forms the Red Sea and the Gulf of Aden. It is usually composed of volcanic rock, ranging from 1000 to 3600 meters above sea level. The mountain of Nabi Shu'ayb is the main peak which reached about 3666 meters above the sea level, which is also the highest peak in the Arabic Peninsula. Among these mountains, there are valleys eastward, southward, westward, and northward.

The coastal line is extended along the Red Sea, the Gulf of Aden, and the Arabian Sea. They connecting each other form the coastline, from the border with Oman on the east side to the Bab Muang Strait on the west side and extending north to the border of Saudi Arabia, with 2,000 kilometers long and 30 to 60 kilometers wide.

Meteorologists classified Yemen as a tropical country, with climate and temperature constantly changing throughout the year. Therefore, the climate in the South part of Yemen, especially the coastline is very hot and humid all over the year. The hot season falls between April to October with an average temperature of 37 degrees. While the moderate climate falls between November to March with an average temperature of 27 degrees. The annual rainfall is about 50 mm. The highest temperature is in Aden during the summer season with a temperature of 41.8 degrees, the lowest temperature in the winter season is about 17.5 degrees, with an average annual rainfall of 94.7 mm.

In the northern part, there are many types of climates. The east slope extends toward the Rubu Desert, which is a desert and semi-desert. The climate is dry, hot, and without rain. The central plateau is 1500-4000 meters above sea level with a cold climate. In the hilly area, the annual rainfall is above 1000 mm, and the rainy season is between March to May and July to September. The western Red Sea coast is the Chatham area, the climate is hot and humid. Therefore, the summer temperature is generally ranging from 35 to 40 degrees, the humidity is generally between 80-90%, and annual precipitation is below 400 mm [12, 13].

Figure 1. The general location and the Study Area –Republic of Yemen

The flowchart of the overall research methodology is shown in Figure 2.

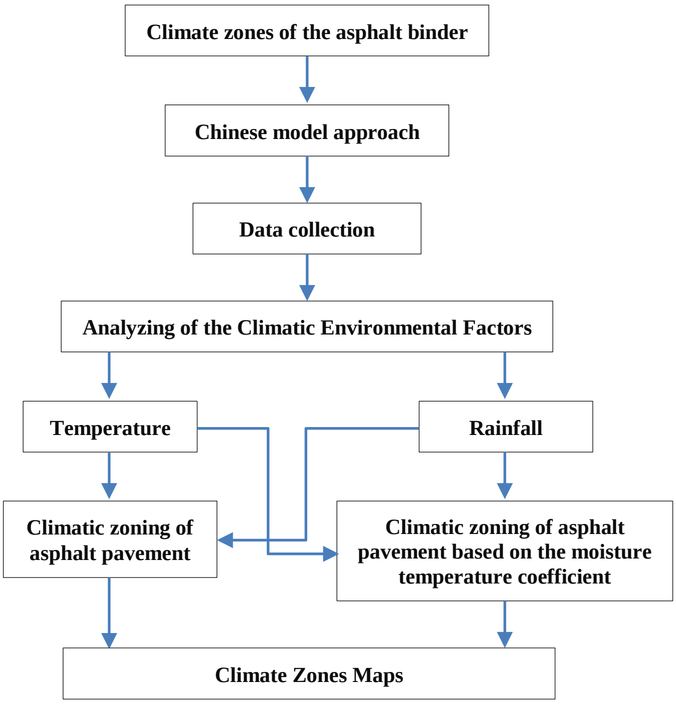

Figure 2. The methodology flowchart

2.2. Climatic and Environmental Factors in Yemen

The air temperature and precipitation data were obtained from the Yemeni National Meteorological Center from the period 2009 to 2018 of 19 provinces and regions in Yemen. The used data were collected then analyzed[14].

2.2.1. Temperature

The temperature data analyzed for the most representative provinces in Yemen such as Sana'a, Taiz, Ibb, Aden, AL-Dale, and Shabwah were selected to be analyzed based on temperature data.

2.2.2. Rainfall

The rainfall in this area is particularly important for the most representative provinces in Yemen which are selected to be analyzed.

2.3. Climatic Zoning of Yemeni Asphalt Pavement

The climate zoning of Yemen provinces is divided based on the method and principle of climate zoning in China, as well as the climate characteristics of Yemen province. The climate zoning indexes of asphalt pavement in Yemen Provinces are obtained based on the rainfall and high and low-temperature indexes which are used as evaluation factors to control water damage and high-temperature rutting of asphalt pavement in Yemen.

2.4. Climate zoning of Yemen Asphalt Pavement Based on the Moisture Temperature Coefficient

According to the data distribution characteristics of climatic factors affecting asphalt pavement, Yemen is divided into different regions by introducing the moisture temperature coefficient, to distinguish how to focus on certain climatic conditions in designing of different regions.

3. Result and Discussion

3.1. Analysis of Climatic and Environmental Factors in Yemen

The author collected the temperature and precipitation data from 2009 to 2018 in 19 provinces and regions. These data were collected from the Yemeni National Meteorological Center and all collected data were analyzed [11].

3.1.1. Temperature

One of the main factors affecting asphalt pavements in Yemen province is air temperature, which is different from high temperature and low temperature. Areas affected by high temperatures are almost all over the coastal area province located in the south of Yemen, and the low temperature is mainly affected by the mountainous area located in the northern part of Yemen. Field Experiments showed that the changes in the temperature of the asphalt pavement structure change with the surrounding environment, these changes make the properties and the conditions of the pavement materials change correspondingly [15–17].

Due to the limited time, the temperature data of the most representative provinces in Yemen such as Sana'a, Taiz, Ibb, Aden, AL-Dale, and Shabwah were selected to be analyzed based on the temperature data for only these provinces. The conclusions were obtained as follows:

- From 2009-2018, the annual average temperatures in the governorates of Sana'a, Taiz, Ibb, Aden, AL-Dale, and Shabwah were 20.2℃, 25.1℃, 22.7℃, 30.06℃, 24.1℃, and 27.3℃ respectively.
- The results showed that the average monthly temperature in each region was subjected to a normal distribution as shown in Figure 3. It can be seen that the lowest temperature across Yemen mainly occurred in January while the highest temperatures were observed in June. The maximum and minimum monthly temperatures are numerically subjected to the normal distribution as shown in Figure 4 and Figure 5 respectively.
- Figure 6 shows that, the average monthly temperature distribution of the coldest month (January) in 6 regions in 10 years. Even in the lowest average temperature in January, the average temperature is still greater than 0 ℃, indicating that the annual temperature in these 6 areas is higher than 0 ℃ (positive values). Therefore, the effect of temperature below 0 ℃ is neglected.
- Figure 7 presents a distribution of extreme minimum temperature (typically in January) in 6 regions for 10 years. Taiz, Ibb, Aden, AL-Dale, and Shabwah experienced the minimum temperature which was higher than 0 ^{0}C, except Sana'a city, experienced the extreme minimum temperature which was less than 0 ℃ with the value of -2.6 ℃, but this extreme minimum temperature below 0 ℃ occurs for a short period, approximately one week.
- Figure 8 shows that the average monthly maximum air temperature in the hottest month (June) for 10 years

registered in 3 districts of Aden province, Taiz province, and Shabwah province which is higher than 30 ℃, and the zoning standard of asphalt pavement climate based on Yemen method belongs to the Summer inflamed area. While the average monthly maximum temperature in Sana'a province, Ibb Province, and Dale province is falling between 20~30 ℃, which belongs to the summer hot area. In general, the high-temperature stability is considered during the design of the asphalt mixture in all Yemeni regions.

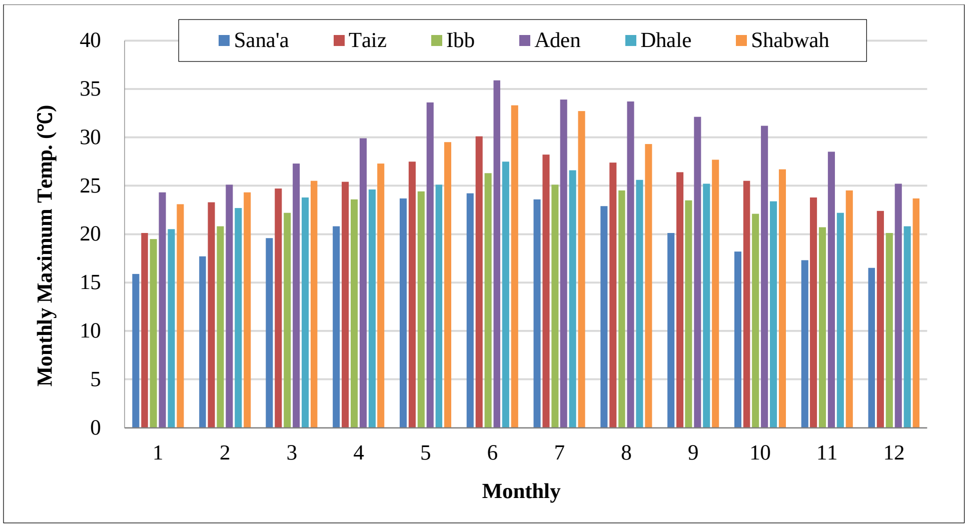

Figure 3. Statistics of average monthly temperature

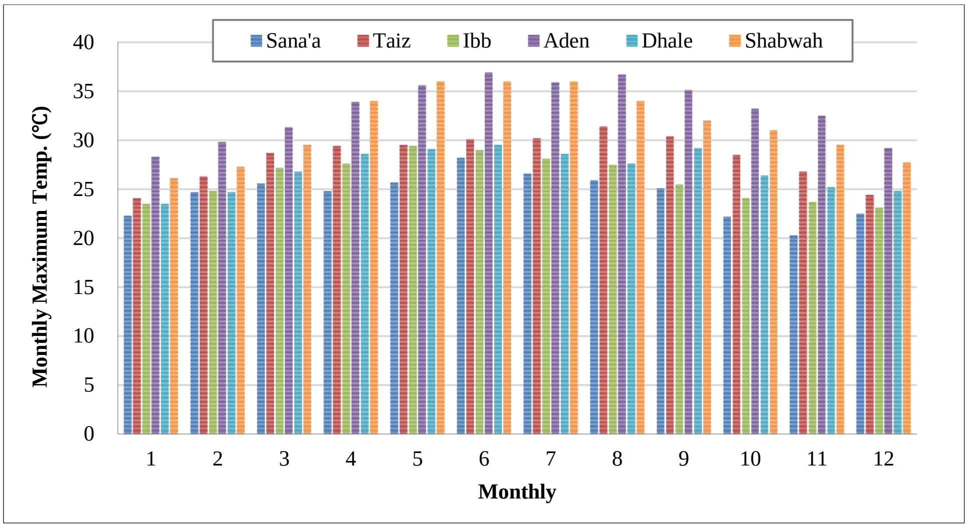

Figure 4. Monthly maximum temperature statistics

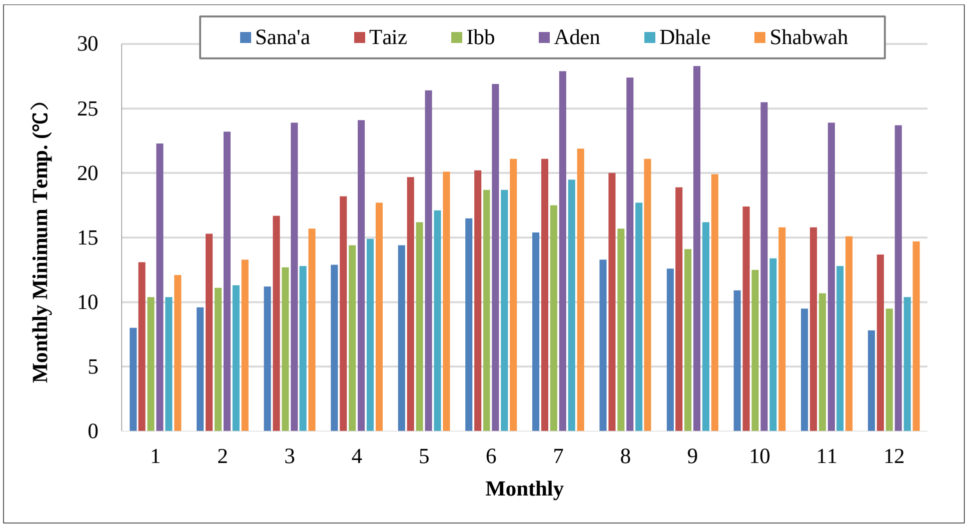

Figure 5. Monthly minimum temperature statistic

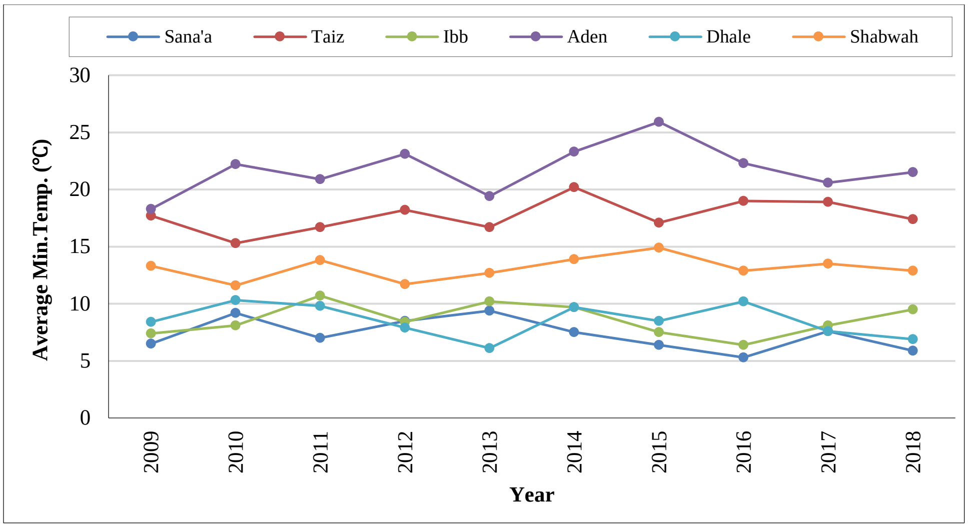

Figure 6. The average temperature of the coldest month (January)

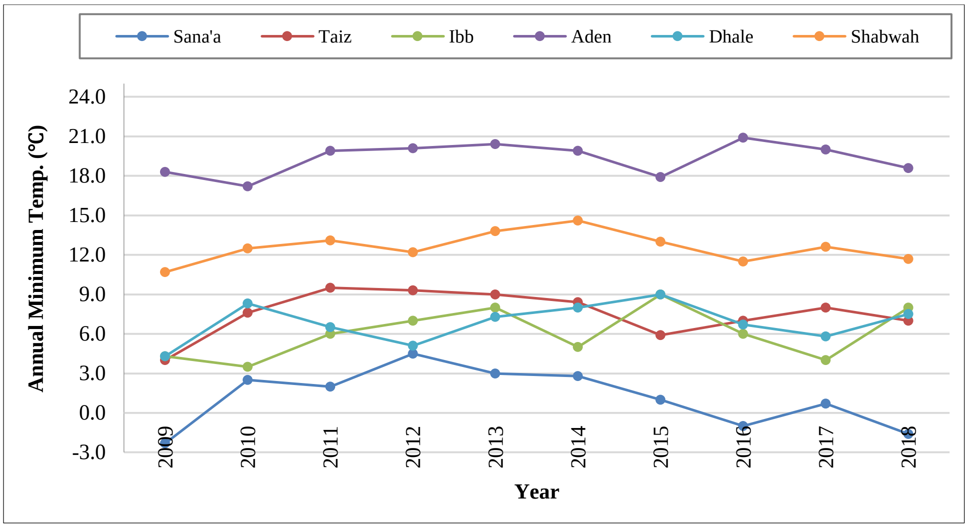

Figure 7. The minimum temperature

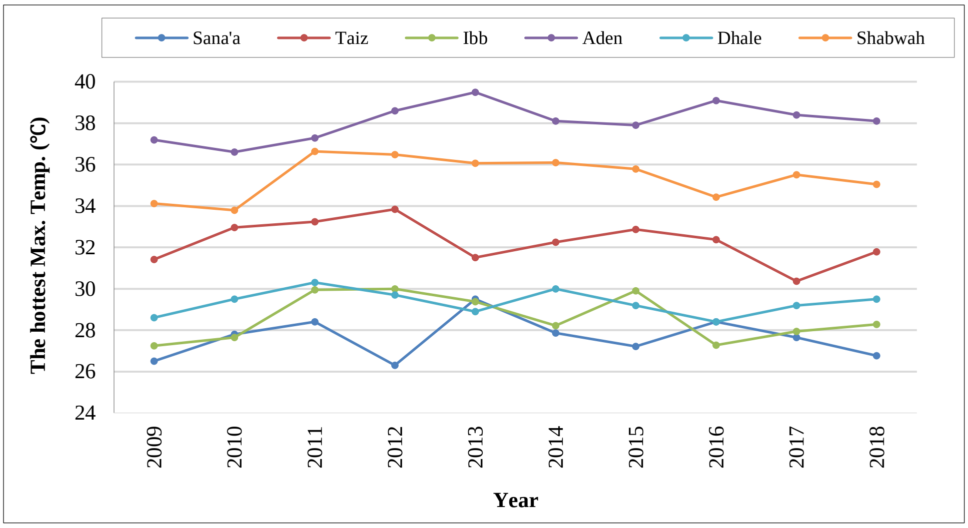

Figure 8. The hottest average month temperature (June)

3.1.2. Rainfall

Statistical analysis of the rainfall data shows that the average annual rainfall in the southern part of Yemen is about 94.7 mm. The weather is hot and humid. In a northern climate, there are more climate types than in the southern part. The gentle slope to the east stretches toward the Rubu Desert, which is desert and semi-desert and the climate is dry and hot as well. The central plateau is 1500-4000 meters above sea level with the cold climate. In the hilly region, Abundant rainfall, the annual rainfall above 1000 mm, and the rainy season concentrated in March-May and July-September. The western Red Sea coast is the Chatham area, the climate is hot and humid. Therefore, the summer temperature is generally between 35-40 degrees, the humidity is generally falling between 80-90%, and the annual precipitation below 400 mm. Most of the rainfall in Yemen is concentrated in the northern and central parts during the rainy season and occurs from the beginning of March to the end of September. The total amount of rainfall accounts for more than 85 percent of the total annual rainfall, while for the early season rainfall accounts only for less than 15% during the dry season. The monthly cumulative rainfall data of each year follows a normal distribution, as shown in Figure 9. Although most parts of Yemen are dry with little rainfall, in the hot and rainy season, the asphalt pavement is seriously damaged after heavy rain, especially after exposure to the sun. Therefore, the negative impact of rainwater must be fully considered when selecting the structural combination and materials of the asphalt pavement [17].

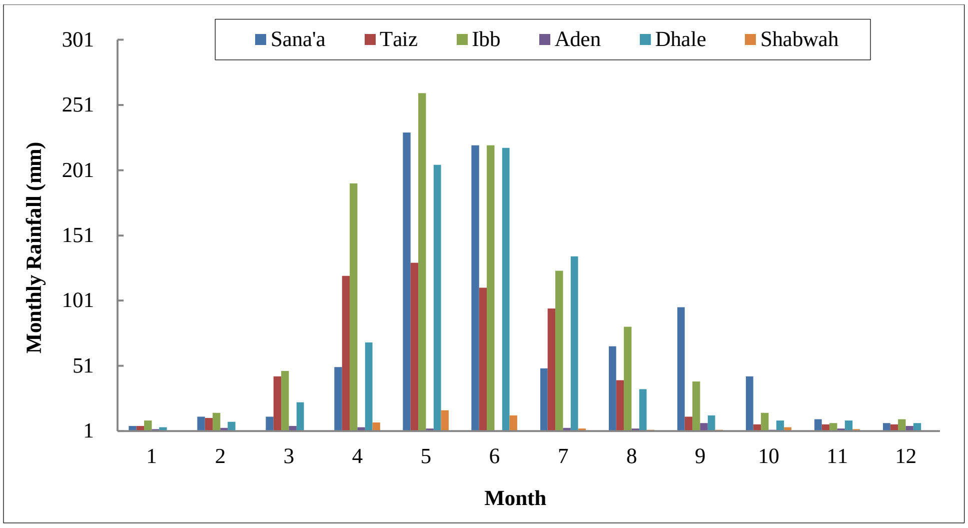

Figure 9. Cumulative rainfall statistics of each month yearly

3.2. Climatic Zoning of Yemeni Asphalt Pavement

The climate zoning of Yemen provinces is divided based on the method of climate zoning in China, as well as the climate characteristics of Yemen province. The climate zoning indexes of asphalt pavement in Yemen Provinces are obtained based on the rainfall and temperature zoning of asphalt and asphalt mixture road performance, as well as the climate zoning in Yemen provinces [18, 19]. In Yemen asphalt pavement climate zoning, rainfall, high temperature, and low-temperature indexes are used as evaluation factors to control high-temperature rutting of asphalt pavement as well as the water damage. Rainfall index uses the average annual rainfall in the past 10 years as the climate factor of asphalt pavement affected by rainfall, which is considered to be the primary indicator of climatic zoning.

The high-temperature index uses the average daily maximum temperature value of the hottest month in the last 10 years to reflect the climatic factor of high temperature and cause asphalt deformation such as rutting, which is considered to be the second index of climatic zoning.

The minimum temperature in the recent 10 years is used as the index of low temperature, which reflects the climatic factors of low temperature cracking of pavement which is considered to be the third index of climatic zoning as shown in Tables 1 to 3.

Table 1. Rainfall climate division

Rainfall climate zoning	**1**	**2**	**3**
Climate zone name	humid area	semi-arid	dry area
Annual rainfall/mm	>500	100-500	<100

Table 2. Hot climate division

Hot climate zoning	**1**	**2**
Climate zone name	Summer inflamed area	Summer hot area
The average maximum temperature in the hottest month/c°	>30	20～30

Table 3. Cold climate division

Cold climate zoning	1	2
Climate zoning name	Cold winter area	Cool winter area
Extreme minimum climate /c°	-9.0 ~ 0	>0

Based on the meteorological data provided by regional meteorological observatories in 19 provinces in Yemen for a total of 10 years from 2009 to 2018, the asphalt pavement climate zoning in Yemen is divided, and the results are shown in Figure 10 [11]. According to the result, southern and Western of Yemen such as Al Hudaydah Province, Abyan Province, Aden Province, Hadhramaut province, Lahj Province, Mahrah Province, Shabwah Province, Ma'rib province, Al Jawf province, all of these areas belong to the 3-1-2 region. The northeast region of Yemen is mountainous and plateau at an elevation of more than 2500 m above the sea level, such as Sana'a province, Dhamar Province, Amran Province, belong to the 1-2-1 region. The northern and central areas of Yemen such as Taiz province, Ibb province, Hajjah province, Al Mahwit province, AL-Dale province, belong to the 1-2-2 region, while the 2-2-2 region representing the mountainous and plain area such as Sadah Province, and Socotra Province.

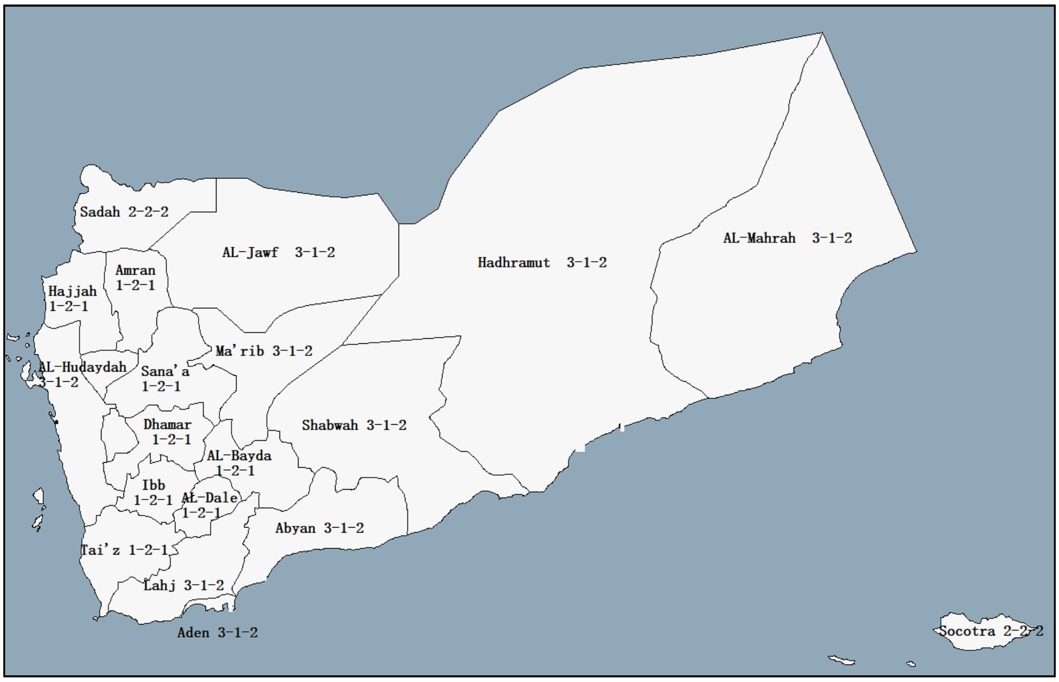

Figure 10. Asphalt pavement climate zoning in Yemen

3.3. Climate Zoning of Yemen Asphalt Pavement Based on the Moisture Temperature Coefficient

As can be seen from the previous analysis, the main climatic factors affecting the Yemeni asphalt pavement road are rainfall and high temperatures, and the low temperature can be ignored. Although both rainfall and high temperature are required to be considered, the final controlling factors are different in different regions.

According to the data distribution characteristics of climatic factors affecting asphalt pavement, 19 provinces of Yemen are divided into different regions by introducing the moisture temperature coefficient, to distinguish how to focus on certain climatic conditions in designing of different regions.

In Yue-Gang (2010) and Sun et al. (2000) study [20, 21], the moisture temperature coefficient (Φ) model is constructed to evaluate the effect of climate on water stability and high-temperature stability of asphalt pavement as shown in Equation 1. The moisture temperature index can simultaneously consider the influence of high temperature and precipitation at the same time. The greater the value of (Φ), the more water stability should be considered in the design of asphalt mixtures, while the lesser value of (Φ), the higher temperature stability should be considered in the design of mixtures.

$$\Phi = \frac{Q}{T_j} \tag{1}$$

Where:

Φ = moisture temperature coefficient (mm/°C);

Q = average annual rainfall (mm);

T_j = the average annual temperature (°C).

Through statistical calculation, the range of Φ value of 19 provinces in Yemen ranges from 1 to 18, the data is according to the normal distribution as shown in Figure 11.

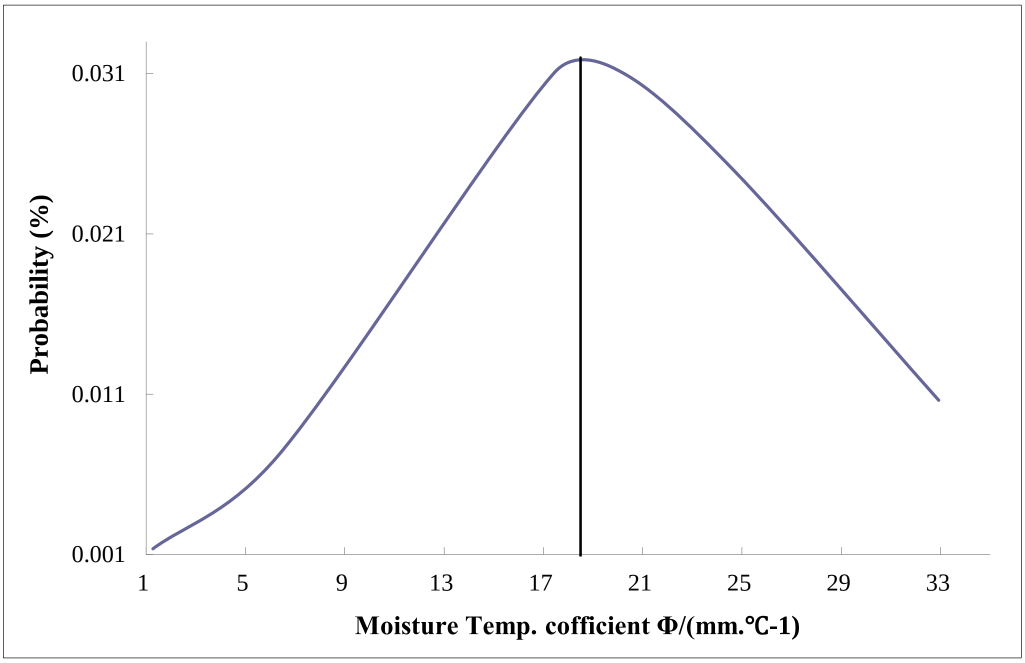

Figure 11. Moisture temperature coefficient Φ value probability distribution

According to the moisture temperature coefficient Φ, the Φ value influencing the humidity and temperature of the asphalt pavement of the Yemen Highway is divided into two regions as listed below:

- Zone A: The moisture temperature coefficient is less than 18, then consider high-temperature stability as the main factor and water stability as well.
- Zone B: The moisture temperature coefficient is greater than 18, then consider water stability as the main factor and high-temperature stability as well.

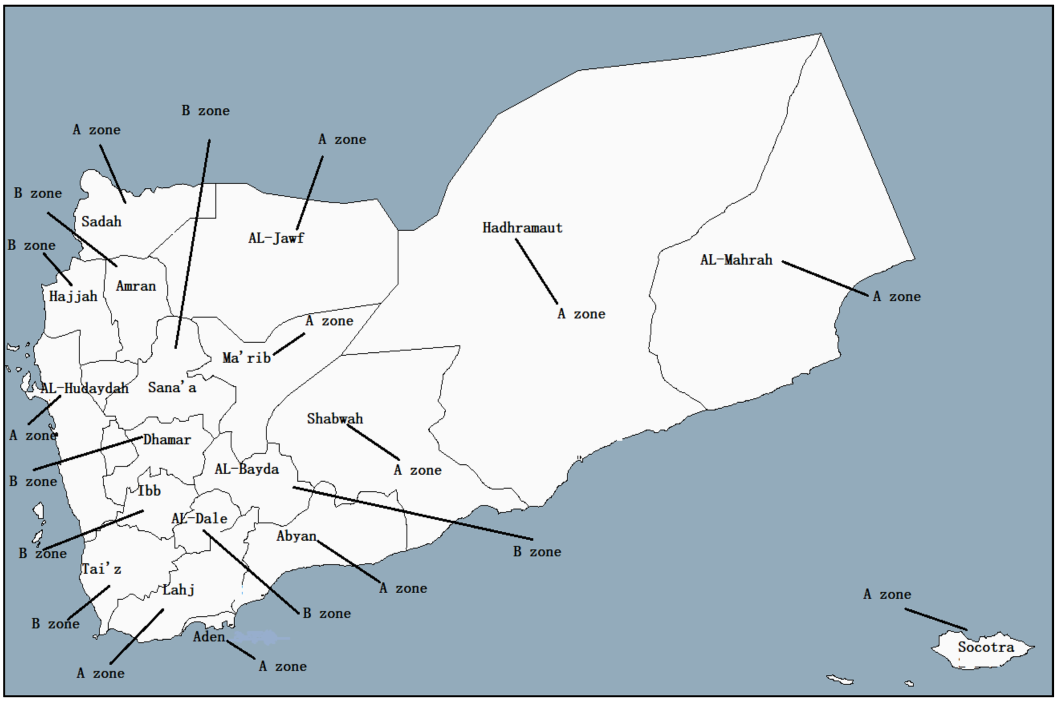

Figure 12. Climate zoning of 19 provinces in Yemen according to the moisture temperature coefficient

As mentioned above, the provinces of Sana'a, Sadah, Taiz, Ibb, Hajjah, Dhamar, Al Mahwit, Amran, AL-Dale, belongs to the zone (B), considering water stability as the main factor, and high-temperature stability as well. Ma ’rib, Al Hudaydah, Abyan, Aden, Hadhramaut, Lahj, Shabwah, Al Jawf, Socotra, and Al Mahrah provinces belong to the zone(A), considering the high-temperature stability as the main factor and water stability as well.

As can be seen, the demarcation line between areas A and B is approximately the same as the annual average rainfall of 500mm, which indicates that the coefficient moisture temperature distribution Φ is consistent with the annual average rainfall distribution and the Φ value contains reasonable information of temperature. Therefore, it is reasonable to divide the asphalt pavement temperature and humidity in the Yemen region into different zones by using the moisture temperature coefficient. Through summarizing and analyzing the climate data of Yemen, this paper uses the moisture temperature coefficient method to carry out the road asphalt climate zoning in Yemen. The results are shown in Figure 12. The findings of this study are consistent with those of the other overseas studies. A Similar study proposed the climate division of asphalt pavement of road in Laos [22]. In this study, the temperature, rainfall, and moisture temperature coefficient were introduced and the probability distribution was analyzed, the result showed that the main influence factors for asphalt pavement performance were the high-temperature and rainfall, the authors concluded that the findings would be more appropriate and reasonable to divide the temperature and humidity the of asphalt pavement for the local system.

4. Conclusions

The main objective of this paper is to determine the asphalt binder performance for the Yemeni region based on comprehensive collected data of the existing meteorological weather stations. These data were analyzed according to the norms in China. The findings of this study are summarized, which can be used as the fundamental implementations for the asphalt pavement mix design in Yemeni roads. The following conclusions can be drawn based on the analyzed data:

- According to the meteorological data of several provinces and regions in Yemen for 10 years, the main climatic factors affecting the performance of asphalt pavement in Yemen were identified as rainfall and high temperature.
- Based on the analysis of meteorological data in 19 provinces of Yemen from 2009 to 2018, the climate zoning of Yemeni asphalt pavement is divided and the zoning map is drawn. The climate zoning of Yemeni asphalt pavement are 1-2-1 zone, 2-2-2 zone, 1-2-2 zone and 3-1-2 zone.
- The probability distribution of the moisture temperature coefficient in Yemen is analyzed. According to the principle of equal probability, the moisture temperature coefficient is determined to be (18). On this basis, the climate zoning map of Asphalt Pavement is drawn based on the moisture temperature coefficient.

The findings of this study are highly significant and provide valuable decision support for pavement management and the development of local transportation system sustainability and social-economic improvements. And can become more helpful and interesting if further research would be considered with more stations to be installed in different areas of the country which could enhance the developed models. Field validation of the proposed asphalt pavement performance would also be recommended.

5. Conflicts of Interest

The authors declare no conflict of interest.

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