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A preliminary study of mechanistic approach in pavement design to accommodate climate change effects

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Abstract. Road damage is caused by some factors, including climate changes, overload, and inappropriate procedure for material and development process. Meanwhile, climate change is a phenomenon which cannot be avoided. The effects observed include air temperature rise, sea level rise, rainfall changes, and the intensity of extreme weather phenomena. Previous studies had shown the impacts of climate changes on road damage. Therefore, several measures to anticipate the damage should be considered during the planning and construction in order to reduce the cost of road maintenance. There are three approaches generally applied in the design of flexible pavement thickness, namely mechanistic approach, mechanistic-empirical (ME) approach and empirical approach. The advantages of applying mechanistic approach or mechanistic-empirical (ME) approaches are its efficiency and reliability in the design of flexible pavement thickness as well as its capacity to accommodate climate changes in compared to empirical approach. However, generally, the design of flexible pavement thickness in Indonesia still applies empirical approach. This preliminary study aimed to emphasize the importance of the shifting towards a mechanistic approach in the design of flexible pavement thickness.

1. Introduction

Road repairs which are performed on regular basis due to the prevalence of short-term damage are high cost [1]. Road damage is caused by some factors, including climate changes, overload, and inappropriate procedure for material and construction process. Climate change is a phenomenon which cannot be avoided, caused by natural process or human activities. Carbon dioxide which is continuously produced and released into the air will damage the ozone layer in the atmosphere and will lead to the occurrence of global climate change. The effects of climate change include air temperature rise, sea level rise, rainfall changes, and higher intensity of extreme weather phenomena [2]. Several studies confirmed the link between climate changes and road damage [3,4,5,6,7,8,9,10,11,12].

To anticipate the occurrence of road damage, several measures should be devised during the road planning and construction, in order to save the cost of road maintenance. In addition, the recent road construction design must also involve the longer design life and higher capacity to hold load and weather effects. The attempt to design longer design life is in accordance with the concept of long life pavement that has been applied for several years in Europe and USA. The Forum of European

National Highway Research Laboratories defines long life pavement as a type of pavement which will be no deterioration formed in the foundations or the road base layers since the correct surface maintenance is carried out [13]. The concept of long life pavement aims to obtain long life in order to get lower life-cycle costs. These life-cycle costs include the costs of construction, maintenance, rehabilitation, user delay, vehicles maintenance, and the cost spent to restore the impacts on the environment [14].

The design of flexible pavement thickness can apply three approaches, namely mechanistic approach, empirical approach and mechanistic-empirical (ME) approach [15,16,17,18]. According to the European Asphalt Pavement Association, the mechanistic approach have been widely applied in the design of flexible pavement thickness [19]. The advantages of this approach have been recognized, including its efficiency and reliability in the design of flexible pavement thickness, in addition to its capacity to accommodate climate change effects in compared to the empirical approach [20]. However, the design of flexible pavement thickness in Indonesia still applies the empirical approach, instead of the mechanistic approach. Therefore, this preliminary study aimed to reveal the importance of the shifting toward the utilization of mechanistic approach in the design of flexible pavement thickness.

2. Climate change

Climate is defined as the regular weather condition (temperature, rain, pressure wind, humidity) at a particular area. Weather is the day to day manifestation of this climate [8]. Climate is subject to change periodically due to both the natural and manmade factors, whether at the global, regional and local level. In all cases, changes in climate are generally unpredictable in which climatologists have to observe and take a period of time, approximately 50 years, in prior to establishing a trend for a particular jurisdiction. Nevertheless, since the second half of the last century, they have identified significant and extreme climatic events that tend to suggest the departures from events that were usually observed in the past. Given that these departures are attributed to an increase in human activities that lead to climate change, it is projected that even more profound climatic events will occur if human activities are continually uncontrolled [21].

A primary cause triggers the climate change is the greenhouse effect which is caused by greenhouse gases. These gases are generated from the natural and man-made sources, such as carbon dioxide, methane, and nitrous oxides, which accumulated in the atmosphere. Furthermore, over the past century, the anthropogenic sources of greenhouse gas emissions have substantially increased particularly since the pre-industrial era. Consequently, the impact of the greenhouse effect is greater than it should be and it contributes to the gradual heating of the Earth's surface [21]. Further investigation on anthropogenic induced climate change revealed that human activities, such as fossil fuel use and land use change, are likely to produce a positive radiative forcing, warm the earth's surface and trigger other changes in climate [22]. Lately, some of the changes have been identified while others have been estimated to occur in the future. Among those changes are the rise in global mean sea level, the decrease in the extent of ice and snow cover, and the rise of temperature in the lowest eight kilometers of the atmosphere during the past four decades [23,24].

Climate change also potentially leads to an increase in precipitation that will contribute to floods [25]. An increase in precipitation will also cause an increase in soil moisture resulting in slope instability and landslides [26].

The Transportation Research Board (TRB) issued Special Report 290 which stated that climate change will have significant impacts on how the transportation professionals will plan, design, construct, operate and maintain infrastructure in general. Subsequently, it lists the five major impacts of climate changes on transportation, namely, the increase of very hot days and heat waves, the increase of Arctic temperatures, the sea level rise, the increase in intense precipitation events, and the increase in hurricane intensity. Based on this list, potentially the greatest impacts of climate change on North America's transportation system are identified as flooding of coastal roads, railways, transit systems and runways as a result of global sea level rise, coupled with storm surges and exacerbated in some locations by land subsidence [27].

In association with the impact of climate change on transportation at the regional level, the United States' Gulf Coast identified the four key "climate drivers" in the Gulf region, namely, rising temperatures, changing precipitation patterns, rising sea levels and increasing storm intensity. The findings of the study showed that the highways, pipelines, ports, rail lines and airports at the study site will suffer severe damages when extreme climate changes at regional level occur [28].

Climate change is already having an influence on UK highways, for examples drier summers causing more incidences of subsidence in South East England and wetter winters creating a greater frequency of flooding. There are also less obvious effects on pavement deterioration with increased average temperatures and changes in rainfall patterns. Nevertheless, the impacts of climate change are not experienced uniformly across the UK. In the South East of England, high summer temperatures and drought are the major concerns, while in Scotland, intense rainfall and storms have more impacts [8].

3. The impacts of climate change on pavement damage

3.1. Environmental impacts on pavement performance

Environmental conditions (weather and climate) have a significant impact on pavement design and performance. Environmental conditions combined with factors such as traffic-related loads, construction methods, constituent layer materials and maintenance and rehabilitation regimens, are the key variables in the assessment of pavement performance [29]. The interaction between those variables and their effects on pavement performance are shown in Figure 1.

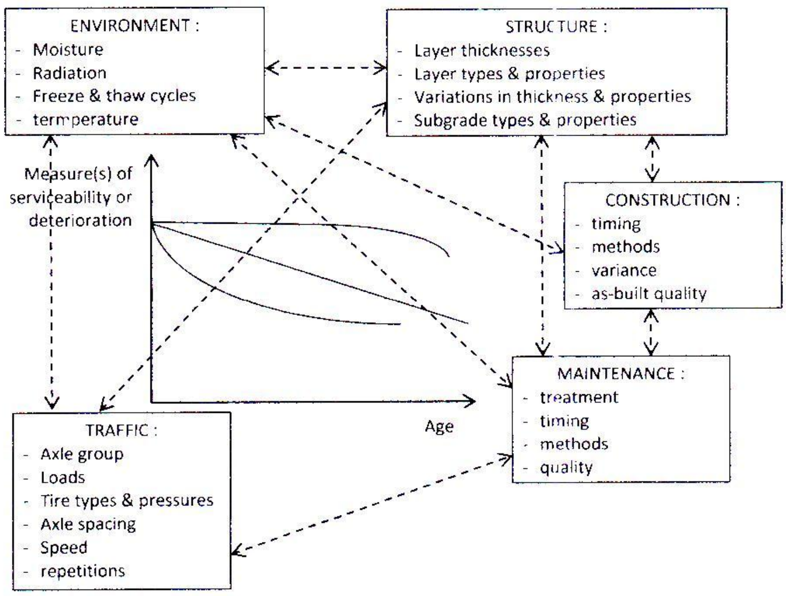

Figure 1. Factors affecting road performance [29].

3.2. Overview of the Impact of Climate Change on Pavement Damage

Climate change is a phenomenon which cannot be avoided. There are three main factors of climate change that influence the infrastructure of road transportation, namely: the increase of temperature, the increase of rainfall, and the rise of sea level [3].

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3.2.1. The Increase in Temperature. The increase in temperature is potential to cause the road pavement construction damage. The temperature will cause the material of road pavement to expand at a very high temperature and to shrink at low temperature. This change leads to the susceptibility of the road from fatigue, which eventually causes the pavement layer to become peeled off, thinner, broken, cracked, bulging, perforated, and the aggregate material to become scrapped off easily. Further evidence from the study at 17 sites located in Southern Canada indicated that permanent rutting on asphalt roads, longitudinal cracking, and alligator issues would be exacerbated by climate change with transverse cracking becoming less of a problem [7].

3.2.2. The Increase of Rainfall. The trend of increased duration and intensity of rainfall will influence the stability of road construction. Several results from previous researches show that rainfall is potential to cause the road infrastructure damage. Soil erosion caused by rain run-off often happens, on the main roads and as a consequence, they cannot function appropriately. Furthermore, additional rainfall resulting in flooding and lane closures is also a potential engineering vulnerability [5].

3.2.3. The Rise of Sea Level. The rise of the seawater causes a tide. This tide can damage road which is near the coast and damage the existing road infrastructure. The road construction which is submerged in water will weaken due to the impact of water, which causes the decrease of bound between aggregate and asphalt and thus hinders the road construction process.

The report "The Changing Climate: Impact on the Department for Transport" stated the key implications of climate change for highway maintenance, which were identified as increased risk of flooding from rivers, sea, and inadequate drainage; deterioration and damage to highway structures from subsidence, heave and high temperatures; and increased road safety problems as a result of adverse driving conditions and deterioration of infrastructure [4]. Subsequently, the London Climate Change Partnership listed potential impacts caused by climate change, including carriageway rutting, embankment subsidence, deterioration of concrete, the problem with expansion joints and reduction in skid resistance [6].

Several recommendations related to climate change are provided to minimize pavement damage in the UK, that are: to undertake a risk assessment of the effects of climate change on structures, drainage and highway management; to prioritize development of guidance for highway authorities into managing the risks of climate change; and to encourage the asphalt industry to develop solutions to the problem caused by climate change [8]. All pavement types are susceptible to deterioration given a potential change in climate occurs [9][20]. From distresses at the surface to collapse of constituent layers, pavements are likely to undergo drastic deformation should they experience extremes in weather or climate. Flexible pavements under the same conditions are affected by bleeding, weathering, bumps, rutting, depressions, potholes, longitudinal and transverse cracking [11].

The research of road damage in Pacitan district, East Java also shows that climate changes (temperature, rainfall, humidity) have impacts on road damage. The data were taken by collecting data on temperature, rainfall, humidity, and road damage from 2002 to 2011 [12].

4. The design of flexible pavement thickness

The design of flexible pavement thickness can apply three approaches, namely the mechanistic approach, empirical approach and mechanistic-empirical (ME) approach [15][16][17][18]. An empirical approach is an approach based on the testing/trial or repeated experiences. Empirical equity is employed to connect the phenomenon being observed (pavement characteristics) and the output (pavement performance). Mechanistic approach is the approach which explains material phenomena (stress, strain) only refers to physical causes (traffic loading and environmental conditions). The relationship between phenomena and physical causes is explained by using mathematics model. Mechanistic-Empirical (ME) pavement design is a method that combines mechanistic models by observing the primary response of pavement in terms of stresses, strains, and displacement and empirical models, and then relating the generated response with pavement performance.

In Indonesia, the empirical method generally used to design flexible pavement thickness is SNI 1732-1989-F Method (Component Analysis Method). This method is based on AASHTO 1972. The modification has been done to adapt it to the condition of nature, environment, the basic nature of the soil, and the types of pavement layer in Indonesia. Then this method is revised as Design Manual of Flexible Pavement Thickness Pt T-01-2002-B follows AASHTO 1993. Only national and arterial roads which are designed based on mechanistic-empiric pavement design method, namely Design Manual of Road Pavement 02/M/BM/2013.

The California Department of Transportation (Caltrans) has changed the implementation of an empirical method to Mechanistic-Empirical (ME) Pavement Design Method. In 2005, Caltrans approved the adoption of Mechanistic-Empirical (ME) Pavement Design Method, an issue memorandum that calls for ME pavement design methodology to replace the existing empirical methods. There are many issues of importance to Caltrans and local governments that empirical methods cannot adequately consider [17].

According to European Asphalt Pavement Association, nowadays there are many types of research using the mechanistic approach in the design of flexible pavement thickness [19]. One of the advantages of mechanistic approach is more efficient and reliable in the design of flexible pavement thickness and relatively accommodates climate change is compared to empirical approach [20]. In mechanistic approach, modulus of elasticity of each layer will vary according to the climatic conditions. The subgrade and aggregate base modulus will change in accordance with moisture content and whether or not it is frozen or thawed [20]. Figure 2 shows how the layer modulus will change according to the climatic conditions.

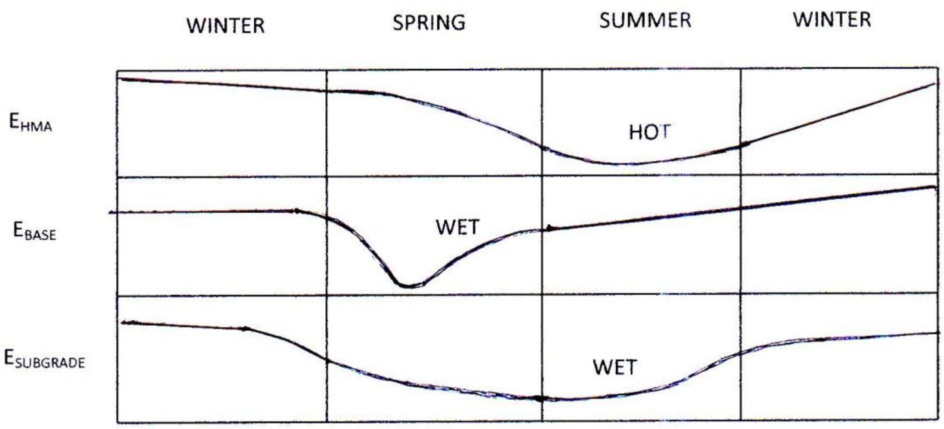

Figure 2. Modulus values changing based on climatic conditions [20].

Several researchers have applied Mechanistic-Empirical (ME) Pavement Design Method in their studies. Li *et al* (2011) used the concept of local calibration for MEPDG prediction models, a framework to incorporate the climate change effects into the mechanistic-empirical-based pavement design was developed by calibrating the coefficients performance models [30].

Federal Highway Administration reported the results of an evaluation of climate data from Modern-Era Retrospective Analysis for Research and Applications (MERRA) for further use in the Long-Term Pavement Performance (LTPP) Program and for other infrastructure applications. MERRA data were compared against the best available ground-based observations both statistically and in terms of effects on pavement performance as predicted using the Mechanistic-Empirical Pavement Design Guide (MEPDG). These analyses included a systematic quantitative evaluation of the sensitivity of MEPDG performance predictions to variations in fundamental climate parameters [31].

The most critical input parameters in terms of their effects on pavements damage and their influence on the determined number of corrective maintenance cycles to be performed during the design life of pavements using Empirical-Mechanistic Pavement Design Guide (MEPDG) method for flexible was identified by Getso (2016). The MEPDG method is used because it is the most comprehensive method that incorporates the effects of both truckloads and climate. The results showed that for flexible pavements, obtaining average monthly temperatures is critical because of the large effect temperatures have on the number of corrective maintenance cycles [32].

5. Conclusion

Nowadays, the current researchers on the design of flexible pavement thickness had already employed the mechanical approach. Previous studies also reported the advantages of mechanistic approach or mechanistic-empirical (ME) approach as well as its higher efficiency and reliability in the design of flexible pavement thickness. In addition, it relatively accommodates the impact of climate change in compared to the empirical approach. However, the design of flexible pavement thickness in Indonesia rarely applies this approach, instead, it is generally constructed based on the empirical approach. Therefore, a discourse on the importance of the shifting towards the using of mechanistic approach is required.

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