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New method for making and selecting the compaction plan of asphalt pavement based on compaction quality and carbon emissions

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ABSTRACT

Road construction projects should attempt to reduce their large amounts of carbon emissions. The objective of this research was to develop a new method for making and selecting the compaction plan of asphalt pavement based on the compaction quality and the amount of carbon emissions. To achieve this objective, new models for the distribution of rolling sections and the corresponding operation time have been proposed in accordance with Chinese standards and engineering experience. The rolling resistance coefficient of the rollers and the energy utilization coefficient were used to quantify the compaction energy. A new model for determining the number of roller passes was established based on the energy balance between laboratory tests and on-site compaction. The feasibility of the designed compaction plan was verified through actual construction. For the new models, the predicted results are in good agreement with the observations. Additionally, for the intermediate rolling phase of a specific project, results indicate that the calculated rolling resistance coefficient of a pneumatic tire roller was approximately 0.09.

1. Introduction

Based on the increasing amount of attention being paid to sustainable development, global climate change caused by concentrations of greenhouse gases (GHGs) appears to be one of the most urgent environmental issues for human development. Among the GHGs, carbon dioxide (CO_2) is the most significant. Unfortunately, the transport sector alone accounts for 23% (globally) of energy-related CO_2 emissions (ITF, 2010). To better mitigate global climate change, a reduction of the carbon emissions in the transport sector should be given more attention (Barandica et al., 2013). Previous studies indicate that asphalt pavement construction consumes large amounts of energy and releases a great deal of GHGs through the production of raw materials, the mixing of asphalt mixtures, the transport of raw materials and asphalt mixtures, paving, and compaction (Anthonissen et al., 2015; del Carmen Rubio et al., 2013). Estimation of carbon emission from the road construction process and the development of appropriate strategies are useful factors in minimizing carbon emissions.

In recent times, significant focus has been given to the quantification of carbon emissions associated with asphalt pavement construction, which is the basis of evaluating carbon emission levels and taking appropriate measures to reduce carbon emissions (Liu et al., 2017; Wang et al., 2015). Carbon emissions from asphalt pavement construction are mainly quantified using carbon emission estimation tools (Melanta et al., 2012), carbon emission factors (Lin, 2014), quotas (Yang, 2012), or other quantitative methods (Frey et al., 2010; Heidari and Marr, 2015). Strategies to reduce carbon emissions from the mixing of asphalt mixtures (Ge et al., 2015), the transport of raw materials and asphalt mixtures (Artenian et al., 2010), and paving (Ge et al., 2015) have been developed. However, relatively little attention has been paid to estimating carbon emissions from the compaction of asphalt pavement. The compaction process requires a sufficient number of rollers (NONROAD vehicles) (USEPA, 2015), which are the main sources of carbon emissions in this area. Road authorities and construction companies apply different compaction techniques across the globe (Zhang, 2014). Carbon emissions of these compaction methods are different and need proper assessment to meet the growing concerns and regulations to minimize the carbon footprint. Although the carbon emissions of compaction account for approximately 1% of the total construction emissions, quantitatively the compaction process accounts for 2783 kg/km of carbon

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emission for a high-speed highway (Kim et al., 2011; Lin, 2014). Consequently, it is important to investigate the estimated carbon emissions of compaction plans for minimizing carbon emissions while attaining a satisfactory level of compaction.

In the United States, the carbon emissions of NONROAD vehicles can be estimated based on the emissions factors from NONROAD model (USEPA, 2009) and the duration of the activities (Arocho et al., 2014). Regardless of the planning, design, or construction stage, the number of operating hours can be predicted through a database, such as the RS Means Cost Works estimation tool (Arocho et al., 2014). However, this method for estimating the duration of operation is lack of pertinence because the duration of operation changes with time, space, types of NONROAD vehicles used, and other influential factors. Existing research has shown that there are some differences between the measured emission rates and the emission rates predicted using NONROAD (USEPA, 2009), OFFROAD (CARB, 2010), or a modal statistical model (Lewis, 2009).

The Chinese standards of JTG/T B06-2-2007 (2007) and JTG/T B06-3-2007 (2007) are commonly used to quantify the fuel use of road rollers based on the volume of a compacted asphalt mixture in China (Yang, 2012). The carbon emission factors are then multiplied with the fuel use of the construction equipment to obtain the total emissions. However, this method likely enlarges the error between the fuel use as predicted by the Chinese standards and the actual amount of fuel consumed for a specific project due to its lack of pertinence. A new carbon emission prediction model needs to be developed to estimate the carbon emission of the compaction process.

The objective of this study was to estimate the number of roller passes and the carbon emissions of the compaction process of asphalt pavement for selecting the optimal compaction plan in terms of compaction quality and carbon emissions. In this study, new models of distribution of the rolling sections and the corresponding operation time were established in accordance with the Chinese standard of JTG F40-2004 (2004). A new method for determining the number of roller passes was developed from the viewpoint of energy balance. The quantification of carbon emissions for a compaction plan was demonstrated based on a case study.

2. Prediction model for carbon emissions of compaction

Several models used to quantify the carbon emissions of compaction were identified and summarized from the articles listed in Table 1. As Table 1 indicates, models 1, 2, and 3 were not suitable for quantifying the carbon emissions of Chinese highway construction because the model data are not based on Chinese highway construction conditions. For the model 1, the compaction plan was provided by the contractor. The carbon emissions were calculated based on the United States Environmental Protection Agency (USEPA) model data, which should be verified or calibrated before they are used for Chinese highway construction. For the model 2, the operation time of rollers was predicted according to the RS Means model, which is based on local conditions (RS Means, 2017). For the model 3, the working hours of rollers were estimated according to the total quantity for rolling and the quantity per unit time of rollers. The production efficiency of rollers is derived from the national standard estimating reference published by the KICT (2010). Clearly, the production efficiency of rollers changes with varying countries. The model 4 is lack of pertinence because the model data represent the average level of road constructions in China. The model 5 cannot be used for predicting carbon emissions before compaction. This is because the data are from the completed road projects. In this study, a new prediction model of carbon emissions from the compaction process was established.

2.1. Operation time

Based on JTG F40-2004 (2004), Bi and Fu (2009) proposed a model for the distribution of the rolling section. However, the movement track of the rollers and the calculation model of the operation time were not provided. Few studies (Arocho et al., 2014; JTG/T B06-2-2007, 2007; Zhang, 2014) have investigated the operation time of rollers used in pavement construction. For the initial, intermediate, and finish rolling, Zhang (2014) developed a model for calculating the operation time, as shown in Fig. 1. The operation time can be quantified using Eqs. (1)–(7).

$$C = V_P / V_R \tag{1}$$

$$l_1 = l \tag{2}$$

$$l_2 = l_{CD} = l + l_{CJ} = l + l_{MD} = l + \frac{l_{BI}}{V_R} V_P + \frac{l + (l_{BI}/V_R)V_P}{V_R} V_P = \left(C^2 + 2C + 1\right) l \tag{3}$$

$$l_3 = l_{EF} = l + l_{EK} = l + l_{NF} = l + \frac{l_{DJ}}{V_R} V_P + \frac{l + (l_{DJ}/V_R)V_P}{V_R} V_P = \left(C^2 + 2C + 1\right) l \tag{4}$$

$$l_m = \left(C^2 + 2C + 1\right) l \tag{5}$$

$$\Delta t = t_a + t_b + t_c + t_d + t_e + t_f + t_g = 5 + 1.8 + 3.2 + 5 + 1.8 + 3.2 + 5 = 25(\mathrm{s}) \tag{6}$$

Table 1
Summary of models used for predicting the carbon emissions of compaction.

Model	Data source	Predicting carbon emissions before compaction	Applicability	Pertinence
1 Avetisyan et al. (2012)	Contractor and USEPA	Yes	United States of America	A specific project
2 Arocho et al. (2014)	RS Means data and USEPA	Yes	United States of America	All road projects
3 Kim et al. (2011)	Korea Institute of Construction Technology, design documents, and field construction conditions	Yes	Republic of Korea	A specific project
4 Yang (2012)	JTG/T B06-2-2007 (2007) and JTG/T B06-3-2007 (2007)	Yes	People's Republic of China	All road projects
5 Wang et al. (2015)	Field construction data and Luo et al. (2011)	No	People's Republic of China	A specific project