Effects of Tire Pressures and Test Temperatures on Permanent Deformation of Direct Coal Liquefaction Residue Mixture

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The main objective of this research is to investigate the permanent deformation of asphalt mixtures containing direct coal liquefaction residue (DCLR) under various tire pressures and temperatures. Three types of asphalt mixtures, including control/DCLR/composite-DCLR modified asphalt mixture, were prepared by the Marshall design method. The rutting test was conducted under a tire pressure range of 0.7–1.0 MPa with a 0.1-MPa interval and at a temperature range of 55–70°C with a 5°C interval. Moreover, the dynamic stability and rutting depth of three asphalt mixtures were obtained to evaluate their resistance of permanent deformation. It was found that the rutting resistance of three asphalt mixtures declines with the increased tire pressures and temperatures. The asphalt mixture containing DCLR has a higher dynamic stability and lower rutting depth compared to the control asphalt mixture under the same conditions. Furthermore, the rutting resistance of composite-DCLR modified asphalt mixture is better than that of DCLR modified asphalt mixture. It indicates that the composite-DCLR is favorable for the improvement of rutting resistance of asphalt mixture. Moreover, the analysis of variance was applied, which analysis results showed that the rutting resistance of asphalt mixture is more sensitive to temperature than tire pressure. Based on the least-squares procedure, the relationship between dynamic stability and rutting depth was obtained, and the accuracy of the prediction is acceptable.

Keywords: direct coal liquefaction residue, tire pressure and temperature, permanent deformation, analysis of variance, regression model

INTRODUCTION

Direct coal liquefaction residue (DCLR), the main by-product from the direct liquefaction process of coal, contains 30% by weight raw coal. It has been found that the DCLR accounts for 30–50% asphaltene materials and heavy oil, which has been considered as a construction material. Based on its performance characteristics, such as high softening point and asphaltene percentage, DCLR has been utilized to modify virgin asphalt binder to improve its high-temperature performance and has the potential to apply as an asphalt modifier (Shu, 2003; Gu, 2012). Because the properties and

component of DCLR are similar to Trinidad Lake Asphalt (TLA), it can potentially be a substitution of TLA (He, 2013; Zhao, 2015). Ji et al. (2014), Ji J. et al. (2015) studied the properties of asphalt binders containing DCLR and found that the DCLR additives improve the high-temperature properties but lower the low-temperature properties of asphalt binders. Meanwhile, the performance of DCLR modified asphalt mixture was studied. The results illustrated that the addition of DCLR into virgin asphalt binder could be a powerful approach to enhance the rutting resistance of asphalt mixture. The rutting resistance and moisture susceptibility of DCLR and composite-DCLR modified asphalt mixture are even better than those of asphalt mixture modified by styrene–butadiene–styrene (SBS) (Moghaddam et al., 2011; Zhao and Ji, 2014).

As one of main pavement distresses, the rutting often leads to the large-scale maintenance, as a result of bringing high economic consumption (Ma et al., 2017; Zhang et al., 2019). Therefore, the research on rutting of asphalt mixture is necessary and imminent. The performance of pavement is affected by many factors, such as tire pressure, materials, layer thickness, and environmental conditions (Saevarsdottir and Erlingsson, 2015; Ding and Zhao, 2019). High temperature and slow-speed vehicle are more likely to cause the rutting of pavement (Moghaddam et al., 2011, 2014; Al-Humeidawi, 2016). In most areas of China, the air temperature can reach 40°C in summer, and the actual road surface temperature can even reach up to 70°C, which dramatically increases the probability of rutting. Khan et al. (2013) predicted the rutting of the pavement by the accelerated test and found that the rutting potential is sensitive to repeated loads and high temperatures. The correlation equation relating to the progression of rutting depth versus number of passes was established (Chen et al., 2020).

The relationship on pavement strains between tire pressure and speed of loading was investigated by Chatti et al. (1996). They pointed out that at the bottom of the layer the horizontal strains increased with the tire pressure increases. The parameters of the temperature and loading were used as the major factors to predict the asphalt mixture permanent deformation (Ji X. P. et al., 2015). Alkhateeb et al. (2011) found that the rutting depth increased with the increase in temperature and tire pressure and with the decrease in subgrade strength by the finite element models. Park (2006) used a triaxial repetitive load test to obtain temperature conversion factor (TCF) parameters and revealed the variation in pavement temperature during full-scale trafficking. The test results showed that TCF could convert the traffic loading at multiple temperatures to its equivalent traffic at a specification temperature. Abed and Al-Azzawi (2012) noted that because of the change of material properties, the rutting depth increased in the leveling and base courses, but the stress level decreased in those layers. Salama and Chatti (2008) investigated the relative rutting damage of different axle types and truck configurations to the hot asphalt mixture. The trucks with wide single-wheel axles increase causing the pavement sensitive to the surface layers' creep, and wide single axles are more combative than dual wheels. Corte et al. (1994) and Attia and Ahmed (2014) studied the impact of tire pressure on overlay performance by the mechanistic-empirical pavement design method. It was noted that the tire pressure plays a serious role on the longitudinal cracks, fatigue cracks, and asphalt pavement rutting and has no significant effect on rutting in base and subgrade layers.

From previous studies, it was summarized that the different axle loading and test temperature have various influences on the rutting resistance of HMA, but few studies were engaged in the permanent deformation of DCLR modified asphalt mixtures. As the DCLR is a relatively new and intricate material, the influence of tire pressures and temperatures on the permanent deformation of DCLR asphalt mixtures is worth being studied. The motivation of this study is to validate the possibility of using DCLR in the highway constructions and to evaluate the high-temperature performance of DCLR modified asphalt mixtures. It is of great scientific significance for the development and application of new environmental-friendly materials in pavement engineering.

OBJECTIVES AND SCOPES

The main purpose of this research is to evaluate the permanent deformation of DCLR and composite-DCLR modified asphalt mixtures under various tire pressures and temperatures. The following tasks were listed for analysis:

- The three kinds of asphalt mixtures are the control asphalt mixtures, DCLR modified asphalt mixture, and composite-DCLR modified asphalt mixture. It is noted that three asphalt mixtures have the equal gradation and optimum asphalt content (OAC).
- Permanent deformation of three kinds of asphalt mixtures was evaluated using the rutting test under multiple tire pressures varying from 0.7 to 1.0 MPa with a 0.1-MPa interval and at temperatures ranging from 55 to 70°C with a 5°C interval.
- The permanent deformations of three kinds of asphalt mixtures related to different tire pressures and test temperatures were explored through the statistical analysis.

Materials
Asphalt Binders
Virgin asphalt binder was produced in South Korea with 80/100 penetration. Two types of modified asphalt binders were prepared through adding DCLR and composite-DCLR into the base asphalt binder. The specific preparation processes of DCLR modified asphalt and composite-DCLR modified asphalt were determined based on experimental experience and previous studies in the research group (Ji et al., 2019, 2020), shown in **Figures 1**, **2**, respectively.
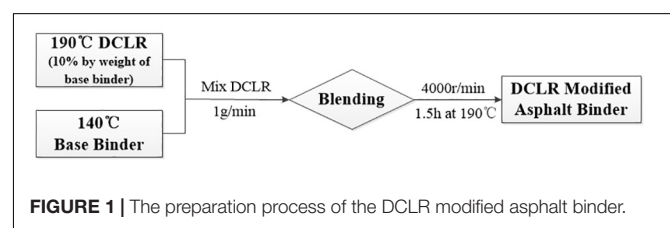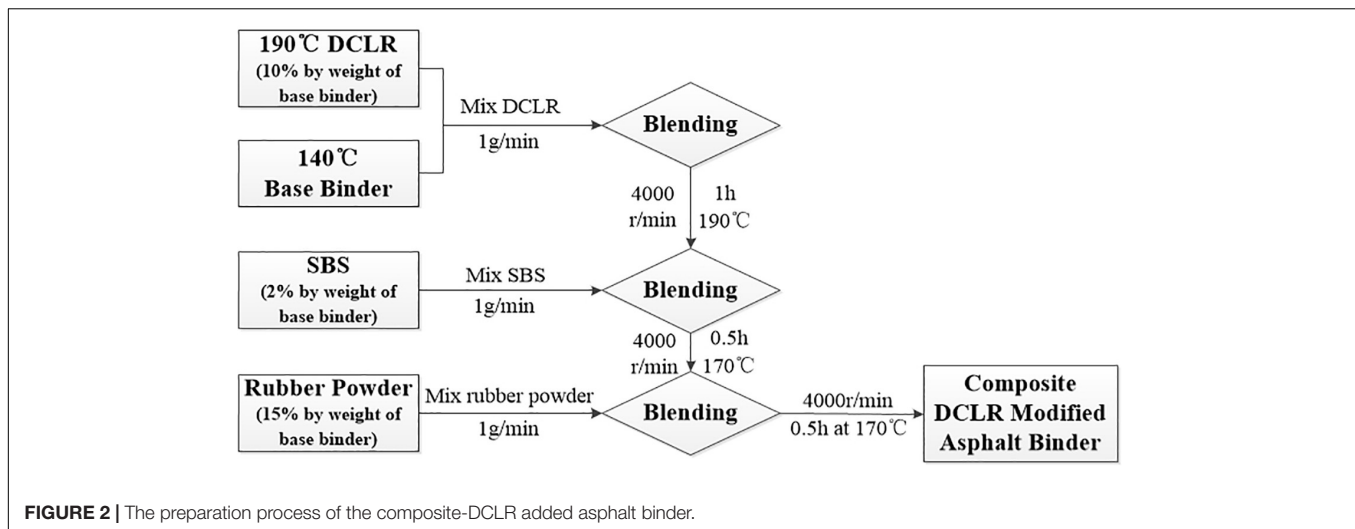

FIGURE 1 | The preparation process of the DCLR modified asphalt binder.

FIGURE 2 | The preparation process of the composite-DCLR added asphalt binder.

TABLE 1 | G*/sinδ of three asphalt binders.

Temperature (°C)	Unaged stage					RTFO stage					PG grade
	58	64	70	76	82	58	64	70	76	82	
Base asphalt binder	2.18	0.96	0.45	0.23	–	4.62	1.97	0.91	0.45	–	58
DCLR modified asphalt binder	6.56	2.75	1.24	0.61	–	21.67	8.86	3.82	1.73	–	70
Composite-DCLR modified asphalt binder	37.31	20.24	11.09	6.39	3.86	49.44	27.13	15.82	7.54	4.54	82
Specification	≥1.0					≥2.2					

RTFO, Rolling Thin-Film Oven.

TABLE 2 | Stiffness and *m*-value of three asphalt binders.

Temperature (°C)	Stiffness (MPa)			*m*-Value			PG
	−6	−12	−18	−6	−12	−18	
Base asphalt binder	49.631	134.026	226.225	0.442	0.361	0.282	−22
DCLR modified asphalt binder	86.083	220.909	–	0.337	0.275	–	−16
Composite-DCLR modified asphalt binder	−S(MPa)	81.518	164.386	–	0.337	0.312	−28
Specification	<300.0			≥ 0.3			

According to the Superpave performance grade (PG) specifications, the physical properties of the three kinds of asphalt binders were measured and are shown in **Tables 1**, **2**.

Aggregates

Limestone was chosen as an aggregate material, and it includes coarse aggregates with the size of 9.5–19.0 mm, 4.75–9.5 mm, 2.36–4.75 mm, and fine aggregates with the size of 0–2.36 mm. The powder left from the limestone was recycled as the mineral powder. The physical properties of the aggregates were measured according to the "Test Methods of Aggregate for Highway Engineering" (JTG E42-2005, 2005), and the results meet the specification requirement in China.

Mixture Design

The type of the mixture was a recommended AC-20, which is popularly used in China. Its gradation is shown in **Figure 3** and met the technical requirements specified in China. The target air void of all specimens was 4 ± 1.0%. The OAC of the mixture was determined in accordance with the ASTM D1559, and the OAC was 4.2%.

The performances of the mixture also meet the technical requirements specified in China. In order to indicate the effect of three asphalts on the permanent deformation of three mixtures, the same gradation and OAC were used. The other testing conditions are the same as that of the control mixture. The performances of the three asphalt mixtures are shown in **Figure 4**.

Test Methods
Test Conditions

Three types of asphalt mixtures, the control asphalt mixture, DCLR modified asphalt mixture, and composite-DCLR modified asphalt mixture, were prepared for the rutting test. During the test, the test temperatures were selected to be from 55 to 70°C
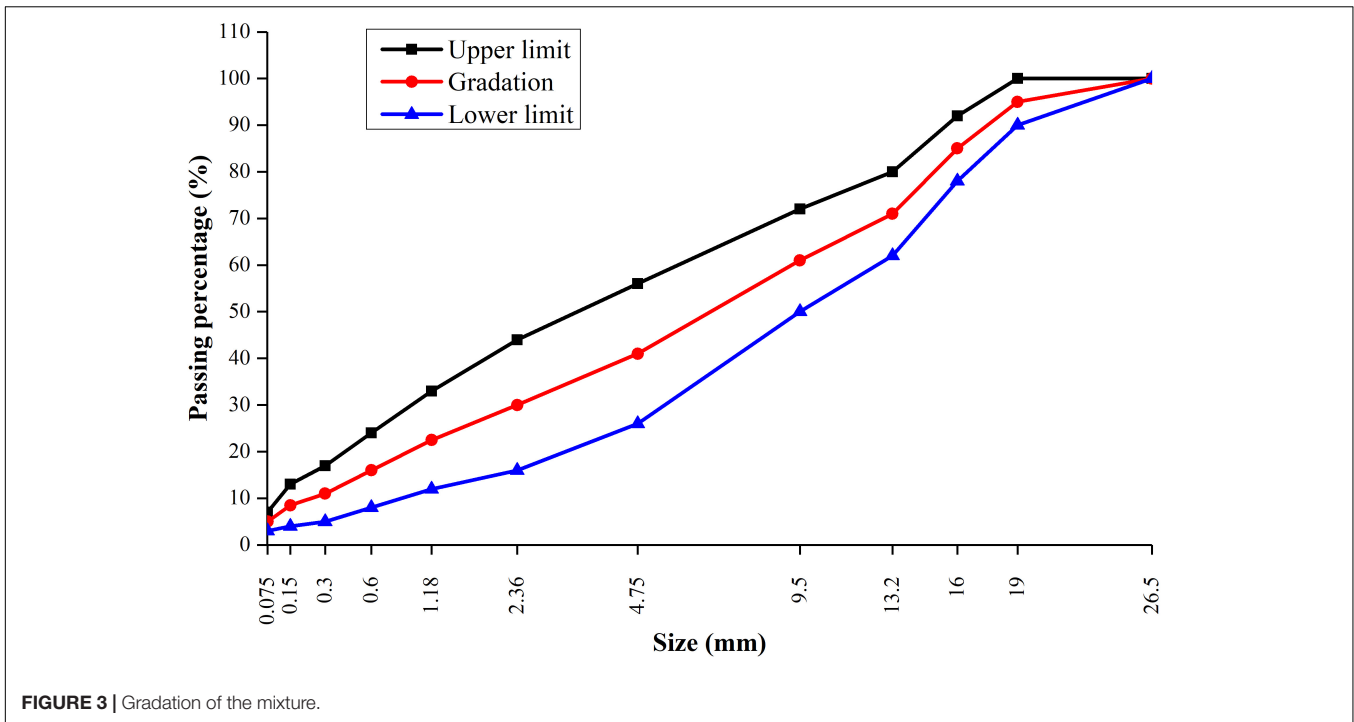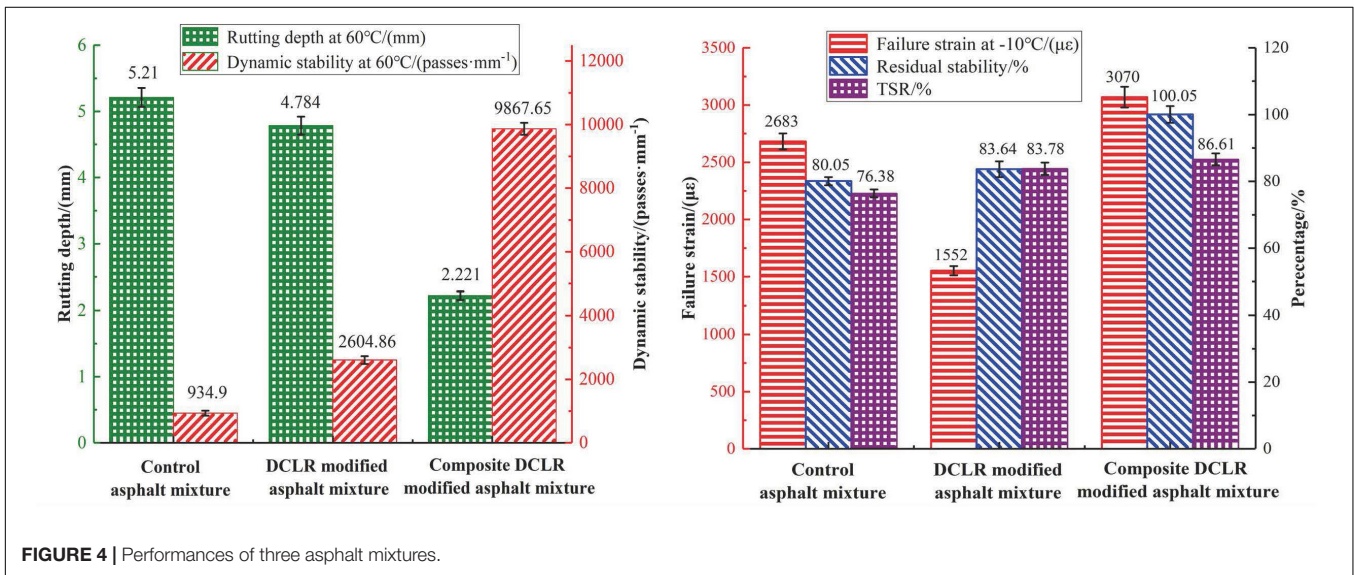
FIGURE 3 | Gradation of the mixture.

FIGURE 4 | Performances of three asphalt mixtures.

with a 5°C interval. And the tire pressures were determined to be from 0.7 to 1.0 MPa with a 0.1-MPa interval. The increase in tire pressure would be caused by the increased axle loading of vehicles. With the tire pressure increases, the contact area of the tire pavement is induced to a reduction. It may prompt an increase in tire-pavement contact stress, which deteriorates the pavement service conditions (Jamy and Najeeb, 1991; ASTM D1559, 2006; Wang and Machemehl, 2006; Abdel-Motaleb, 2007; Homsi et al., 2011). In China, the standard axle loading is specified as a single axle with the dual tires at 100 kN, and the standard tire pressure is 0.7 MPa. However, several surveys conducted in China revealed

the traffic volumes of trucks and their tire pressures had increased steadily in the last several decades. The truck axle loading was always larger than 100 kN, and tire pressure was higher than 0.7 MPa. Therefore, in this study, a tire pressure range of 0.7–1.0 MPa with a 0.1-MPa interval was selected in order to simulate the impact of high tire pressure on the pavement response. Additionally, the standard test temperature is 60°C during the process of the rutting test in China. However, the actual pavement temperature in summer months is also far higher than 60°C. Sometimes, the actual pavement temperature can achieve a peak at 70°C. In this study, to simulate the impact of temperature on pavement response, the
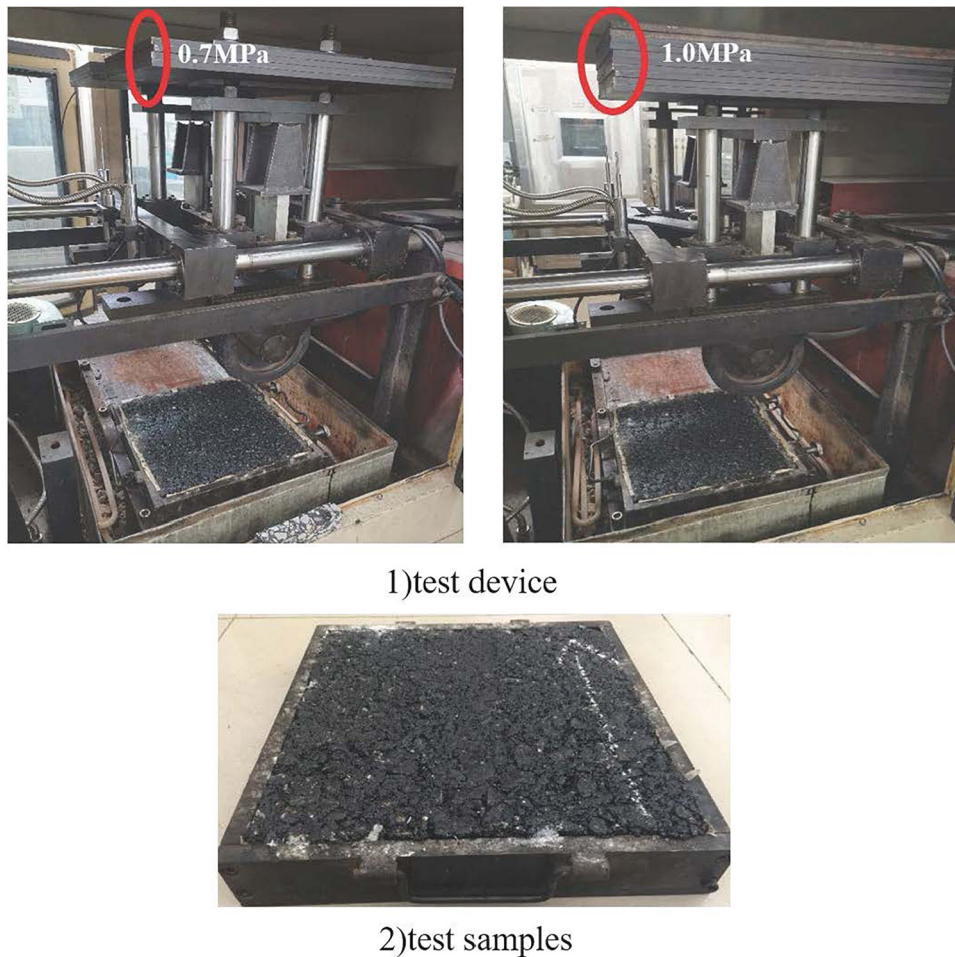
1)test device

2)test samples

FIGURE 5 | Test device and samples.

test temperature range was selected to be from 55 to 70°C with a 5°C interval.

Specimen Preparation

At least three specimens, with each sample the length is 300 mm, the width is 300 mm, and the depth is 50 mm, were tested to measure their resistance to rutting. Before testing, the specimens of the control mixture were cured at the room temperature for 12 h, and the specimens of the DCLR and composite-DCLR modified asphalt mixtures were cooled at room temperature for 48 h, as required by the China Specification "Test Methods of Asphalt and Asphalt Mixtures for Highway Engineering" (JTGE20-2011).

Rutting Test

As reported by Test Methods of Asphalt and Asphalt Mixtures for Highway Engineering (JTGE20-2011), the standard experiment was supervised to apply a smooth rubber wheel load of 0.7 MPa on each wheel traveling at a speed of 42 ± 1 passes/min on specimens at 60°C. The test device and samples are shown in **Figure 5**.

The two indexes of dynamic stability and rutting depth were obtained for three asphalt mixtures. The dynamic stability refers to the passes of each 1-mm deformation between 45 and 60 min, and the rutting depth reflects the total deformation during the 60 min in the test. High dynamic stability and low rutting depth indicates a stiff mixture, which is likely to be less sensitive to the temperature and loads.

RESULTS AND DISCUSSION

Properties of Three Asphalt Binders and Mixtures

The high-temperature PG (AASHTO T 315, 2012) and low-temperature PG (AASHTO T 313, 2012) of the asphalt binders were measured. The physical properties of three kinds of asphalt binders are presented in **Tables 1**, **2**. The performances of the three asphalt mixtures are shown in **Figure 5**.

The test outcomes in **Tables 1**, **2** demonstrated that the composite-DCLR added asphalt binder has the highest high-temperature PG value and lowest low-temperature PG value.

It indicated that the composite-DCLR significantly improved the high-temperature and low-temperature properties. From **Figure 5**, it is seen that the DCLR increased the dynamic stability, residual stability, and TSR of asphalt mixture while decreasing its rutting depth. This demonstrated that the addition of DCLR contributes to the improvement of high-temperature performance and moisture susceptibility of asphalt mixture. However, the DCLR decreased the low-temperature performance of asphalt mixture to some extent, which can be reflected by the test results of failure strain at $-10°C$. This is the main reason why the composite-DCLR was used and investigated in this study. The composite-DCLR significantly improved the high-temperature performance and low-temperature performance of asphalt mixture. The reason may be that the composite-DCLR, which includes SBS and rubber powder, increases the bonding strength with the matrix of the asphalt binders and reinforces the network of modified asphalt binders. This possible effect causes the asphalt binder stiffer and leads to an improvement of properties of asphalt binder and mixture, especially for the high-temperature performance (Ji et al., 2017).
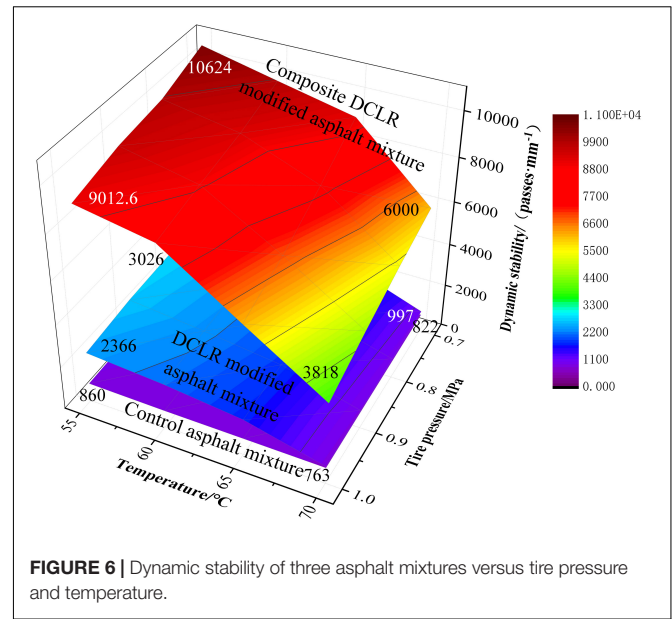
Rutting Resistance of Three Mixtures

The permanent deformation of three asphalt mixtures was conducted using the rutting test under a test temperature range from 55 to 70°C with a 5°C interval and at a tire pressure range from 0.7 to 1.0 MPa with a 0.1-MPa interval. The rutting resistance of three asphalt mixtures was characterized in terms of the rutting depths and dynamic stabilities. The results are shown in **Figures 6**, **7**.

In **Figure 6**, the dynamic stabilities of asphalt mixtures decrease with the increase in tire pressures and test temperatures, but the change amplitudes are different. The rise in tire pressure and test temperature led to a degeneration in dynamic stability and a deterioration in rutting potential. Moreover, when the tire pressure increased from 0.7 to 1.0 MPa under 55–70°C, the dynamic stabilities of asphalt mixtures decreased by 12.3, 25.0, and 20.6%, respectively. Furthermore, when test temperature increased from 55 to 70°C under the condition of 0.7- to 1.0-MPa tire pressures, the dynamic stabilities of asphalt mixtures decreased by 16.2, 66.4, and 49.6%, respectively. It can be deduced that the temperature has a more positive effect than the tire pressure on the permanent deformation. Although the dynamic stabilities of the DCLR modified asphalt mixture and composite-DCLR modified asphalt mixture decreased at a high rate, which were still higher compared with the control asphalt mixture. The DCLR and composite-DCLR had significant effects on the advancement of the rutting resistance. The composite-DCLR
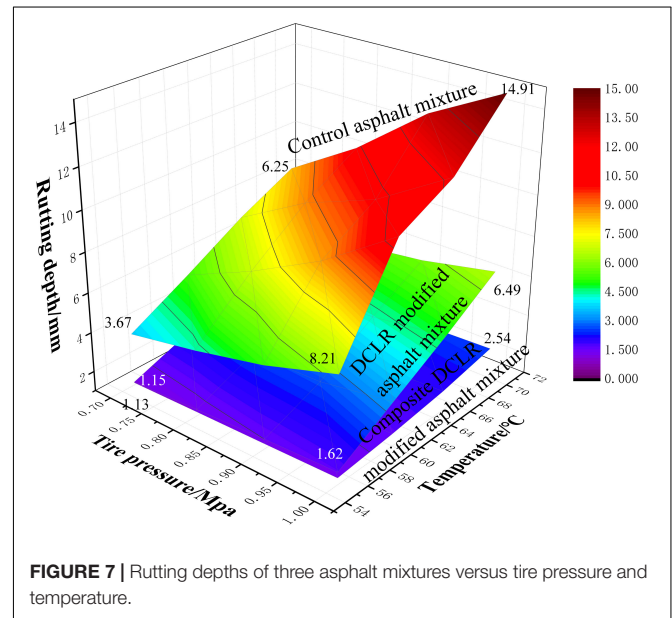

FIGURE 6 | Dynamic stability of three asphalt mixtures versus tire pressure and temperature.

FIGURE 7 | Rutting depths of three asphalt mixtures versus tire pressure and temperature.

mixture had the highest dynamic stability compared to the other two asphalt mixtures under identical tire pressures and test temperatures, which indicated that the composite-DCLR mixture has the least sensitivity to the temperature and tire pressure. The

TABLE 3 | Value range analysis of three asphalt mixtures.

Mix types	Dynamic stability/(passes mm^{-1})		Rutting depth/mm	
	Tire pressure	**Temperature**	**Tire pressure**	**Temperature**
Control mixture	115.68	155.66	5.01	6.78
DCLR mixture	471.96	1785.08	1.12	4.38
Composite-DCLR mixture	2077.54	4811.96	0.25	1.11

composite-DCLR modified asphalt mixture has higher elasticity, stiffness (Ji et al., 2016), and viscosity compared to the control asphalt mixture and DCLR modified asphalt mixture.

Figure 7 displays that the increases in test temperature and tire pressure introduce an increase in rutting depth of asphalt mixtures. An increase in tire pressures or test temperatures yielded an increase in rutting potential. When tire pressure increased from 0.7 to 1.0 MPa, the rutting depths of asphalt mixtures increased by 95.8, 34.4, and 17.9%, respectively. When the test temperature increased from 55 to 70°C, the rut depths of asphalt mixtures increased by 307, 139, and 93.1%, respectively. The influence of the test temperature on the rutting resistance of asphalt mixtures is more noticeable than that of tire pressures, and the rutting depths of control asphalt mixture decreased at the highest rate. The base asphalt binder has the lowest high-temperature properties. The composite-DCLR modified asphalt mixture had the lowest rutting depth compared to

the other two asphalt mixtures under the same tire pressures and test temperatures. The composite-DCLR modified asphalt mixture had a good resistance to rutting. As a result, it can be concluded that the composite-DCLR modified asphalt mixture is identified as a good mixture for application in pavement construction.

Analysis of Variance

Analysis of variance (ANOVA) is used for isolating the relevant factors and estimating the effects of these factors on the total deviation. In ANOVA, the F-value is defined as the ratio of the variance between treatments and variance in treatments. An enormous F-value represents more significant effects of the factor on the sample. In this article, the ANOVA was applied to detect the effects of multiple tire pressures and test temperatures on the permanent deformation of asphalt mixtures by using the ORIGIN software, and the confidence level was set as 0.95. The significant

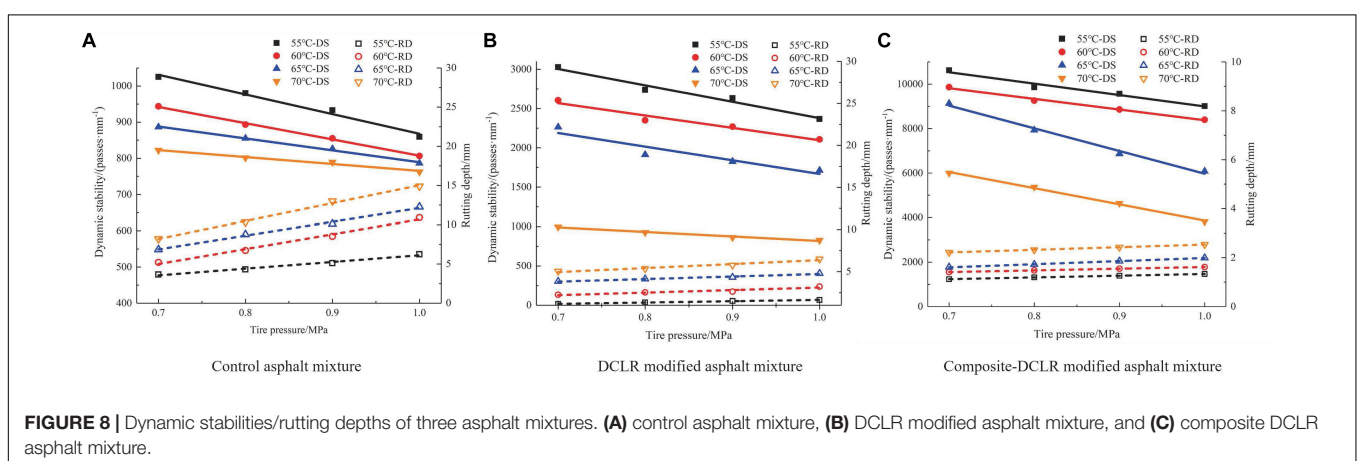**TABLE 4 |** Variance of ANOVA of three asphalt mixtures.

Mix types	Dynamic stability			Rutting depth		
	Variances	F-value	P-value	Variances	F-value	P-value
Control mixture	Tire pressure	14.5	0	Tire pressure	29.78	0
	Temperature	61.4	0	Temperature	50.81	0
DCLR mixture	Tire pressure	18.7	0	Tire pressure	17.12	0
	Temperature	288.6	0	Temperature	254.12	0
Composite-DCLR mixture	Tire pressure	28.3	0	Tire pressure	31.89	0
	Temperature	164.6	0	Temperature.	355.19	0

As stated in the China Specification JTG E20-2011 (2011), during the rutting test, two sets of samples for each mixture are needed under each temperature and tire pressure test condition, respectively. Then, the total number of samples for each mixture is 32 for predicting the rutting model and analyzing the value range and variance of ANOVA.

TABLE 5 | Regression coefficients for three asphalt mixtures.

Mix types	a_1	a_2	a_3	R^2
Control mixture	−378.73/16.94	−10.06/30.4	1815.08/−33.43	0.92/0.95
DCLR mixture	−1493.05/3.09	−115.33/0.29	10441.10/−17.15	0.91/0.99
Composite-DCLR mixture	−6856.40/0.93	−320.64/0.07	33698.70/−3.72	0.92/0.96

The left and the right number of the slant are regression coefficients used to predict dynamic stability and rut depths for the mixes, respectively.

FIGURE 8 | Dynamic stabilities/rutting depths of three asphalt mixtures. **(A)** control asphalt mixture, **(B)** DCLR modified asphalt mixture, and **(C)** composite DCLR asphalt mixture.

degree of variances can be detected using the range value in the value range analysis approach. The F-value is used to detect the significant degree of variances.

Tables 3, 4 list the range value and ANOVA of permanent deformation affected by different tire pressures and test temperatures.

According to the results of ORIGIN software, there was no interaction between temperatures and tire pressures. The test results in Tables 3, 4 illustrated that the temperature was a significant factor in the rutting resistance of asphalt mixtures. The rutting resistance of asphalt mixtures is more sensitive to temperature than tire pressure. The conclusion is coincident with the above outcomes of the rutting test.

Development of the Prediction Model for Dynamic Stability and Rutting Depths

The prediction model of rutting resistance was developed to verify the correlation between the predicted value and the measured value of dynamic stability and rutting depth under different tire pressures and temperatures. In the model, the temperatures and tire pressures were independent variables. The constitution of the model was regressed based on the least-square procedure, shown in Eq. 1.

$$R_{DS,RD}(T, P) = a_1 \cdot T + a_2 \cdot P + a_3 \tag{1}$$

where, $R_{DS,RD}(T, P)$ is the prediction results (dynamic stability and rutting depths) of mixtures; T is the temperature, °C; P is the tire pressure, MPa; a_1, a_2, and a_3 are regression coefficients.

The regression coefficients a_1, a_2, and a_3 and coefficient R^2 value for three mixtures are listed in Table 5 and Figure 8.

The coefficient R^2 value of the prediction model ranges from 0.91 to 0.99. The test results in Table 5 and Figure 8 show that the dynamic stabilities and rutting depths of three asphalt mixtures have good linear correlations with the tire pressure or test temperature. Two parameters with three coefficients were used to predict the high-temperature performance of asphalt mixtures according to the dynamic stabilities and rutting depths, and the prediction is acceptable according to the accuracy. Furthermore, the model of dynamic stability and rutting depth is fitted by the laboratory test data, and the linear model better reflects the dynamic stability and rutting change under the laboratory conditions. The future study will be extended to the real road fields. The rutting reaction of the pavement under real load and temperature will show significant non-linear characteristics, and the non-linear model for correlation analysis will be applied in the future study.

CONCLUSION

The DCLR and composite-DCLR were applied as additives to modify the virgin asphalt binder, and the corresponding preparation procedures of modified asphalt binders were illustrated. Meanwhile, the properties of modified asphalt binders were evaluated and estimated. Moreover, three asphalt mixtures, including the control mixture, DCLR modified asphalt mixture, and composite-DCLR modified asphalt mixture, were designed. The permanent deformation of asphalt mixtures under different tire pressures and test temperatures were explored. Based on the above results and analysis, the conclusions are drawn below:

- The addition of DCLR or composite-DCLR improves the resistance to permanent deformation of asphalt mixtures. The composite-DCLR modified asphalt mixture has a better resistance to rutting compared to the control asphalt mixture and DCLR modified asphalt mixture. As a result, it is recommended that the composite-DCLR modified asphalt mixture is a better mixture for roads in tropical regions, where the rutting is one of the main distresses of pavement.
- The ANOVA was adopted to evaluate the development of tire pressures and test temperatures on the permanent deformation of three asphalt mixtures. The analysis results demonstrated that the rutting resistance of asphalt mixtures is more sensitive to the temperature than the tire pressure.
- The test temperatures and tire pressures have influence on the rutting resistance of asphalt mixtures. The prediction model was established to predict the dynamic stabilities and rutting depths of the asphalt mixtures based on the least-squares procedure, and the accuracy of the prediction is acceptable. However, the further improvement of accuracy of the model and the application of more parameters in the model are worth to be studied in the future.

DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

All authors contributed to the article and approved the submitted version.

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