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Developing Resilient Modulus Model for Modified Asphalt Mixes with Crumb Rubber and Buton Natural Asphalt Based on Penetration Index and Temperature

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Abstract

Resilient modulus is used in the mechanistic analysis of pavement response under dynamic traffic loads, and the evaluation of the material quality is influenced by ambient temperature. This study aims to investigate the effect of hot mix asphalt additives on the resilient modulus (M_r) of crumb rubber (CR) and Buton natural asphalt (BNA)-modified asphalt mixes. Two different HMA additives were used to fabricate HMA specimens. The hot mix asphalt used asphalt Pen 60/70, coarse aggregates, fine aggregates, and filler obtained from the stone crusher machine. The CR is made from scrap tire rubber, in the form of a fine powder through sieve no. 30 (0.6 mm). CR-modified asphalt mixtures were obtained using the wet mixture method, with proportions of 5%, 10%, 15%, and 20% by total weight. BNA was added to the asphalt in proportions of 8%, 10%, and 12% by total weight. The resilient modulus of the specimens prepared having a 100-mm diameter and then compacted with a Marshall hammer. The test data using the indirect tensile test with the Universal Material Testing Apparatus (UMATTA) tool were recorded at temperatures of 25, 30, 35, 40 and 45 °C. The test results indicate that the levels of CR and BNA on the asphalt decreased the penetration rate, increased the bitumen softening point. The addition of the additive has improved the penetration index thus reducing the sensitivity to temperature. The model was developed by a linear relationship between log M_r and asphalt penetration index.

Keywords: Resilient Modulus, Buton Natural Asphalt, Crumb Rubber, Penetration Index.

I. INTRODUCTION

Increasing air temperatures, especially in tropical countries, can increase the temperature of the road surface. Meanwhile, an increase in traffic volume and load on vehicle wheels require asphalt mixtures that are resistant to increased temperatures and loads. Some researchers have engineered new materials from the conventional asphalt mixture by introducing additives.

Currently, the demand for good asphalt mixture performance is increasing and the need to protect ecosystems have led designers of pavement structures to develop new technologies, use new materials, improve analysis models, and improve asphalt mixture design methods for pavements. The criterion is to promote the use of available resources more rationally and consider low environmental impact techniques [1].

The use of standard materials and the use of new materials as additives to improve the performance of asphalt mixes, especially against the effects of temperature changes or other environmental changes. Two primary components exist in a road pavement: a combination of asphalt binder and aggregates as a mixture that serves to realize excellent performance. However, several other factors such as water penetration, traffic loading, poor asphalt, and aggregate binding can cause the collapse of bonds between the asphalt binder and aggregate particles [2].

The measurement of resilient modulus (M_r) of asphalt mixtures in the laboratory is typically performed by applying haversine pulses with a certain duration and rest period that cannot simulate the actual voltage pulses that occur in the field. The modeling of hot mix asphalt (HMA) as a linear viscoelastic material enables the behavior of stress strain and the modulus of HMA material resistance to be determined accurately at various temperatures and frequencies [3]. Many factors can affect the M_r of the pavement mixture when performing the M_r test using the indirect tension test setup. These include the bitumen grade, specimen thickness and diameter, nominal maximum aggregate size, temperature, the load waveforms and pulse durations applied to the specimens, and types of compaction [4].

The M_r test is used to measure the elastic properties of the asphalt mixture by calculating the stress–strain behavior of the asphalt specimens. The M_r is highly dependent ontemperature because when the softening point of the asphalt binder and the temperature increase, the M_r of the asphalt mixture decreases. The results of the M_r test provide a basic constitutive relationship between the stiffness and stress status of the pavement material to be used in the pavement design procedures and structural analysis of layered pavement systems [5]. This test is called a non- destructive test; therefore, the specimens tested with this test can be used in other tests. The M_r will be of a lower value at higher temperatures at any frequency. The M_r response varies from one frequency to another in an irregular manner, and the profile of each temperature change is sufficient from one frequency to another [6].

The values of strength and stiffness for modified bitumen are greater than those of unmodified bitumen. Similarly, the specimen of resilient modulus test made having a diameter of 100 mm and compacted with hammer, it's higher than specimens made having a diameter of 150 mm and compacted with compactors [7].

Modified asphalt mixtures can produce mixed cavities filled with additive materials such that the mixture becomes better. The effect of temperature shows that an increase in temperature will reduce asphalt viscosity; therefore, more additive materials are required to improve the asphalt mixture properties [8]. In principle, with increasing asphalt properties from conventional mixtures to modifications, an increase in M_r occurs, thus indicating that asphalt mixtures with higher asphalt content produce extra-viscous or highly viscoelastic responses [9].

The asphalt mixture modified with Buton Rock Asphalt (BRA) exhibits a much higher M_r than the unmodified asphalt mixture. The BRA-modified asphalt mixture modulus is 20% better than the unmodified asphalt mixture [10]. Other additive materials such as CR from used tires in hot asphalt mixes have become a promising technique for performance improvement in recent years. Two techniques used to add CR to bituminous mixes are wet and dry processes. From these two methods, the dry process is less popular because it produces poor results initially [11]. The wet-processed CR mixture is stronger than the dry mixture in indirect tensile strength [12].

Variant analysis indicates that among the three factors of CR type, particle size, and content, content is the primary factor that influences the performance of CR-modified asphalt, followed by the type of CR and particle size [13]. The dosage and percentage of CR used, the addition of wet and dry process-CR process to asphalt mixed with conventional asphalt increases its resistance to plastic deformation. This also increases the stiffness modulus, creep modulus, and its resistance to plastic deformation caused by vehicle traffic loads [14]. Penetration, ductility, and asphalt binder phase angles decreased, and softening points, elastic recovery, viscosity, complex modulus, and asphalt rutting parameters increased when CR was added to asphalt. A high CR swelling rate is advantageous for preparing a successful CR as a modification of the asphalt binder [15].

The primary objective of this study is to investigate the M_r from modified asphalt using BNA and CR owing to changes in temperature with the penetration index (PI) as an influence factor. A series of tests have been conducted on the variations in asphalt content and additive material content in asphalt mixtures. This test is to determine the values of the M_r and recoverable horizontal deformation with the influence of temperature.

II. MATERIALS AND METHOD

Hot asphalt mixture (HMA) has been used in this study; it consists of densely graded aggregates of the Indonesian Highways Asphalt Concrete Wearing Coarse (ACWC) specification. This aggregate has been mixed with virgin asphalt penetration of 60/70 Shell production (5.5%, 6%, and 6.5% bitumen content of aggregate asphalt mixture), BNA-type additives (8%, 10%, and 12% of bitumen content), and CR (5 %, 10%, 15%, and 20% of the asphalt content).

II.I Aggregates

The material aggregate consisted of course, medium, and fine aggregate with the largest size of 19 mm, and the composition is shown in Fig. 1.

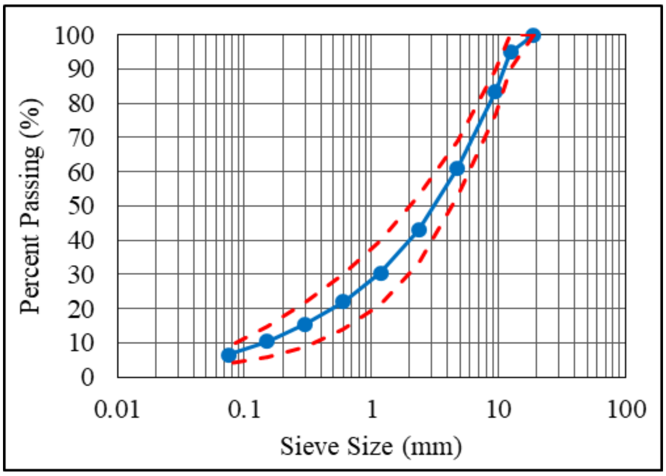

Fig. 1. Aggregate gradation type used in the study.

II.II Crumb Rubber (CR)

The increasing number of vehicles has increased the number of used vehicle tires. The utilization of used tires includes processing them into new materials, such as rubber powder. The application of used tires to roads began in the 1960s when Charles MacDonald applied used tires for maintenance work in urban areas. Rubber tires can be used as an additive in asphalt cement to improve hollow roads [8]. CR is made from used tire rubber, in the form of fine powders through no. 30 (0.6 mm). For the CR modification asphalt preparation process, asphalt binder is heated when it reaches 177 ˚C and CR powder (5%, 10%, 15%, and 20% of the total weight of asphalt) are added gradually into the asphalt in a high rotary mixer at a speed of 700 rpm until it reaches a homogeneous mixture [16]; the characteristics are shown in Table-1.

II.III Buton Natural Asphalt (BNA)

BNA originates from the rock asphalt on Buton Island, Southeast Sulawesi, Indonesia, called Buton asphalt (Asbuton). This type of asphalt has been used widely in Indonesia with various processing methods because deposits of almost 677 million tons exist while the production is still low [17]. Asbuton can be used directly as a lightweight traffic surface layer material, and through processing for moderate and heavy traffic. This is because Asbuton still contains large amounts of minerals. The asphalt content in Asbuton varies between 20–30% depending on location; further, several Asbuton mining locations exist such as in Lawele, Kabungka, and several other places. Asbuton contains high aromatic and resin that increase its adhesion and flexibility. In this study, the BNA used was the result of extracting Asbuton by separating the asphalt from its mineral content. Table-1 shows that the addition of BNA decreases the value of penetration at 25˚C, and increases the softening point and flash point.

Table 1. Modified asphalt properties.

Binder property	Standard	Unit	O	Percentage of CR				Percentage of BNA		
			0%	**5%**	**10%**	**15%**	**20%**	**8%**	**10%**	**12%**
Penetration at 25^{o}C	ASTM-D5	0.1mm	69.3	54.0	45.0	41.0	36.0	47.5	41.6	37.3
Softening point	ASTM-D36	°C	49.5	55.4	58.7	61.7	66.4	52.0	53.0	54.0
Flash point	ASTM-D92	°C	254	314	309	298	262	327	320	328
Ductility at 25^{o}C	ASTM-D113	cm	>140	74.4	54.5	49.6	42.3	>140	>140	>140
Specific Gravity	ASTM-D70	g/cm3	1.023	1.042	1.043	1.046	1.052	1.046	1.048	1.045
Loss on heating	ASTM-D1754	%	0.03	0.17	0.2	0.22	0.33	0.012	0.011	0.014
Viscosity at 135^{o} C	ASTM-D1665	cST	390	508	721	837	1,315	569	933	1,152
Penetration after TFOT	ASTM-D5	0.1mm	63.3	59.6	57.4	53.6	51.7	34.3	29.6	26.0

II.IV Resilient Modulus

Resilient modulus is used to evaluate the elastic properties of asphalt mixtures according to ASTM D7369 [18], as a parameter in the design of surface layers of pavement structures. Samples were made from cylindrical asphalt mixtures of 102 mm in diameter and 63 mm in height, which were compacted and tested with diametric repetitive loading. The test was performed at 25 °C, 35 °C, and 45 °C by applying repeated compression loading at a frequency of 1 Hz. Each cycle includes a 0.1-s loading and a 0.9-s unloading. Horizontal deformation is produced by measuring through a deformation gauge that is mounted horizontally (Fig. 2).

Fig. 2. Test device for resilient modulus.

To provide representative analysis results, the samples were tested for each mixture five times at different positions that are selected randomly.

III. RESULTS AND DISCUSSION

III.I Penetration Index (PI) of Modified Asphalt

This method is used widely to measure the consistency of bitumen at a certain temperature; it is a method to establish a classification rather than a measure of quality. Penetration is related to viscosity, and empirical relationships have been developed for Newtonian materials. By measuring the penetration at various temperatures, the susceptibility of the asphalt temperature can be determined. PI values can be used to determine the stiffness (modulus) of asphalt at each temperature and loading time. It can also, to a certain extent, be used to identify certain types of asphalt [19]. PI is a quantitative measure of the response or susceptibility of a binder (asphalt) to variations in temperature, and its behavior can be predicted in asphalt mixture applications [20].

Fig. 3 shows the value of PI-modified asphalt using CR and BNA as an additive with the value ranging from -0897 to +1422, and virgin asphalt PI value of -0531. The PI value of the asphalt-modified BNA is negative and continues to decrease with increasing BNA content; meanwhile, the addition of CR increases the PI value and is positive.

The PI values start from approximately -3 (highly susceptible to asphalt temperatures) to high PI asphalt approximately +7 (highly vulnerable to low temperatures). The lower the PI value, the more susceptible they are to temperature. Asphalt binders with a PI value below -2 are more susceptible to low temperatures, rendering them more susceptible to thermal cracking [21].

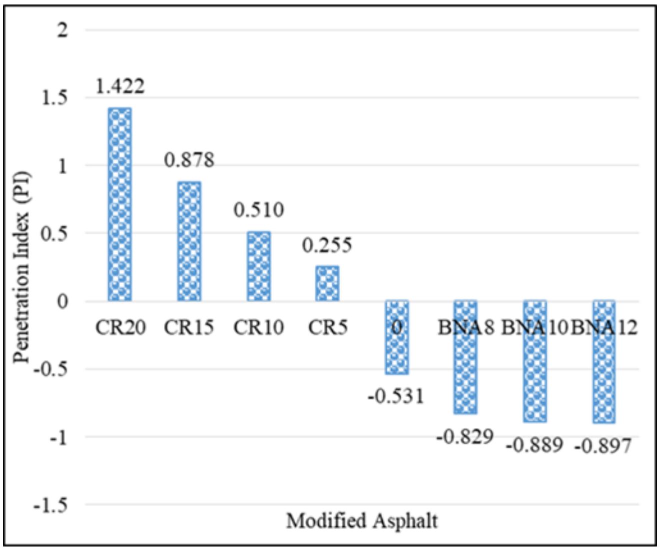

Fig. 3. Penetration index value on various modified asphalt.

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Similarly, for changes in PI values from negative to positive values, at low temperatures, M_r values with negative PIs exhibit a significant difference in the positive PI values. The increase in temperature demonstrated a smaller difference; at the temperature of 45 °C the M_r is almost close to the same value.

Fig.4 shows the change in the decline of M_r value owing to increases in temperature. Asphalt mixtures with BNA additives have produced higher M_r values at various temperature changes than CR additives.

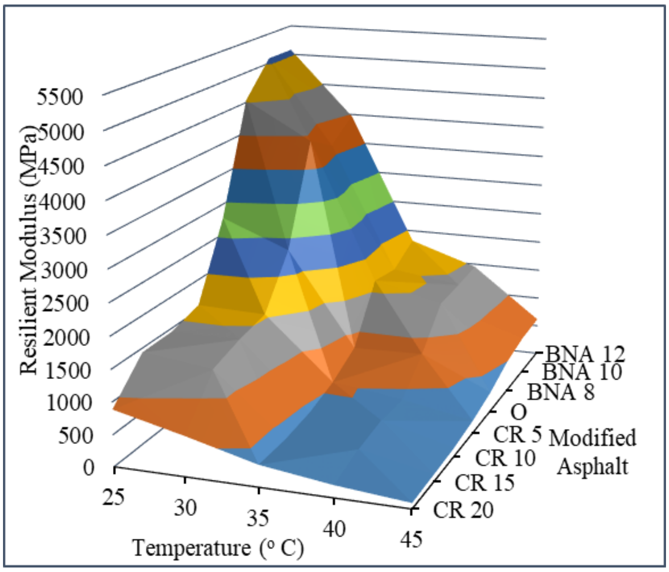

Fig. 4. Resilient modulus on various modified asphalt and temperatures.

III.II Influence of Modified Asphalt on Resilient Modulus

M_r is a parameter to estimate the pavement response to traffic loads, and can be mathematically defined as the repeated applied stress ratio to recoverable strains after a number of loading cycles. Increasing the M_r using an asphalt mixture can yield better performances at certain temperatures, because the mixture is recoverable after releasing the stress applied [19].

III.III M_r Model development

The M_r predictive model was developed as a function of the asphalt penetration index and temperature. As shown in Fig. 5, the results of M_r tests at various asphalt penetration index represent that the relationship between M_r and PI could be determined using a nonlinear function. The resilient modulus was taken as an independent variable, and the temperature and asphalt penetration index were the dependent variables.

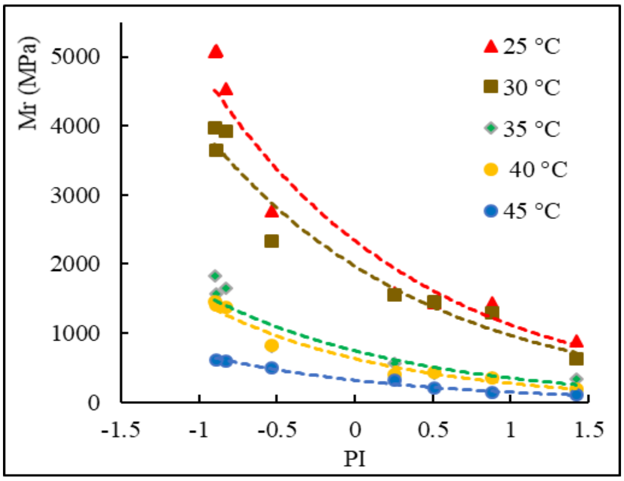

Fig. 5. Relationship between resilient modulus and PI.

Linear functions were obtained by changing the M_r value with a logarithmic function. Statistical analysis showed high R^2 value for linear relationship between Log M_r and PI. The relationships obtained are shown in Fig. 6.

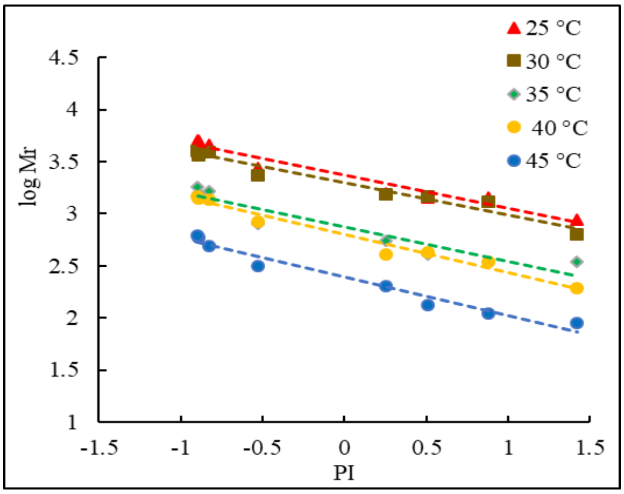

Fig. 6. Relationship between log M_r and PI.

The data showed that the curved relationships between the M_r and asphalt penetration index showed a fairly strong correlation. In general, the equation is formed as follows:

$$Y = a (X) + b \quad (1)$$

$$\text{Log} (M_r) = a (\text{PI}) + b \quad (2)$$

The linear regression between log M_r and asphalt penetration index gave the regression coefficients; a, b, shown in Table 2.

Table 2. Equation resulting from the relationship between log M_r and PI.

Temp. (^{O}C)	Equation	R^2
25	Y = -0.3195 X + 3.3686	0.9497
30	Y = -0.3096 X + 3.2945	0.9583
35	Y = -0.3311 X + 2.8719	0.9065
40	Y = -0.3664 X + 2.7990	0.9710
45	Y = -0.3694 X + 2.3921	0.9640

Then, the coefficients of the equation were obtain by varying the temperature relationships to provide a linear regression with $R^2 = 0.8225$ and $R^2 = 0.9457$, as shown in Fig. 7 and Fig. 8.

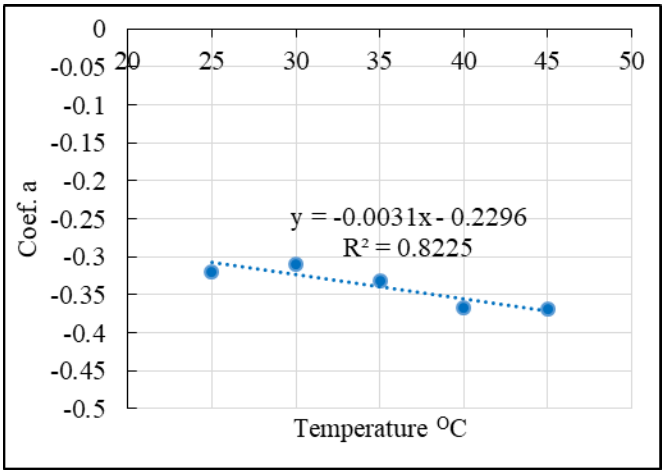

Fig. 7. Relationship between temperature and a coefficient regression of asphalt penetration index.

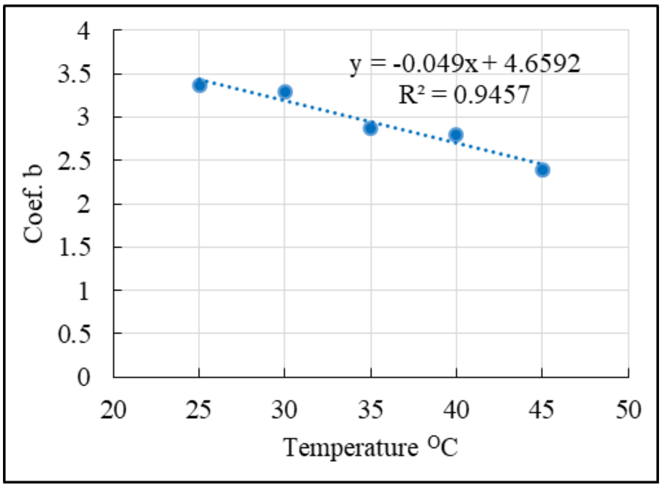

Fig. 8. Relationship between temperature and b coefficient regression of asphalt penetration index.

The relationship resulted in the following equations:

$$a = -0.0031\ T - 0.2296 \quad (3)$$

$$b = -0.049\ T + 4.6592 \quad (4)$$

The relationship between the M_r equation with the temperature and asphalt penetration index in Eq. (2) was obtained by combining Eq. (3) and Eq. (4).

The final model was given by:

$$\text{Log}\ (M_r) = (-0.0031T - 0.2296)\ PI + (-0.049T + 4.6592) \quad (5)$$

Where, M_r: Resilient Modulus of asphalt mix (MPa), T: temperature (°C) and PI: Penetration Index of asphalt binder.

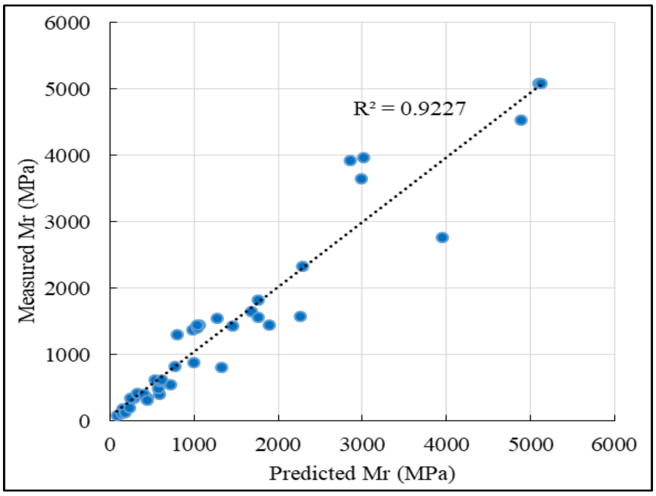

Fig. 9. Experimental results versus model predicted M_r.

Comparison between the experimental results and calculations using the model confirmed the appropriateness of the very strong relationship shown in Fig. 9 with a value of $R^2 = 0.9227$.

IV. CONCLUSION

The addition of BNA and CR to the asphalt mixture was compared herein based on the characteristics of asphalt binder and aggregate asphalt mixture. Physical tests of ductility, penetration, and softening point were performed to determine the effectiveness of asphalt modification toward the asphalt penetration index. Furthermore, tests have been performed to determine the mechanical performance characteristics of the asphalt mixture based on the M_r.

Based on the findings of this study, the conclusions are as follows:

- Based on the physical property tests of asphalt, the additives of BNA and CR as asphalt modification materials increased the softening point but decreased the penetration.
- Using additives affected the binder's susceptibility to temperature; both additives have different PI values and hence demonstrated different levels of susceptibility to temperature. Additive BNA with negative PI was more susceptible to high temperatures while CR additives were susceptible to low temperatures.
- The M_r values produced from these two additives indicated vastly different results, especially at 25 °C, in which the modified asphalt mixture with BNA indicated a much higher M_r value than the modified asphalt mixture with CR; however, at higher temperatures (45 °C), the difference became smaller. It can be concluded that using BNA additives is more appropriate at low temperatures.
- The final model was given by:
  $\text{Log}\ (M_r) = (-0.0031T - 0.2296)\ PI + (-0.049T + 4.6592)$
  The model confirmed the appropriateness of the very strong relationship.

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