Influence of the modulus of elasticity of the asphalt layer considering vehicular congestion in urban intersections.

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Abstract*– Currently, traffic congestion is a problem that is present in many cities around the world. This problem not only has become synonymous with stress and anxiety for users, but also represents a challenge for pavements experts. Congestion not only implies a large increase in road loading but can also generate changes in the mechanical properties of the pavement. These modifications can reduce the design life of roads by affecting the behavior of the modulus of elasticity. Vehicular speed, temperature and pavement overload in traffic are components that should undoubtedly be reflected in a methodology, since these values have a direct influence on the useful life of the roads. This research proposes an empirical methodology for the determination of the modulus of elasticity in an asphalt pavement. This new proposal includes concepts such as temperature, speed, and weight of vehicles in congestion. The experiment was carried out on a road at congested and non-congested temperatures, 35°C and 25°C, respectively. Finally, a discrepancy of more than 50% was obtained between the modulus of elasticity obtained in the laboratory by the conventional method and the modulus calculated by the proposed methodology. The value obtained with the methodology is higher because it includes the increase in the temperature of the asphalt layer due to congestion.

Keywords*-- Speed, vehicular congestion, modulus of elasticity, flexible pavement, pavement temperature.

I. Introduction

A. Problem

In recent years, the increase in the number of vehicles has been higher than the rate of population growth [1]. Due to this "boom", traffic congestion in different cities around the world has become a latent problem [2]. For example, vehicular congestion in Lima in 2019 has increased by 10.5% over the previous year. This is due to private transportation, which includes cars and trucks [3].

Congestion damages the pavement in the sense that it exposes it to cyclic loading for which it is not designed. High traffic problems are reflected in the poor durability of urban pavements, which are generally flexible designs [4]. In Lima, between 70%-80% of urban roads present some type of deterioration, either functional or structural. [5].

The conventional design of flexible pavement contemplates a variety of factors, such as modulus of elasticity, Esal, initial serviceability, final serviceability, normal standard deviation, and others, but the influence of congestion on these factors has not been incorporated [6]. In view of this, it is necessary to propose a methodology that can contemplate the different factors involved in vehicular congestion.

Congestion is generally understood as the condition of a vehicular flow that is saturated due to excess demand on the roads, producing increases in travel times and bottlenecks [7]. Within the way congestion is perceived, the consequences of this phenomenon on the performance of the roadway are usually not considered. The final condition of pavements, in the face of this constant exposure to congestion, is a fact that leads to a decrease in the useful life of roads [8].

There are multiple factors that generate this problem. For example, when a vehicle is stopped by traffic, it not only generates prolonged overloading of the pavement, but also increases the temperature of the pavement surface [9]. Then, we should question whether the existence of these anomalies affects the durability of pavements, for which we should analyze the modulus of elasticity.

B. State of the art

The effect of the increase in the level of vehicular congestion on hot pavements in Latin American roads was studied by Hugo Rondón [10]. This research concludes that this increase has therefore a decrease in traffic speed. The study was validated by means of fatigue tests in the laboratory and equations for the calculation of the number of repetition cycles (Nf), to calculate the deformations. As a result, it was possible to propose an equation for the calculation of the Nf for warm mixes at a temperature of 35°C or, as it was called, the temperature of vehicular congestion.

The influence of temperature and type of asphalt mix on the fatigue behavior of flexible pavements was investigated by Valdés et al [11]. The study validated that the mixes with a higher content of fines in their composition presented better fatigue failure behavior without the intervention of the type of binder and the environmental temperature evaluated. In addition, it was concluded that the mixes produced at lower temperature and with higher viscosity have superior characteristics to the conventional ones in terms of useful life and durability. As a result of this research, it was decided to work with a warm asphalt mix, which contains a higher percentage of voids than the conventional average and makes it a more viscous mix.

On the other hand, the effect of the temperature applied to the pavement was investigated by Pazmiño et al [12]. In this study, it can be determined that temperature variation can cause structural damage and reduce the service life of pavements. The concept of heat island is defined as the energy produced by the

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environment where the road infrastructure is located. Because of this we were able to relate that the heat and the subsequent increase in temperature is a consequence of the large number of vehicles in the same place for a prolonged period.
The addition of rubber grains in hot asphalt mixtures was studied by Diaz et al [13]. It has been shown that this type of modifications in asphalt mixtures increases durability with respect to conventional mixtures. This decreases the number of maintenances and increases its durability. By incorporating this type of material, mechanical aspects of the mix are improved. In congruence with our research, this material was also chosen, but now of including it in the mix design, it was decided to incorporate rubber shredding, which would have a superior benefit, since it would contribute a higher percentage to the mix, being smaller particles, but in greater quantity.

II. MATERIALES Y METODOLOGÍA

This research proposes a methodology for the calculation of the modulus of elasticity of an asphalt layer, which considers the vehicular congestion factor as part of the design. For this analysis, the overload, speed, and temperature caused by vehicle saturation were considered as input data. With these data, a modulus of elasticity factor is determined for pavements that considers the real conditions under vehicular congestion [14].

The flow chart of the methodology used is shown in Figure 1.

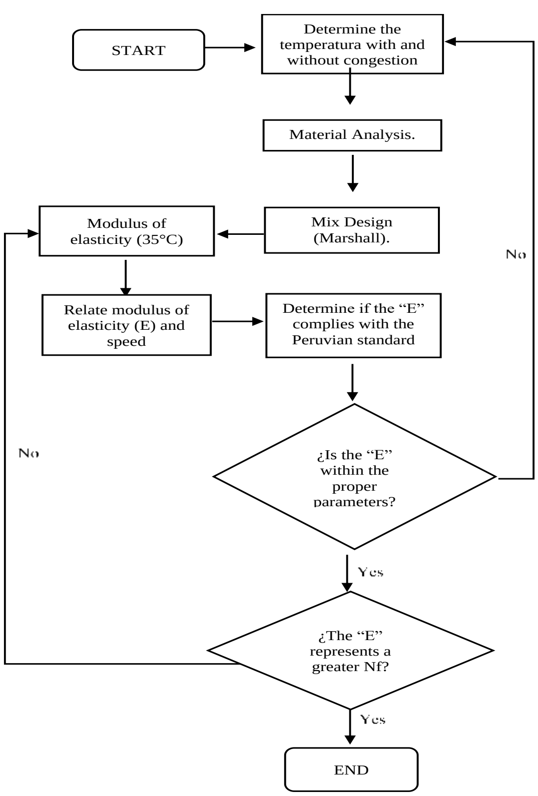

Figura 1 Research methodology

A. *Determination of temperature with and without congestion.*

Figure 2 below shows the thermographic images of the congested pavement on Mendoza Merino Avenue and García Naranjo Street. A Fluke model Ti10 thermographic camera was used for this recording.

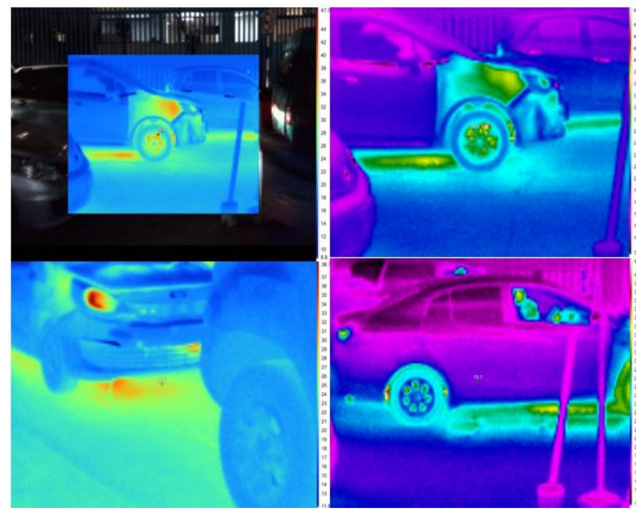

Figure 2 Thermographic images of the asphalt layer under vehicular congestion

B. *Analysis of the materials.*

The aggregate used in this research was obtained from the "Excalibur" quarry, which complies with the MAC-2 requirement according to the Peruvian Ministerio de Transportes y Comunicaciones (MTC). Figures 3 and 4 show that the aggregate mixture complied with the parameters given by Peruvian regulations for use in the design of hot asphalt mixtures.

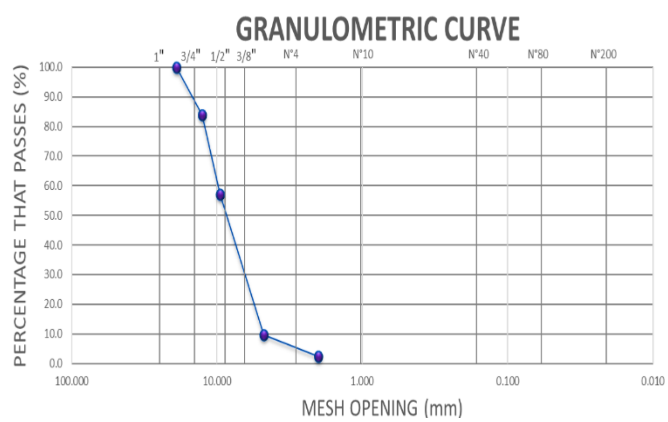

Figure 3 Granulometry of coarse aggregate

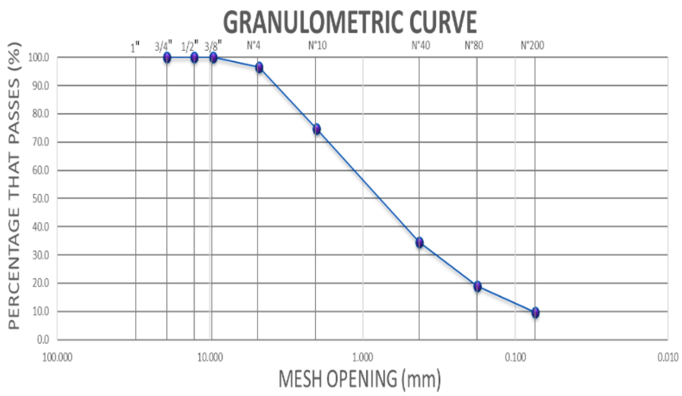

Figure 4 Granulometry of fine aggregate

The asphalt cement used was PEN 60/70, which complies with the tests required by the MTC. Then we proceeded to design the mix according to the Marshall methodology. Here we obtained an optimum percentage of CA asphalt of 5.9% in four 4" briquettes.

C. Mix design (Marshall).

The Marshall test was performed using ASTM D1559, for the granulometric test the recommendations of ASTM C136 were followed, for the maximum theoretical specific gravity test ASTM D2041 was considered and for the retained strength test we took AASHTO T283 as the basis. These studies comply with the minimum requirements, according to Peruvian standard EG 2013. For all the stages of the research, both the warm asphalt mix with the addition of 18% rubber (MAT+18%CR) and the hot asphalt mix (MAC) were considered. The test results of these mixtures are shown in Table I below.

In addition, the Loghman test was performed, which resulted in a contact load of 65 N and 130 N, for the hot and warm asphalt mix, respectively. The cyclic load was 650 N and 1300 N for the hot and warm asphalt mix, respectively.

Table I. Results of the hot and warm asphalt mix according to Marshall.

Design parameters	Unit	HMA	WMA+18%Cr	EG 2013
Hits	N°	75.00	75.00	75
Asphalt Cement	%	5.90	5.90	-
Unit Weight	Kg/m3	2.48	2.43	-
Empty	%	4.30	4.70	3.0-5.0
V.M.A	%	17.00	18.50	14
V.LL.C.A	%	74.00	74.80	-
Dust/Asphalt	%	0.70	0.80	0.6 - 1.3
Flow	mm	13.80	14.30	8.0-14.0
Stability	kN	1007.50	1154.40	8.15
Stability/Flow	Kg/cm	2928.70	3225.80	1700 - 4000
Compressive Strength	Mpa	2.70	2.70	2.1

D. Módulos of elasticity test

The modulus of elasticity test was performed at congestion temperature, 35 °C. For this test, the recommendations of the AASHTO TP-31 standard were followed. In the laboratory tests, 4" and 6" briquettes were used, with diameters of 100 mm and 150 mm, and heights of 66.6 mm and 74.6 mm. The test was performed under 5 pulses with a pulse repetition period of 3000 ms and a rest period of 2750 ms. The results of this test are shown in Table II.

Table II. Modulus of Elasticity test results

Resultados del ensayo	HMA		WMA+18%CR	
	Media	% CV	Media	% CV
Módulo Elasticidad (Mpa)	825	4.12	1462	3.54
Fuerza de carga pico (n)	651.2	0.7	1290	1.5
Fuerza de asentamiento	72	9.5	131.6	8.3
Deformación total recuperable deformación	2.56	3.21	3.75	2.81

E. Relationship modulus of elasticity and speed

After performing the modulus of elasticity tests, we proceed to determine the equation that analyzes the frequency of congestion. Equations 1 and 2 are obtained by evaluating the speed of vehicles during congestion.

A congestion temperature of 35 °C was considered for the calculations [15].

$$E_{HMA} = 846.11(F^{0.0601})\ldots (1)$$

$$E_{WMA} = 1493.2(F^{0.0495})\ldots (2)$$

Where: E is the modulus of elasticity, F is the frequency, and the temperature is constant 35°C.

F. Determine if the modulus of elasticity complies with the Peruvian technical standard.

Using the formulas obtained, the numerical value of the modulus of elasticity was found, then the number of repetition and deformation cycles for each "E" was determined. The maximum deformation obtained should be corroborated with the Peruvian technical standard.

III. RESULTS AND ANALYSIS

A. *Equations obtained*

Figure 5 shows the graphical relationship between the modulus of elasticity and frequency in relation to a warm (typical) mix. On the other hand, Figure 6 shows the same relationship for a warm asphalt mix.

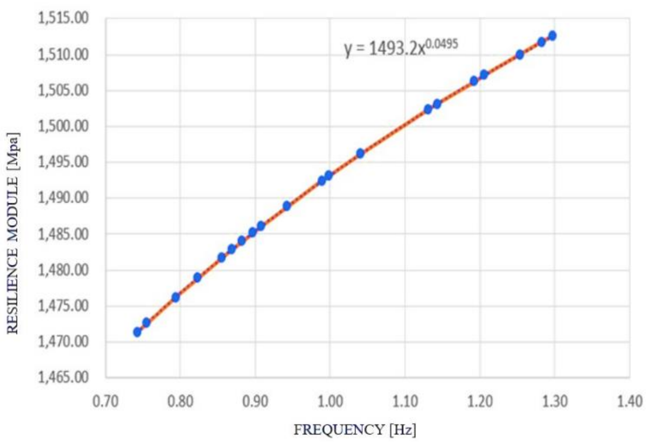

Figure 5. Modulus of elasticity vs. frequency (MAT).

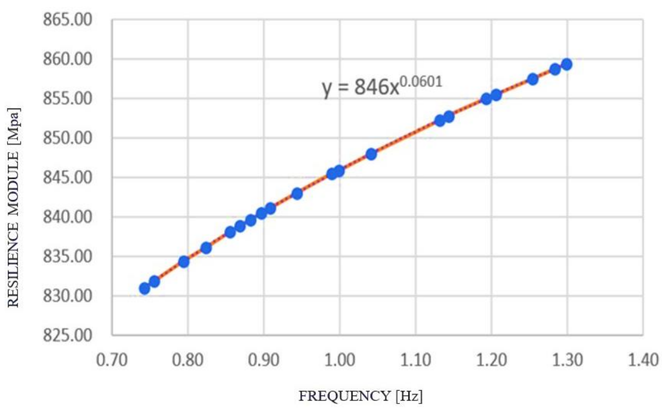

Figure 6. Modulus of elasticity vs. frequency (MAC).

B. *Módulo de elasticidad*

The equation considers the influence of congestion on the value of the modulus of elasticity. The results indicate that the value of E should be considered higher by up to 3.75% for warm mixes and 4.38% for hot mixes. This increase in the modulus of elasticity should be considered in the design of pavements, with the objective of achieving more resistant and durable roads in the face of the real effects of vehicular congestion. The results of the modulus of elasticity of the warm and hot mix are shown in Table III.

Table III. Comparison of modulus of elasticity in MAT

	Modulus of elasticity (Mpa) MAT			
F (Hz)	Equation	Laboratory	Difference	%
0.33	1413.46	1406	7.46	0.53
0.66	1462.80	1408	54.80	3.75
0.99	1492.45	1475	17.45	1.17
1.32	1513.86	1545	31.14	-2.06
1.65	1530.68	1479	51.68	3.38
Modulus of elasticity (Mpa) MAC				
0.33	791.47	793	1.53	-0.19
0.66	825.13	789	36.13	4.38
0.99	845.49	814	31.49	3.72
1.32	860.23	873	12.77	-1.48

In Figure 7, the values obtained with the formula have a much more uniform relationship compared to the laboratory results.

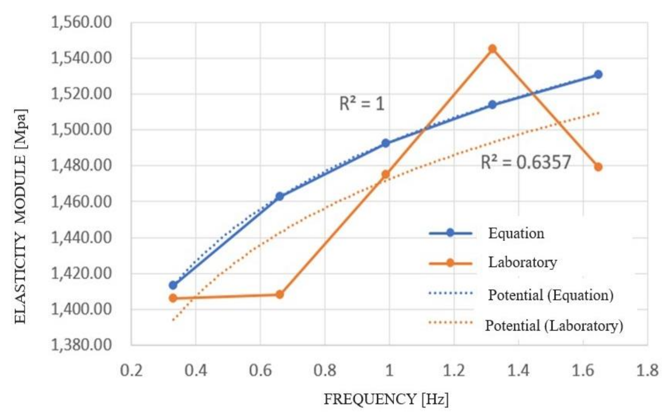

Figure 7. Modulus of elasticity vs. frequency (MAT+18%CR).

C. *Calculation of Nf and deformations.*

The following formulas were used to obtain the number of repetition cycles and deformations. The permanent deformations were calculated using the formula proposed by Schmidt and Santucci [16]. These authors gave the values of k1=6.24x10-6, k2=0.48 and k3=15.79.

$$\varepsilon_{max} = k_1 + \frac{k_2}{E} + \frac{k_3}{E^{3/2}} \ldots (3)$$

$$N_f = 4.74 * \left(\frac{\sigma}{E}\right)^{-2.96} * 10^{0.165} \ldots (4)$$

Where: E is the modulus of elasticity. K1, k2 and k3 are constants, Nf is the number of repetition cycles.

With the formulas obtained and the recently mentioned formulas, it was possible to calculate the Nf and the deformations. The difference of the maximum value of the Nf in the warm mix is 4.26, the percentage corresponding to this numerical value is 10.69%. This means that in the design of pavements, an additional 10.7% should be considered in the calculation of the modulus of elasticity, so that the roads respond to the current traffic needs.

The deformations obtained in the WMA have a difference, between the theoretical value and the calculated value, of 8.68 x 10-6, which is equivalent to 4.55%. All of them are shown in Table IV and V.

Table IV. Comparación del Nf en el WMA.

	Laboratory	Equation		
F (Hz)	Nf	Nf	Dif	%
0.33	35.47	36.03	0.56	1.55
0.66	35.62	39.88	4.26	10.69
0.99	40.87	42.32	1.45	3.42
1.32	46.88	44.14	-2.74	-6.21
1.65	41.20	45.61	4.41	9.67

Table V Comparación del emax en el MAT.

	Laboratory	Equation		
F (Hz)	e	e	Dif	%
0.33	0.00065	0.00064	4.17E-06	0.64
0.66	0.00065	0.00062	2.94E-05	4.55
0.99	0.00061	0.00060	8.68E-06	1.42
1.32	0.00058	0.00059	-1.45E-05	-2.51
1.65	0.00061	0.00058	2.49E-05	4.09

As for the hot mix (MAC), as can be seen in Figures 8 and 9, a difference of up to 0.91 was obtained in terms of Nf, this represents a value of 12.41%. As for the maximum deformation, a maximum difference of 7.29x10-05 is observed, this is equivalent to 5.5%. The calculations show that the Nf are lower in terms of those obtained by laboratory. In other words, by including the impact of congestion, the asphalt layer would support fewer load cycles, and this would lead to an early failure of the pavement.

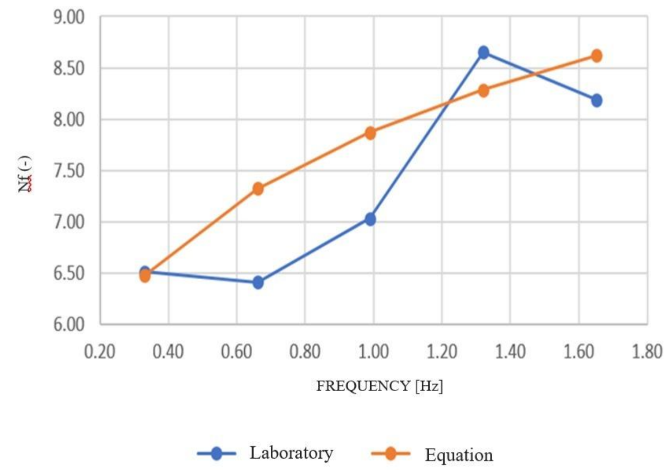

Figure 8. Nf vs Frecuency (MAC).

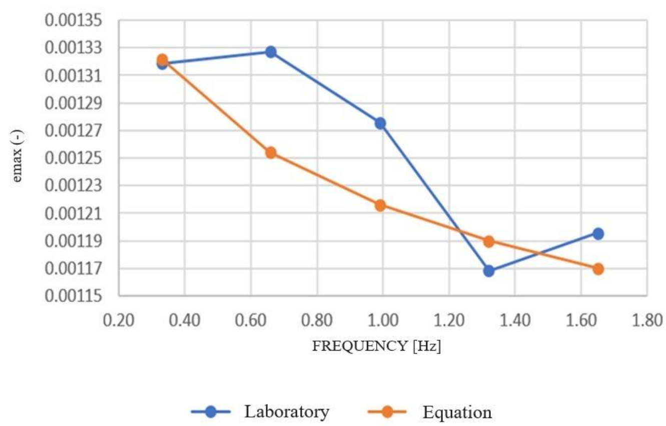

Figure 9. emax vs Frecuency (MAC).

IV. CONCLUSIONS

The variation of the modulus of elasticity obtained by a conventional method and the method with the inclusion of the factors of congestion, speed, and vehicle overload, resulted to be higher by 50%.

The analysis of the congestion factors in the pavement design methodology allowed finding a formula that responds to current needs, where the congestion temperature, traffic speed and vehicle load are considered. These formulas, obtained for warm and hot mixes, show that the values considered in the pavement designs are not the closest to reality, since there are differences of up to 54.80Mpa and 36.13Mpa for warm and hot mixes, respectively.

Given the results obtained in the modulus of elasticity, the variation of the number of repetition cycles (Nf) and maximum deformation (emax) was analyzed. It was shown that this pavement would fail under the influence of congestion and vehicular overloading.

In warm mixes, the Nf presents a difference between both methods in the E value of 4.26, which represents a dispersion of 10.69%. On the other hand, in the emax value, the warm mixtures present a difference of 2.94 x10-5, which represents a dispersion of 4.55%.

As for the hot mixtures, an Nf difference of 0.91 (12.41%) and an emax of 7.29x10-5 (5.5%) were obtained. It should be noted that the higher the emax, the lower the modulus of elasticity, which leads to brittle failure in less time. These results are the result of the decrease in vehicle speed due to congestion. Therefore, it is essential to consider the influence of this phenomenon in pavement design.

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