Revista Ingeniería de Construcción RIC
Vol 39 Nº1 2024
www.ricuc.cl
DOI: 10.7764/RIC.00096.21

ENGLISH VERSION...

Incidence of cumulative degree-days on asphalt mixture aging in regions of Ecuador

Incidencia de grados-día acumulados en el envejecimiento de la mezcla asfaltica en regiones del ecuador

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Fecha de Recepción: 26/07/2023
Fecha de Aceptación: 06/03/2024
Fecha de Publicación: 30/04/2024
PAG:17-31

Abstract

The aging of asphalt mixes affects the durability of the pavement. The characteristics of the mixture interact in a complex way with the temperature and service time on site, so the use of the cumulated degree-days (CDD) criterion is possible. The work's objective is to analyze the aging of the mixtures in the Coastal and Andean regions, through the application of the CDD related to the stiffness modulus at 20 °C in the NAT equipment, obtained from cores sampling in roads built in different years and to make observations regarding existing damages associated with durability. Seven sections were selected from similar mixtures placed between 0 and 14 years ago, made with crushed alluvial materials and AC-20 asphalt from the Esmeraldas refinery. The results show that the aging evaluated through the stiffness modulus presented a greater impact in the Coastal region than in the Andean region due to its higher temperatures, allowing the use of the CDD to unify the behaviors in the two regions into a single relationship. Observations show that the probable range of the progressive evolution of damages, from its beginning to its critical phase, is from 45.000 to 80.000 °C-days.

Keywords: *Asphalt mixtures; aging; durability; cumulative degree-days; stiffness modulus.*

Resumen

El envejecimiento de las mezclas asfálticas afecta la durabilidad del pavimento. Las características de la mezcla interactúan de manera compleja con la temperatura y el tiempo de servicio en sitio, esta condición posibilita el uso del criterio de grados-día acumulados (CDD). El objetivo de este trabajo es analizar el envejecimiento de las mezclas en las regiones Costa y Andina, mediante la aplicación del CDD para el módulo de rigidez a 20 °C en los equipos NAT, obtenido a partir de testigos muestreados en caminos construidos en diferentes años, con el objeto de realizar observaciones respecto de los daños existentes asociados a la durabilidad. Se seleccionaron siete tramos de mezclas similares colocadas entre 0 y 14 años, elaboradas con materiales aluviales triturados y asfalto AC-20 de la refinería de Esmeraldas. Los resultados revelaron que el envejecimiento, evaluado a través del módulo de rigidez, presentó un mayor impacto en la región Costa que en la región Andina debido a sus mayores temperaturas, por lo que el uso del CDD posibilitó unificar el comportamiento de las dos regiones en una sola relación. Las observaciones muestran que el rango probable de evolución progresiva de los daños, desde su inicio hasta su fase crítica, es de 45.000 a 80.000 °C-día.

Palabras clave: Mezclas asfálticas; envejecimiento; durabilidad; grados-día acumulados; módulo de rigidez.

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1. Introducción

The hardening of asphalt mixes over time due to oxidation, molecular agglomeration and other chemical processes is called aging. Short-term aging occurs due to the heating of the binder to produce the mix in the plant plus its laying and compaction on site. Subsequently, in the long term, aging continues due to environmental factors (oxygen, temperature, solar radiation). The reactions that are generated in the bitumen are dependent on its chemical composition, and an increase in the amount of oxygenated functional groups is expected, such as carbonyls and sulfoxides, carbon-carbon double bonds, and aromaticity (Mouillet et al., 2008); (Yang et al., 2014). These transformations increase the polarity and rigidity of the material, making energy dissipation by flow less efficient. In other words, an oxidized bitumen dissipates energy through fracture (Villegas et al., 2018).

Other factors also affect the aging of the mix, such as the percentage of air voids and their interconnectivity, the thickness of the binder film and the type of asphalt, which interact in a complex way with field in-service temperature and time. Already in the 1980s, some researchers had shown that the main factor affecting aging is the average temperature and the time in service. (Kemp and Predoehl, 1981). The criterion of cumulated degree-days (CDD) allows considering both the temperature associated with climatic regions, and the elapsed service time. This criterion was used in research on asphalt aging at Texas A&M University, associated with the variation of the resilient modulus in the mixtures (Newcomb et al., 2015); (Newcomb et al., 2019).

As asphalt mix ages, its durability, that is, its ability to maintain structural integrity throughout its useful life when exposed to the damaging effects of weather and traffic loads, is affected (Nicholls et al., 2008). Raveling and surface-initiated cracking are the primary distresses associated with durability issues (Bonaquist, 2016). Although stresses induced by traffic exacerbate distress, the evolving rheological properties of aging asphalt are sufficiently damaging to cause a pavement to crack from thermal stresses alone (King et al., 2012).

Asphalt layers in Ecuador present durability problems, showing severe deterioration a few years after being built. Often, well-designed, and rigorously supervised roads require important rehabilitation works between four and six years after they are built. This situation can be attributed in part to the fact that most of the asphalt cement used (AC-20) from the Esmeraldas Refinery has the particularity of being prone to premature aging and therefore low durability, which has been indicated in several works (Vila et al., 2003; (Vila et al., 2017), but the problem persists to this day.

The objective of this work is to analyze the aging of the mixtures in the Coastal and Andean regions, through the application of CDD related to the stiffness modulus at 20 °C in the NAT equipment, obtained from cores sampling from roads with different service times and to make observations regarding existing damages associated with durability.

2. Observations on the quality of asphalt produced at the Esmeraldas Refinery

Aging problems can be assessed from the viscosity and ductility values of the residue in the rolling thin-film oven test (RTFOT). (Table 1) shows the results of some tests carried out on 128 AC-20 samples taken, approximately every 15 days, from the tankers upon arrival at an asphalt plant near the city of Guayaquil, between July 2015 and February 2023. The table shows average values obtained, standard deviation and coefficient of variation. The requirements correspond to viscosity classification considered in the Ecuadorian standard INEN 2515-2010, Amendment 1.

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Table 1. *Results obtained in 128 samples of Ecuadorian asphalt (2015 – 2023)*

Test	Viscosity, 60ºC	Viscosity, 60ºC (Residue RTFOT)	Ductility, 25ºC, 5 cm/min (Residue RTFOT)
Mean	231 Pa.s	1060 Pa.s	38 cm
Standard deviation	30 Pa.s	144 Pa.s	7 cm
Coefficient of variation	12,80%	13,6 %	18,40%
Requirement AC-20	200 ± 40 Pa.s	Max 800 Pa.s	Min 50 cm

Test results show a uniform behavior over time, with relatively low coefficients of variation. In most cases, the original asphalt qualifies as AC-20, while the residue tests from the RTFOT fail to meet the requirements, showing high viscosity and low ductility

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3. Climatic factors in Ecuador

In continental Ecuador there are three well-defined geographical zones or regions, as represented in (Figure 1). This research was carried out on sections of roads in the Coastal and Andean regions, since in the Amazon region there is a low density of roads with less vehicular traffic than the other two.

Figure 1. *Regions of continental Ecuador*

31 Temperature

(Table 2) shows the monthly average air temperatures at two meteorological stations of the National Institute of Meteorology and Hydrology, INAMHI, close to the sections of roads studied (INAMHI, 2017). The temperature variation between months within each region is very small, due to the geographical position of the country. The average temperature difference between the two stations, is 10,8 ºC for the maximum, 15,7 ºC for the minimum and 13,1 ºC for the monthly temperature. The maximum and minimum temperatures indicated in Table 2 correspond to the average values of the

maximum and minimum daily air temperatures respectively during the indicated month.

Table 2. *Monthly average air temperatures in Celsius degrees*

Station	MILAGRO (Coastal region)			IZOBAMBA (Andean region)		
Month	**Maximum**	**Minimum**	**Monthly**	**Maximum**	**Minimum**	**Monthly**
January	29,7	22,7	25,9	19,8	6,2	13,2
February	30,2	22,9	26,1	17,8	7,3	11,8
March	31,3	23,7	26,9	19,0	6,9	12,7
April	31,4	23,2	26,9	19,2	6,2	12,5
May	30,0	22,0	25,7	18,2	6,5	12,1
June	28,4	21,4	24,6	19,7	5,7	12,7
July	27,4	20,4	23,6	19,8	5,7	12,4
August	29,2	20,3	24,3	19,7	5,3	12,3
September	30,2	20,9	25,0	19,7	6,2	12,7
October	29,7	21,4	25,1	19,1	6,6	12,3
November	29,6	21,6	25,1	18,7	6,0	11,9
December	32,2	22,3	27	18,9	6,0	12,3
Mean	29,9	21,9	25,5	19,1	6,2	12,4
Standard dev.	1,31	1,09	1,09	0,66	0,55	0,39
C. Variation, %	4,37	4,99	4,29	3,44	8,86	3,12

3.2 Ultraviolet radiation (UV)

Solar radiation has three kinds of waves: ultraviolet (UV), visible, and infrared. The UV region is divided into three bands according to the wavelengths they cover: UVA (315–400 nm), UVB (280–315 nm) and UVC (100–280 nm). When sunlight passes through the atmosphere, ozone, water vapor, oxygen, and carbon dioxide absorb all the UVC radiation and about 90% of the UVB radiation. Consequently, the UV radiation that reaches the Earth's surface is composed mostly of UVA rays, with a small part of UVB rays (OMS, 2003). Thus, only 7% of incoming UV radiation reaches the surface of the earth. (Reyes and Camacho, 2008).

UV radiation´s effect on long-term aging was noted by (Bell, 1989), and different procedures have been developed since then. However, UV aging only occurs on the most superficial asphalt layer. (Verhasselt, 2000). In investigations carried out with Colombian asphalt, it was found that UVB rays cause the greatest damage to asphalt binders (Afanasieva and Cifuentes, 2002)

UV radiation is greater the closer to the equator. (Table 3) shows the average values of global solar radiation and UV (W/m2/h/day) in two INAMHI stations, evaluated with data between 2013 and 2019 (Chiguano and Tigasi, 2020). It can be determined from the values shown in (Table 3), that from 0 m to 3,000 m altitude (approximate values for the analyzed stations) global radiation increased by almost 30%, which confirms that the radiation in the Andean region is much greater than on the Coast. However, UVB radiation only increased from 14.2 to 20.8 W/m²/h/day, which are very low values when compared to total radiation.

Table 3. *Radiations in the different regions*

Region	Global solar Radiation	UVA	UVB	UV TOTAL	UVA	UVB	UV TOTAL
	(W/m²/h/día)				(% UV TOTAL)		(% GLOBAL)
Coastal	3.701,5	259,0	14,2	273,2	94,8	5,2	7,4
Andean	4.788,5	294,8	20,8	315,6	93,4	6,6	6,6

4. Selected field sites

Different sections of roads were studied in the Coastal and Andean regions, with rigorous construction controls and adequate drainage. Roads with overlay layers built between 0 and 14 years old at the time of cores sampling were selected. See (Table 4). In the Coastal region the sections have an altitude between 10 and 30 m and in the Andean between 2,600 and 3,000 m.

Table 4. *Summary of field sites*

Road	**Location**	**Service time (months)**
Coastal region		
Km 26- Puerto Inca- Naranjal	31+000	0
Milagro- Naranjito- Bucay	19+240	46
Milagro- Naranjito- Bucay	33+240	88
Crossing town of Durán	1+400	169
Andean region		
Alóag- Santo Domingo	15+520	42
Alóag- Santo Domingo	5+100	91
Alóag- Santo Domingo	24+650	131

An important selection criterion was that in all cases the mixes were made with crushed alluvial materials of good quality, meeting the same granulometric requirement corresponding to a dense mix with a nominal maximum size of 12.5 mm (MOP, 2002). The asphalt cement used in all cases was AC-20 from the Esmeraldas Refinery, with the shortcomings. The asphalt weight content in the mixtures varied in a very small range, between 5.8 and 6.0%.

The cores were extracted close to the road edges, in locations outside the wheel paths, to avoid the effects of vehicle loads in the mixture as shown in (Figure 2). (Table 5) shows the average results on three cores of the volumetric parameters: maximum specific gravity of the mix (Gmm), bulk specific gravity of the mix (Gmb) and percentage of voids with air (Pa). The results indicate an acceptable compaction in the different sections, with Pa values between 6.54 and 7.31%.

Figura 2. *Core extraction in road Milagro- Naranjito- Bucay. Location 19+240*

Table 5. *Average volumetric parameters of the mixtures in the different sites*

Region	**Coastal**				**Andean**		
Time, months	0	46	88	169	42	91	131
Gmm	2,536	2,543	2,538	2,551	2,511	2,506	2,523
Gmb	2,361	2,358	2,354	2,378	2,334	2,323	2,358
Pa, %	6,90	7,27	7,25	6,78	7,07	7,31	6,54

To assess the effect of aging of the mix, the resilient modulus (MR) test is considered because the properties of the binder govern the magnitude of the MR and it can be used to compare the stiffness of cores sampling and in laboratory prepared specimens (Newcomb et al, 2015). In the present study, the stiffness modulus was used according to the European Standard EN 12697-26:2012, Appendix C, being determined in the Nottingham Asphalt Mix Tester (NAT). The evaluation of the modules with this equipment was carried out at a temperature of 20°C, using a controlled deformation level of 5 microns and haversine waves with a time interval between the start of the load pulse and the maximum load of 0.12 seconds.

5. Cumulates Degree-Days Criterion

It was decided to assess the application of the CDD criteria, in addition to the aging times of the mixtures on the sites; thus, the variation of the modules in similar mixtures placed in different climates such as the Coastal region (warm) and the Andean region (temperate-cold) can be shown in a single relationship. The cumulated degree-day is a unit used to measure the severity with which the temperature impacts an area.

The CDD is the sum of the daily maximum temperature above freezing for all the days being considered from the time of construction to the time of core sampling (Newcomb et al., 2015). Working with Celsius degrees, the freezing point of water is 0 ºC, so (Equation 1) is defined as:

$$CDD\ (^{0}\mathrm{C} - \mathrm{días}) = \sum_{i=1}^{n} Tdmax \qquad (1)$$

Where: Tdmax is the maximum daily air temperature (ºC) and n is the number of cumulative days.

For the determination of the CDD, the information on the monthly average maximum temperatures in the air was obtained from the INAMHI yearbooks, from two stations located in places close to the selected sections: Station M037 in the city of Milagro and M003 in Izobamba, located south of Quito. For greater precision, the last five years published for each region were processed, determining the accumulated degree-days per month by multiplying the maximum average temperature by the corresponding number of days. In practice, this is favored by the fact that the monthly temperature varies very little in each region.

The sum of all degree-days divided by the 60 months analyzed results in cumulated monthly average degree-days for the region, allows to calculate the CDD according to the months of construction of each section. Although the Coastal region presents an average value per month of 914.75 ºC-days, for the Andean region it is only 565.74 ºC-days, that is, 62% of the value in the Coastal region. (Table 6) shows these results.

Table 6. *CDD values (ºC-days) calculated*

Region	Coastal				Andean		
Time, months	0	46	88	169	42	91	131
CDD, ºC-days	0	42.079	80.498	154.593	23.761	51.482	74.112

Obviously, the mathematical procedure applied to obtain the CDD in both regions will imply perfect linear relationships between the times and the CDD. (Figure 3) shows these relationships.

DOI: 10.7764/RIC.00096.21

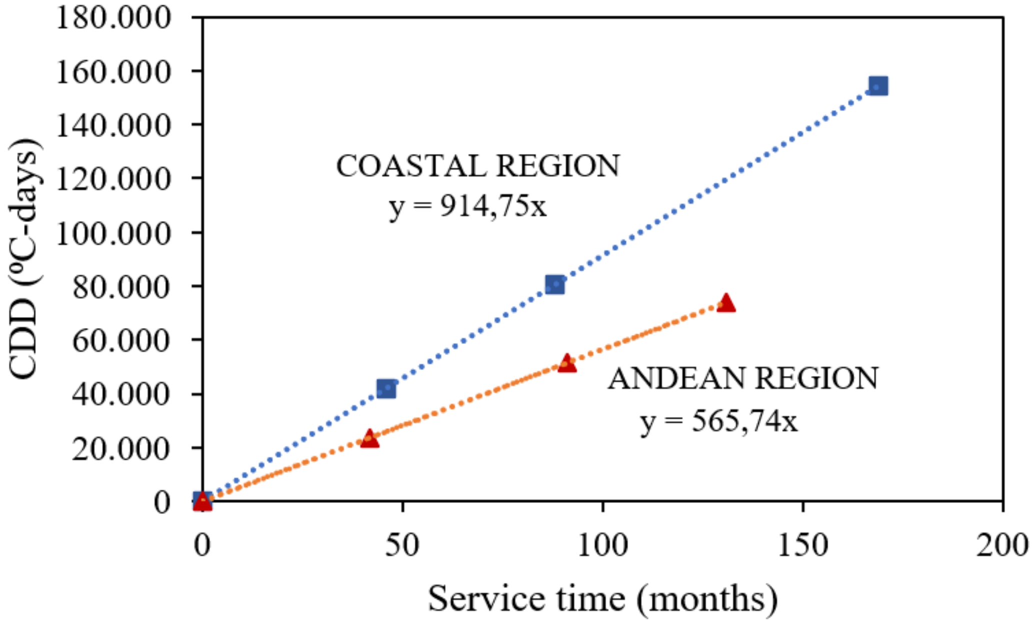

Figure 3. *Variation of CDD versus service time in the regions*

6. Results

The cylindrical cores tested have diameters of 101.6 mm and heights between 40 and 50 mm. The modules of each core correspond to the average of two tests carried out on two previously marked diameters perpendicular to each other. The results are shown in (Table 7) and (Figure 4).

Table 7. *Results of the stiffness modulus tests*

Region	**Coastal**				**Andean**		
Time, months	0	46	88	169	42	91	131
M1, MPa	2.674	7.430	7.485	10.311	3.826	5.171	4.887
M2, MPa	2.560	7.560	8.330	8.592	3.826	5.625	5.547
M3, MPa	2.728	6.147	8.552	10.794	3.999	5.414	5.707
Mean	2.654	7.046	8.122	9.899	3.884	5.403	5.380
Standard dev.	86	781	563	1.157	100	227	435
C. Variation, %	3,2	11,1	6,9	11,7	2,6	4,2	8,1

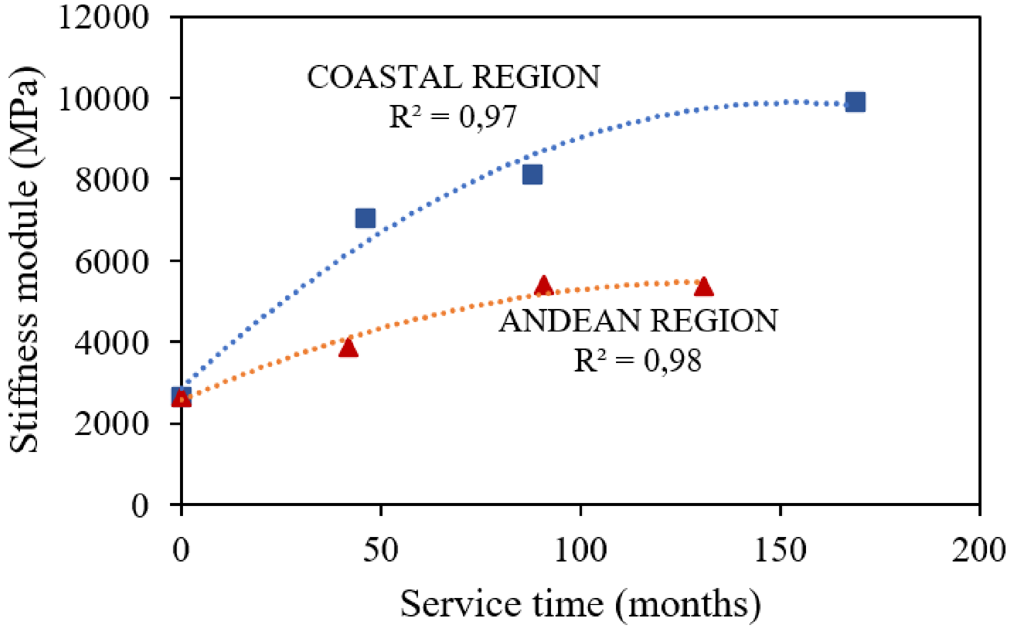

Figure 4. *Variation of stiffness modules versus service time in the regions*

The results indicate that with the aging time, the modules tend to increase, reaching the value of 9,899 MPa in the Coastal region and 5,380 MPa for the Andean region. Aging evaluated through the module is more related to temperature than with UV radiation, which impacts only the most superficial layer of the core.

(Figure 4) shows the large increase in modules during the first months, which later decreases. Particularly in the coastal region, in the first 48 months (4 years) the modulus increased by 3,900 MPa. In the Andean region, such increase was only 1,600 MPa, less than half of that the Coastal region. The environmental conditions of each region, especially the temperature, will cause significant aging at different times.

From the calculated CDD, a single relationship can be established with the stiffness modules for each of the sections studied, as shown in (Table 8). This also includes the ratio between the modules obtained (Mi) and the initial modulus at zero month (Mo), which allows to easily visualize the rate of increase of the moduli over service time with respect to their initial modulus, which in our study is a unique value. In fact, the Mi: Mo ratio represents an aging index in the asphalt mixtures that can be used for the overall analysis of the behavior of mixtures produced and placed in different locations.

Table 8. *Relations between the stiffness modulus, stiffness ratio and the CDD*

Region	**Coastal**				**Andean**		
Time, months	0	46	88	169	42	91	131
Module, MPa	2.654	7.046	8.122	9.899	3.884	5.403	5.380
Mi: Mo Ratio	1,00	2,65	3,06	3,73	1,46	2,04	2,03
CDD, ºC-days	0	42.079	80.498	154.593	23.761	51.482	74.112

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(Figure 5) and (Figure 6) show the values of the Mi and the Mi: Mo ratio as a function of the CDD. Notice that the values of both regions can be linked in a single relationship. It is interesting to note that the determination coefficient R2 reaches an acceptable value of 0.82 despite working with mixtures produced in different years, where certain variations are possible in the quality of the constituent materials and therefore in the mixture itself, as well as in construction particularities.

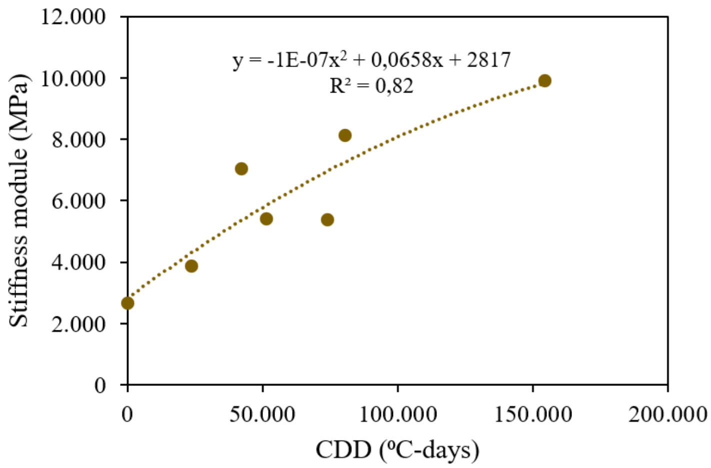

Figure 5. *Variation of stiffness modules versus the CDD*

In a study on requirements in performance tests with the NAT equipment for Ecuador (Vila, 2017), one of the considerations for conventional asphalt mixes to be considered unsuitable was that they had stiffness moduli at 20°C above 5,000 MPa because they are more likely to crack. In (Figure 5), this value would correspond to a CDD of only 35,000 ºC-days. On the other hand, according to previous investigations using 80 samples taken in different streets of the city of Guayaquil with placement times between 8 and 12 years (Giler and Zambrano, 2005), modules obtained had a range between 6,000 and 10,000 MPa, with an average of 8,000 MPa. Many of the streets where cores were extracted had areas with mixtures in the disintegration phase, due to the loss of their cohesion and adherence capacity. In (Figure 5), a module of 8,000 MPa would correspond to a CDD of 90,000 ºC-days.

Figure 6. *Variation of stiffness ratio versus the CDD*

According to (Figure 6), the Mi/Mo ratio that would be obtained for the CDD of 35,000 ºC-days is 1.9 and for 90,000 ºC-days it is 2.9. In other words, the range of time in which the deteriorations of our mix occur due to durability problems, corresponds approximately to the interval between double and triple the initial modulus.

6.2 Impact of the CDD on the durability of the asphalt layer

Below is a photographic sequence showing the progress of distresses in the asphalt mix layers located around the drilled sites, outside the wheel paths, as the CDD increases. See (Figure 7), (Figure 8), (Figure 9), (Figure 10), (Figure 11), (Figure 12) y (Figure 13).

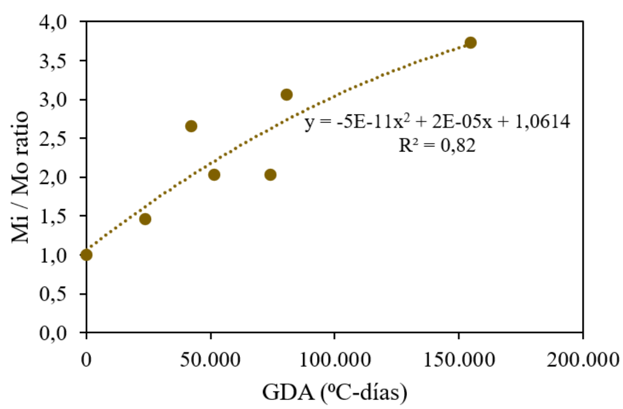

Figure 6. *Variation of stiffness ratio versus the CDD*

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Figure 7. *Surface damage for CDD=0 ºC-days*

Figure 8. *Surface damage for CDD=23.761 ºC-days*

Figure 9. *Surface damage for CDD=42.079 ºC-days*

Figura 10. *Surface damage for CDD=51.482 ºC-days*

Figura 11. *Surface damage for CDD=74.112 ºC-days*

Figure 12. *Surface damage for CDD=80.498 ºC-days*

Figure 13. *Surface damage for CDD=154.593 ºC-days*

(Table 9) shows a summary of the distresses observed in the asphalt mix layer of the mentioned sites with the increase in CDD. The three final distresses and their severity levels correspond to ASTM D 6433-16.

Table 9. *Incidence of CDD on superficial aging damage*

CDD, ºC-days	Observed surface damage
0	Good condition.
23.761	Some aggregates are unpainted. There are some small cracks.
42.079	Loss of some fine particles. Cracks and their length increase.
51.482	Loss of fines and cracks increase.
74.112	Weathering and raveling with low severity level. Different types of low severity cracks.
80.498	Weathering and raveling with low severity level. Different types of medium severity cracks.
154.593	Weathering and raveling with high severity level. Different types of high severity cracks.

The data indicate that the probable range of the evolution of the deterioration in the asphalt pavement in Ecuador (such as weathering, raveling and cracks) begins at approximately 45,000 ºC-days and becoming critical at 80,000 ºC-days. The indicated range is located within that suggested in the previous numeral, from 35,000 to 90,000 ºC-days, although it is narrower. In the Andean region, with a CDD of 51,482 ºC-days, block cracks are also observed caused by the stresses generated by daily temperature cycles. With the aging of the mixture this type of cracking will increase.

Since the study carried out corresponds to well-constructed roads, the CDD range between 45,000 and 80,000 ºC-days would move towards lower values if inadequate construction procedures were executed, such as, producing mixtures in the plant with excessive moisture in the mineral aggregates, using very high mixing temperatures or not carrying out proper compaction on site.

7. Conclusions

The aging of the mixture, evaluated through the stiffness modulus, presents a considerably greater impact in the Coastal region than in the Andean region. This occurs mainly due to the higher temperatures existing on the coast; UV radiation only affects the surface of the mixture and is not influential in this type of test. In the first 48 months, the modulus rises in the Coastal region from 2,654 MPa to 6,600 MPa according to the adjustment curve, while the Andean region it rises to 4,300 MPa, which indicates an increase of less than half that occurred in the coast. The maximum values in the time analyzed are close to 10,000 MPa in the Coastal region, while in the Andean region only 5,500 MPa.

The use of the cumulative degree-days (CDD) criterion was satisfactory. The unique relationship obtained between the ratio of modules and the CDD of both regions is strong according to the coefficient of determination R2 of 0.82, demonstrating the need to consider the local temperature that the pavements support in the different geographical regions.

The observations on the impact of the CDD on the durability of the asphalt mix layers show that the probable range of the progressive evolution of damages, that is, between its beginning and its critical phase, is from 45,000 to 80,000 ºC-

days. This damage range can be considered valid for the climatic conditions of Ecuador and the AC-20 asphalt cement produced at the Esmeraldas Refinery and would imply useful lifetimes for the coastal region between 4.1 and 7.3 years and

in the Andean region between 6.7 and 11.8 years. It is recalled that this range has been estimated from cores sampling from roads with rigorous construction controls and adequate drainage. ***Adnan, Enajar; Ashraf, El Damatty; Ashraf, Nassef. (2021).*** *Solución semianalítica para techos a dos aguas bajo cargas de viento ascendente. Estructuras de Ingenieria, 229. 1-2*

8. Recommendations

It is recommended to apply the CDD criteria in the study and comparison of the properties of the recovered asphalts from cores. In addition, knowledge of the CDD-related damage range can be an important element in planning maintenance and rehabilitation activities.

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