# ECOLOGICAL ASPHALT MIXTURES

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## ABSTRACT

This article presents experimental results obtained on road materials and their improvement from the use of non-biodegradable waste, such as polystyrene and tire rubber. A dense hot mix was analyzed, which is of great use in flexible pavements. A chemical and rheological analysis of the modified binders with non-biodegradable waste was performed.

In this phase of research the asphalt mixture's response to effects such as rutting, fatigue and the alteration of the dynamic modulus was proved depending on the modifier used. For the analysis of the studied mixture, the aggregates, the asphalt and the modifiers were characterized. The trials were conducted for chemical stability, deformation, fatigue and dynamic modulus. Finally, the obtained results were analyzed and the benefit, the improvement and proper utilization of the investigated mixture are presented. The scope of this phase of the research is to observe this new material's response for asphalt mixtures.

KEYWORDS: modified asphalt mixtures, polystyrene, tire powder, recycling, paving, trapezoidal fatigue, dynamic modulus, rutting, SARA.

## INTRODUCTION:

Colombia is one of the countries with the largest deficit in road infrastructure in the world. The main problems that occur in asphaltic pavements currently in service are low resistance to fatigue and permanent deformation, which is generally the result of an inadequate dosage of binder-aggregate interactions, the method of placement, mixing and compaction of the asphalt mixture and the performance of materials under extreme temperature changes.

Modified asphalt binders are the products designed to exceed the original asphalt properties, improving pavement performance over time. Although the modifiers can affect

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many properties, most of them try to reduce the dependence on temperature, oxidation hardening of asphalt cement and the moisture susceptibility of the asphalt mixture (Coinsky, 1994).

Polymer modified bitumen (PMB) used in road paving are new materials that are currently widely used in paving for roads with heavy traffic or extreme temperatures. Overall, polymer modified asphalt improves properties such as: lower temperature susceptibility, a greater range of plasticity, greater cohesion, a better elastic response, greater resistance to water and aging. In this paper, the feasibility of improving the mechanical behavior of asphalt mixtures was studied with CIB asphalt (from the Barrancabermeja Industrial Complex[5], CIB) when modifying the conventional binder with two polymer waste products, expanded polystyrene (Styrofoam) and tire powder. The products developed from the physicochemical and mechanical characterization were a dense hot mix of asphalt mixture MDC-2 and an INVIAS (Colombian National Road Institute) norm.

## BACKGROUND

### 1. *MODIFIED ASPHALT BINDER*

Modified asphalt binders are products designed to exceed the original asphalt properties, improving asphalt performance over time. Although the modifiers can affect many properties, most of them try to reduce the dependence on temperature, oxidation hardening of asphalt cement and the moisture susceptibility of the asphalt mixture (Coinsky, 1994).

The modifiers used in this research are:

Tire powder: improves the flexibility and tensile strength of asphalt mixtures reducing the appearance of cracks resulting from fatigue or changes in temperature. It is used in thin open grain films and surface treatments.

Among the most used synthetic rubbers used to modify asphalt are those of styrene butadiene rubber type. After curing, this material contains 20 to 23% of styrene. The presence of butadiene allows cross-linking with sulfur, being able to produce the CIS isomer[5], which has a greater elasticity than natural rubber. Styrene permits obtaining a harder and tougher rubber, resulting that it does not crystallize under great forces.[5]

Polystyrene: a transparent and relatively fragile plastic material, but it can be modified with rubber, making it expandable and impact resistant. The presence of a benzene ring in each carbon atom of the main chain produces a rigid configuration with sufficient steric hindrance to make the polymer very inflexible at ambient temperature. It is applied to interior pieces of automobiles, appliance buttons and household items. (Yip & Dalton 1971).
At high temperatures in the polymer-modified binders, creaming and sedimentation phenomena can be caused, enriching the polymer binder in the bottom or top of the tank depending on the density of the polymer binder. This destabilization may occur due to the lack of compatibility between the two and / or the incorrect dispersion of the polymer, because the system and mixing conditions are poor.

[5] See Figure 12

One of the older and most complete works on polymer modified asphalt is that of J. Collins et al (1991), in which the authors demonstrated the effectiveness of polymers in improving the properties of the asphalt at high and low temperatures.
(Socal da Silva et al 2004) studied the effect of the chemical composition of polymer modified asphalt mixtures on the linear viscoelastic properties of asphalt and correlated these properties with the thermal susceptibility.
In Colombia, the Urban Development Institute (Instituto de Desarrollo Urbano, 2002) conducted an investigation for the use of tire powder on pavements. In it, they establish the methodology to be followed to improve the mechanical properties and the durability of asphalt mixtures made with asphalt from the Barrancabermeja industrial complex (Complejo Insustrial de Barrancabermeja, CIB) and the Apiay refinery, using ground rubber.
(Reyes & Figueroa 2008) studied the different types of asphalt mixtures with different gradations, as amended by dry and wet modifiers from non-biodegradable wastes applied independently in each mixture. The scope of this research was physical mechanical. Finally, the work of (Figueroa, Reyes 2005) was reviewed, in which modified asphalt mixtures were elaborated with the wet method, using asphalt from the Barrancabermeja industrial complex (CIB) and a percentage of shredded polystyrene (Styrofoam) from disposable cups as a modifier. The results indicated that the asphalt mixture made from modified CIB asphalt is stronger and stiffer than the conventional asphalt mixture prepared.

## *2. ENVIRONMENTAL CONTRIBUTION*

In Bogota, approximately 600 tons of waste are produced every day and are ultimately destined for landfills. According to studies, in Colombia 55% of the waste is organic, 10% plastic, 13% paper and cardboard, 7% glass, 3.5% metals and 12% others (textiles, leather, ceramics, etc.). Most landfills do not have a proper recycling system, plant selection or use of such wastes or manual selection for sustenance and support to communities that live from recycling. This research aims to draw attention to the importance of garbage organization and to show that it is possible to take advantage of materials for roads, like it is the case in other countries of the world.

If we look at the background on the use of waste and energy saving, it can be observed that the major interest internationally has been aroused by the Organization for Economic Cooperation and Development, OECD. In 1980 they presented a project for the incorporation of plastic waste in asphalt mixtures which received funding from the Advisory Scientific and Technical Research in France.

Throughout the process there emerged two seemingly intractable problems: how to incorporate plastic asphalt and the choice of a proper disposal. The first of the two above problems stemmed from the idea that plastic could only act in the bituminous mixture as a modifier of the rheological properties of asphalt, and the second lay in waste having a nature which was suitable for the alleged modification and that it can be available in form and amounts that would ensure a minimum technical feasibility.

After that various research programs around the world started with the aim of improving the response of materials with the use of these wastes. (Reyes, Figueroa, 2008).

This research presents an approach to what we can do with this type of non-biodegradable waste.

## 3. *ASPHALT MIXTURE*

For this research, an INVIAS[6] MDC-2 standard rolling mix for high usage in the country was designed. The design process of the mixture was of Marshall type and properties obtained are presented in Table 1.

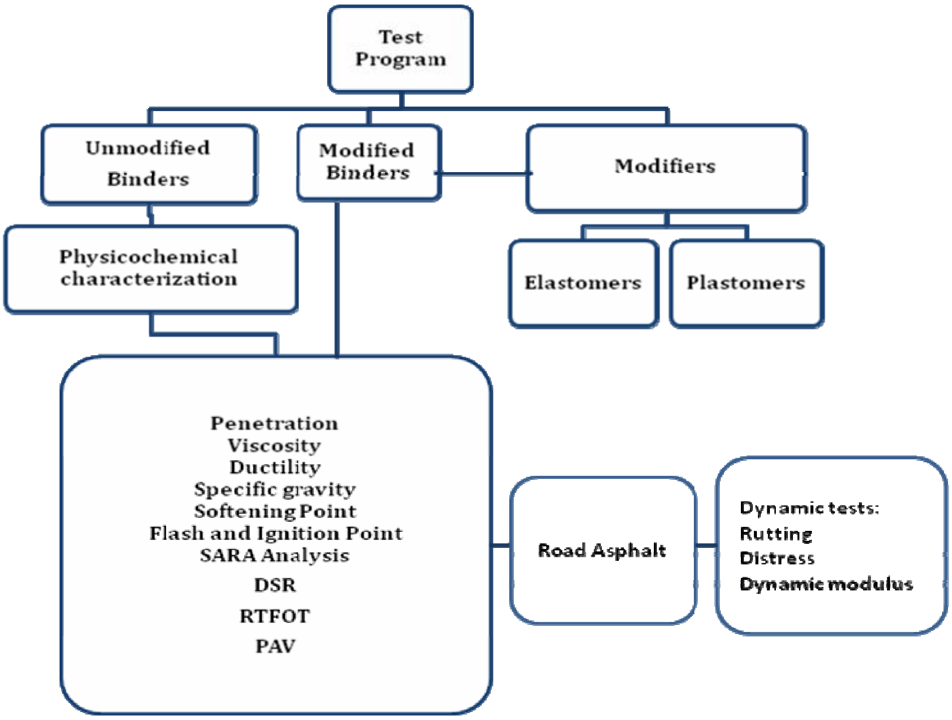
Table 1 Results of the asphalt mix design

| TEST | RESULT | | TEST | OBTAINED VALUE |
|---|---|---|---|---|
| Applied Granulometry | sieve | %passed | Minimum stability (pound) | 2900 |
| | 3/4 | 100% | Flow(mm) | 3,2 |
| | 1/2 | 90% | Voids in the mixture % | 4,9 |
| | 3/8 | 80% | | |
| | N°4 | 61% | Voids in the aggregates % | 15,2 |
| | N°10 | 45% | | |
| | N°40 | 21% | Unit weight (g/cm3) | 2,24 |
| | N°80 | 12% | | |
| | N°200 | 6,50% | | |

MATERIALS AND METHODS

The asphalt used for this research came from Ecopetrol's Barrancabermeja industrial complex with a penetration of 80-100, while the used modifiers were polystyrene (Styrofoam cups) and tire powder from used tires. An overview of the tests carried out in this investigation is shown in Figure 1.

Figure 1 Tests carried out in this investigation




[6] INVIAS, Instituto Nacional de Vías, Colombia.

Modifying polymers were characterized according to their physical and chemical properties in the chemical laboratories at La Salle University's Candelaria branch, as they were studied morphologically by scanning electron microscopy in the SEM laboratory of the Interfaculty Center at the National University of Colombia. The equipment used for the analysis was a Fei Quanta 200 scanning microscope at a voltage of 30kV of the Interfaculty Center at a high vacuum mode operation (3 x 10-6 torr.).

1. Asphalt modification

The asphalt was modified mechanically using the asphalt disperser at the pavement laboratory at La Salle University. In accordance with the conditions established in preliminary tests and previous works (Figueroa A. et al, 2007), (Ocampo et al, 2002), an experimental design was proposed to establish the optimum percentage of tire powder for the previously established modification conditions.

The levels studied for the variable of tire powder percentage were 0%, 12%, 14%, 16% and 20%, and instead of a single response variable, the experimental conditions that produced the modified asphalt with the best performance according to the compatibility and stability were standardized, as well as for chemical and morphological characteristics.

Each asphalt-polymer mixture prepared was submitted to the test of storage stability and temperature described in (U.S. Pat. No. 5.348.994) on an apparatus built for research, which meets the specifications in The Shell Bitumen Handbook (2004). See Figure 2.

Figure 2 Asphalt disperser - La Salle University Laboratory

**Asphalt disperser**
**La Salle University Laboratory**

**Asphalt disperser**
**La Salle University Laboratory**

2. Conventional and modified Asphalt Characterization

The asphalt from Ecopetrol's Barrancabermeja industrial complex (CIB asphalt) with an original penetration of 80-100 and the modified mixtures prepared according to the preceding paragraph were characterized physicochemically and rheologically. Physicochemical analysis of samples from conventional and modified asphalt was conducted in accordance with the rules of the National Roads Institute (INVIAS) and included the following tests: ductility, penetration, specific gravity, flash and ignition point, softening point and mass loss in thin film.

The tests that are explained hereafter were performed only with conventional asphalt and modified asphalt that showed the best results in the previous tests.

2.1 Chemical characterization of original and modified binders

The procedure that describes the standard indicates that the asphalt analyzed by solvents can be separated into four clearly differentiable fractions; one fraction in the solid state, which is identified as asphaltenes, which provide rigidity and hardness to the binder, is the heaviest fraction. The following three fractions are liquid in the following order: first, saturated hydrocarbons are distilled using heptanes and toluene. This solution has an almost translucent color. Immediately afterwards, the aromatic hydrocarbons, which react to the presence of toluene and methanol are distilled, whose color is yellow. Finally, resins are distilled in the presence of Trichloroethylene and its color is brown. See figure 3.

The analysis of the four fractions or SARA analysis (Saturates, Aromatics, Resins and Asphaltenes) was performed in duplicate in each of the following samples:

| | |
|---|---|
| ORIGINAL UNMODIFIED WITHOUT AGING | ASF 80-100 UM-WA |
| ORIGINAL UNMODIFIED WITH AGING | ASF 80-100 UM-A |
| MODIFIED WITHOUT AGING | ASF 80-100 M-WA |
| MODIFIED AGED | ASF 80-100 M-A |

The results of column chromatography analysis with the SARA method, developed for the unmodified and modified asphalt in conditions with RTFO and without aging can be observed in Table 1; the calculation of the colloidal instability index (CII) was determined using Equation 1 and the Solubility Index (SI) using Equation 2. The SI value indicates the colloidal structure as follows:

- SI < 4 = GEL Structure
- 4 < SI < 9 = SOL-GEL Structure
- SI > 9 = SOL Structure

Figure 3 Separation of the asphalt into its four SARA (Saturates, Aromatics, Resins, Asphaltenes) fractions.

$$CII = \frac{Flocculated\ constituents}{Dispersed\ Constituents} = \frac{SATURATES + ASPHALTENES}{AROMATICS + RESINS}$$
(Equation 1)

$$SI - \frac{RESINS}{ASPHALTENES} + \frac{AROMATICS}{SATURATES}$$ (Equation 2)

If asphalt is of GEL type, it has a low thermal sensitivity. It is characterized by having a retarded elastic deformation and showing low permanent deformations due to loading and temperature. If the asphalt behaves like SOL type, it means that it has a high thermal sensitivity, given the low percentage of asphaltenes (hardness and stiffness), a condition that causes permanent deformation (rutting) in the asphalt mixture. If the asphalt is of SOL-GEL type, it is characterized by its elastic behavior and an immediate thermal sensitivity. See table 2.

Table 2 Results of the SARA analysis, modified and unmodified asphalt in aged and unaged state.

| ASPHALT | SATURATED | AROMATICS | RESINS | ASFALTENOS | MALTENOS | IC | IS |
|---|---|---|---|---|---|---|---|
| Unmodified Asphalt - Sampling 2 | 19.45% | 25.27% | 42.32% | 12.96% | 87.04% | 0.48 | 4.56 |
| Modified Asphalt - Sampling 3 | 14.21% | 19.85% | 44.94% | 21.00% | 79.00% | 0.54 | 3.54 |
| Modified Asphalt - Sampling 4 | 14.54% | 20.96% | 42.50% | 22.00% | 78.00% | 0.58 | 3.37 |
| Unmodified Asphalt , Aged - Sampling 1 | 13.25% | 34.97% | 31.21% | 20.58% | 79.42% | 0.51 | 4.16 |
| Unmodified Asphalt , Aged - Sampling 2 | 11.88% | 30.24% | 36.23% | 21.65% | 78.35% | 0.50 | 4.22 |
| Modified Asphalt Aged - Sampling 3 | 12.56% | 17.89% | 46.43% | 23.12% | 76.88% | 0.55 | 3.43 |
| Modified Asphalt Aged - Sampling 4 | 13.83% | 16.08% | 45.66% | 24.42% | 75.58% | 0.62 | 3.03 |

Below some indices calculated from the four fractions of each analyzed sample can be observed. See table 3.

Table 3 SARA analysis indices: unmodified and modified asphalt in aged and unaged states.

| ASPHALT | SATURATED / RESINS | SATURATED AROMATICS | AROMATICS / RESIN S | RESINS / AROMATICS | RESINS / ASFALTENOS |
|---|---|---|---|---|---|
| Unmodified asphalt - Sampling 2 | 0.46 | 0.77 | 0.60 | 1.67 | 3.27 |
| Modified Asphalt - Sampling 3 | 0.32 | 0.72 | 0.44 | 2.26 | 2.14 |
| Modified Asphalt - Sampling 4 | 0.34 | 0.69 | 0.49 | 2.03 | 1.93 |
| Unmodified Asphalt,aged Sampling 1 | 0.42 | 0.38 | 1.12 | 0.89 | 1.52 |
| Unmodified Asphalt, Aged – Sampling 2 | 0.33 | 0.39 | 0.83 | 1.20 | 1.67 |
| Modified Asphalt Aged -Sampling 3 | 0.27 | 0.70 | 0.39 | 2.60 | 2.01 |
| Modified Asphalt, Aged – sampling 4 | 0.30 | 0.86 | 0.35 | 2.84 | 1.87 |

These results show that the modified asphalt in its two states, aged and unaged, is considered asphalt of type GEL, while unmodified asphalt samples are considered SOL-GEL type. It can be seen that the samples, where the asphaltene percentage is higher, are considered more rigid because the asphaltenes give the binder properties of structure and stiffness. The same happens with resins, which should also increase. These results are confirmed by looking at Table 4, which shows that modified asphalt is more rigid, while the penetration in the sample decreases, as well as ductility.

Table 4 Results of physical analysis of unmodified and modified asphalt in aged and unaged state.

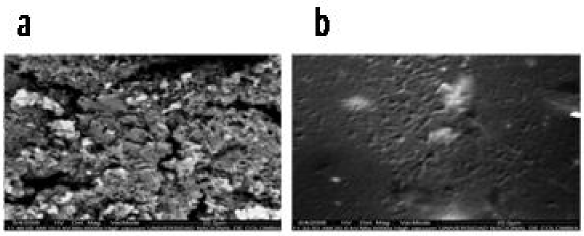
| TEST | UNIDAD | REGULATIONS | UNMODIFIED ASPHALT | | | | MODIFIED ASPHALT | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | MIN. | MAX. | WITHOUT AGING | AGED | MIN. | MAX. | WITHOUT AGING | AGED |
| DUCTILITY (25ºC, 5 cm/min) | cm | INV-E-702 | 100 | - | 140 | 140 | 15 | - | 42.9 | 35 |
| PENETRATION (25ºC, 100 g, 5s) | 0.1 mm | INV-E-706 | 80 | 100 | 90 | 31 | 55 | 70 | 60 | 47 |
| SPECIFIC GRAVITY | g/cm3 | INV-E-707 | - | - | 1.0083 | N.A. | - | - | 1.0262 | N.A. |
| IGNITION POINT | ºC | INV-E-709 | 230 | - | 306 | N.A. | 230 | - | 299 | N.A. |
| FLAME POINT | ºC | INV-E-709 | - | - | 348 | N.A. | - | - | 349 | N.A. |
| SOFTENING POINT | ºC | INV-E-712 | - | - | 46 | 48.5 | 58 | - | 55 | 55 |
| PENETRATION RATE | - | INV-E-724 | -1 | +1 | -0.7907 | -2.5159 | -1 | +1 | 0.4394 | -0.0648 |
| BROKFIELD VISCOSITY (80ºC) | cP. | INV-E-717 | - | - | 21642 | 36902 | - | - | 147333 | 147125 |
| BROKFIELD VISCOSITY (135ºC) | cP. | INV-E-717 | - | - | 418.8 | 583.3 | - | - | 3106 | 2533.9 |
| BROKFIELD VISCOSITY (180ºC) | cP. | INV-E-717 | - | - | 75 | 86.9 | - | - | 521 | 426.5 |
| MASS LOSS | % | INV-E-720 | - | 1% | -0.431% | | - | 1% | -0.511 | |
| ELASTIC RECOVERY | % | INV-E-742 | - | - | N.A. | N.A | - | - | 61.17% | 59.00% |
| PENETRATION TO THE WASTE % OF THE ORIGINAL | % | INV-E-706 | 48 | - | 34% | | - | - | 78% | |
| SOFTENING POINT TO INCREASE WASTE | ºC | INV-E-712 | - | 5 | 2.5 | | - | - | 0 | |

With these chemical indices, one can start to define and predict the behavior of the binder during its lifetime.

Looking at Table 3, it can be seen that the modified, RTFO aged and unaged asphalt present a higher percentage amount of resins and a decrease in percentage of aromatics and saturates. This means that the asphalt has a higher rigidity and supports higher mixing and compaction temperatures, this being the asphaltenes and resins that contribute stability and support within the asphalt mixture.

Another test conducted with the modified binder was the “Fraction of resins” test, for which the original CIB asphalt showed weak bands at 750 cm-1 (deformation vibration out of plane methyl group of aromatic CH4 links), 1605 cm-1 (stretching bands of aromatic carbons), 1705 cm-1 (stretching bands of carbonyl and/or carboxyl groups), 2852 cm-1 (stretching vibration bands of CH bonds) and a band of medium intensity around 1465 cm-1, corresponding to deformation vibrations of methyl and methylene groups. The modified asphalt shows absent band or of higher intensity than the corresponding fraction of the conventional asphalt: 750 cm-1, 1000 cm-1 to 1200 cm-1 (oxygenated), 1305 cm-1 and 1605 cm-1, which are explained by reasons similar to those described above. Figure 4 shows the photographs obtained by high vacuum scanning electron microscopy (SEM), for the conventional and modified CIB asphalt.

Figure 4 a) Conventional CIB asphalt SEM analysis (6000X)[7] b) Modified CIB asphalt SEM analysis (6000X)[8]

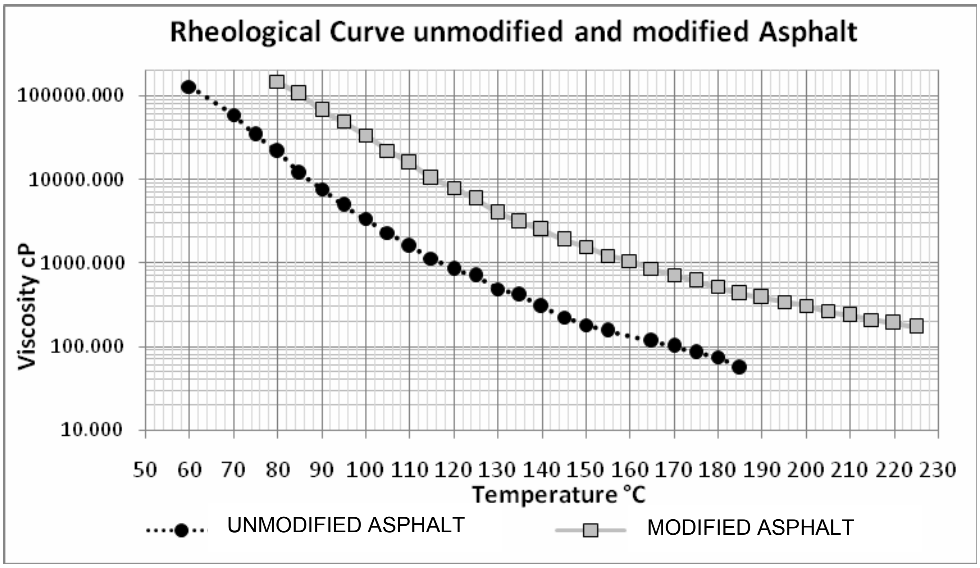



In the photographs above one can see the influence of polymers on the morphological characteristics of asphalt. Figure a) that corresponds to the original CIB asphalt showed sandy aspects of the sample, while in Figure b) the homogeneity of the resulting bitumen is evident, which suggests good compatibility between the asphalt and the polymer and therefore stability of this binder against storage and elevated temperatures.

### 2.2 Brookfield Viscosity Curve

To get an indication of viscosity change with temperature variation, the same was measured form the Brookfield viscometer test. See figure 5.

Figure 5 Comparison of the rheological curve between unaged, modified and unmodified asphalt.




### 2.3 Aging process in primary RTFO

After completing the physical characterization of normal and modified binders in unaged state, the aging process of the binder was performed using the Rolling Thin Film Oven Test (RTFO), which is a method used to bring the asphalt binder to a condition equal or close to that present at the time of entering into service. See figure 6.

[7] The autors, 2008
[8] The autors, 2008

Figure 6 Primary aging test in RTFO oven


Figure 7 Mass change after RTFO.

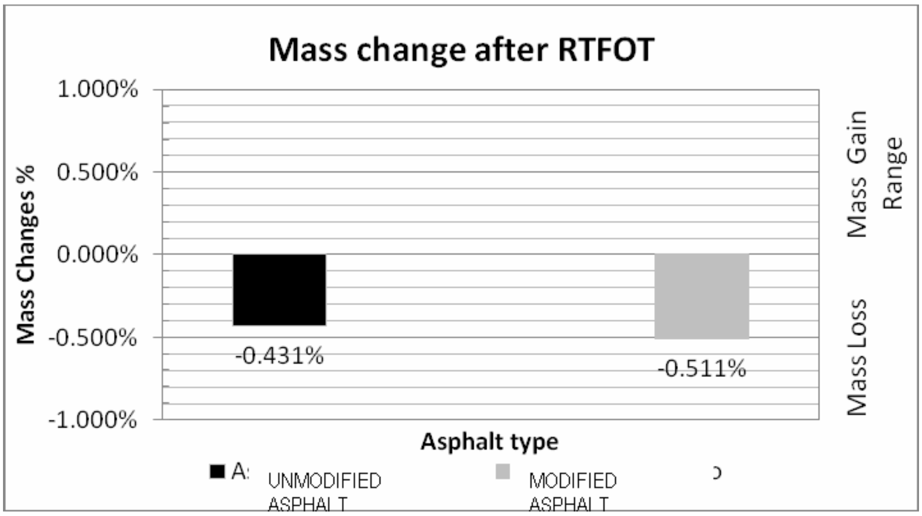



Figure 8 Comparison of the rheological curve of aged, unmodified and modified asphalt.

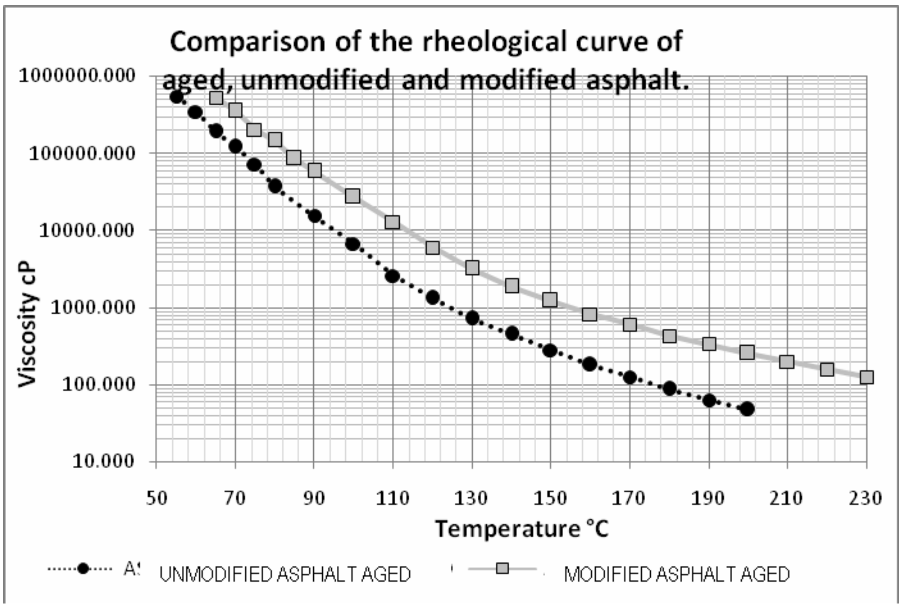


Table 5 Results of physical analysis of unmodified and modified asphalt in an aged and unaged state.

| ENSAYO | UNIDAD | NORMATIVIDAD | ASFALTO NORMAL | | | | ASFALTO MODIFICADO | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | MIN. | MAX. | SIN ENVEJECER | ENVEJECIDO | MIN. | MAX. | SIN ENVEJECER | ENVEJECIDO |
| DUCTILIDAD (25°C, 5cm/min) | cm | INV-E-702 | 100 | - | 140 | 140 | 15 | - | 42.9 | 35 |
| PENETRACIÓN (25°C, 100g, 5s) | 0.1 mm | INV-E-706 | 80 | 100 | 90 | 31 | 55 | 70 | 60 | 47 |
| GRAVEDAD ESPECIFICA | g/cm$^3$ | INV-E-707 | - | - | 1.0083 | N.A. | - | - | 1.0262 | N.A. |
| PTO. IGNICIÓN | °C | INV-E-709 | 230 | - | 306 | N.A. | 230 | - | 299 | N.A. |
| PTO. LLAMA | °C | INV-E-709 | - | - | 348 | N.A. | - | - | 349 | N.A. |
| PTO. ABLANDAMIENTO | °C | INV-E-712 | - | - | 46 | 48.5 | 58 | - | 55 | 55 |
| INDICE DE PENETRACIÓN | - | INV-E-724 | -1 | .+1 | -0.7907 | -2.5159 | -1 | .+1 | 0.4394 | -0.0648 |
| VISCOSIDAD BROKFIELD (80°C) | cP. | INV-E-717 | - | - | 21642 | 36902 | - | - | 147333 | 147125 |
| VISCOSIDAD BROKFIELD (135°C) | cP. | INV-E-717 | - | - | 418.8 | 583.3 | - | - | 3106 | 2533.9 |
| VISCOSIDAD BROKFIELD (180°C) | cP. | INV-E-717 | - | - | 75 | 86.9 | - | - | 521 | 426.5 |
| PERDIDA DE MASA | % | INV-E-720 | - | 1% | -0.431% | | - | 1% | -0.511 | |
| RECUPERACIÓN ELASTICA | % | INV-E-742 | - | - | N.A. | N.A. | - | - | 61.17% | 59.00% |
| PENETRACIÓN AL RESIDUO % DE LA ORIGINAL | % | INV-E-706 | 48 | - | 34% | | 65 | - | 78% | |
| INCREMENTO PTO. ABLANDAMIENTO AL RESIDUO | °C | INV-E-712 | - | 5 | 2.5 | | - | - | 0 | |

2.4 Rheology with a Dynamic Shear Rheometer

The rheological analysis was determined by using a dynamic shear rheometer (DSR) at Javeriana University, which is regulated by the AASHTO TP-5. Its functionality relies on a sinusoidal pattern of shear stress on a previously defined sample (1mm thick and 25mm in diameter or 2mm thick and 8mm in diameter), and takes results from the response by applying the cut (deformation). The sample is kept at the test temperature using the thermal camera of the DSR equipment. See figure 8.

Figure 1: Direct Shear Rheometer DSR

**DSR Equipment La Salle University Laboratory**

**DSR equipment and ETC camera**

**Sampling of 8mm diameter Modified Asphalt**

**Sampling of 8mm diameter Modified Asphalt**

The analyzed patterns determine two important parameters among many others:

- Dynamic Modulus (G*): is considered an indicator of stiffness or resistance of the asphalt binder to deformation due to shear stress applied to the sample.

- Phase angle (δ): is the indicator of elastic (recoverable) and viscous (non-recoverable) deformation.

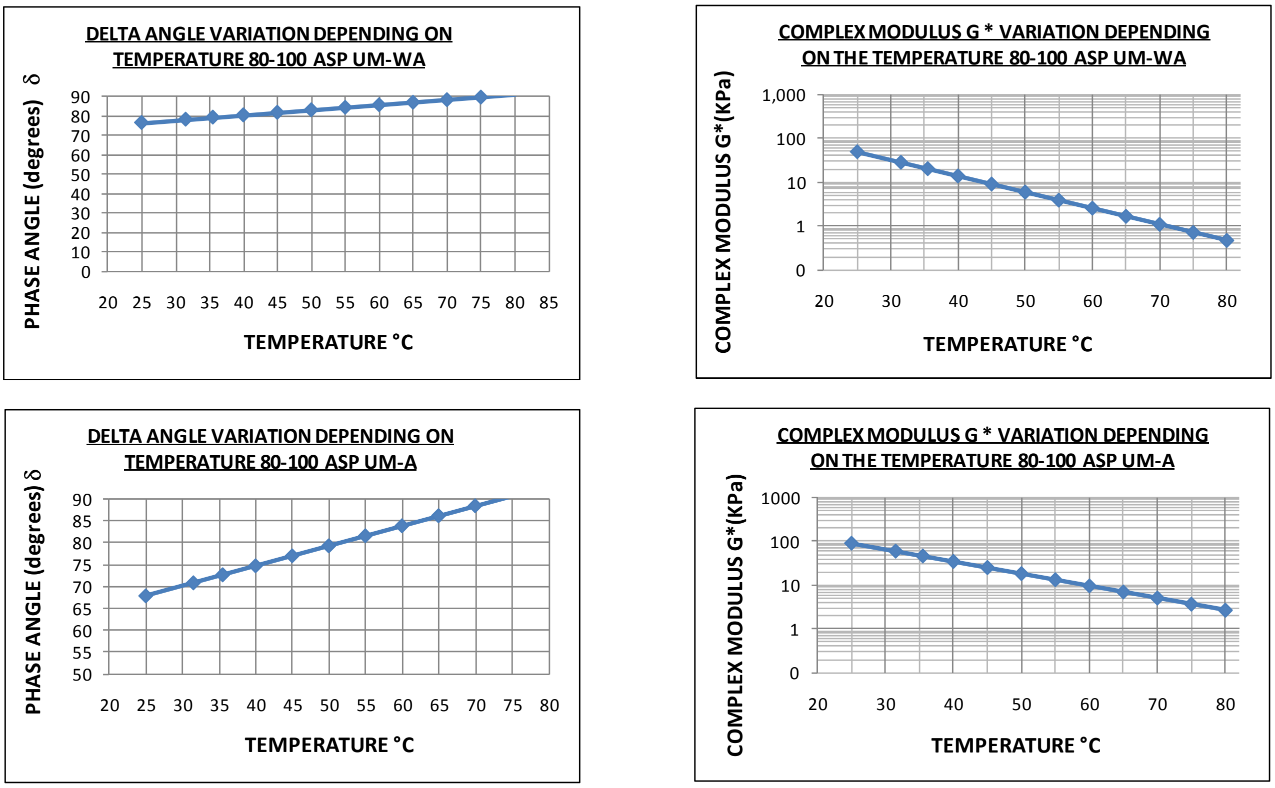
With these two parameters, the shear strength of an asphalt binder and other properties directly related to these parameters can be determined. See Table 6 and figure 9.

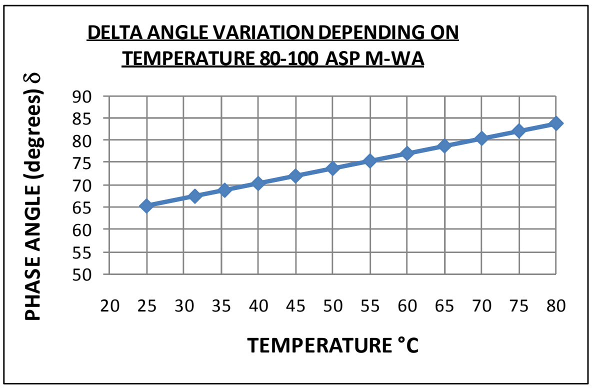
Table 6: Rutting control in the DSR

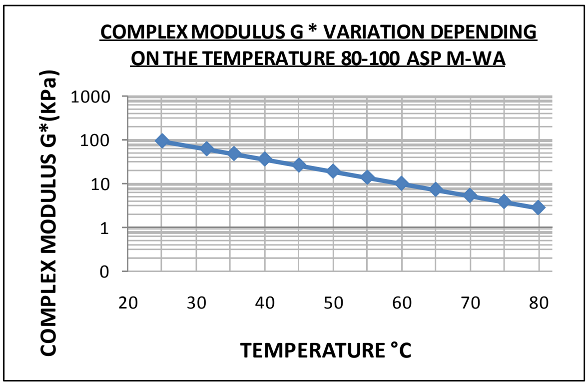
| FORMULA | ASPHALT TYPE |
|---|---|
| G*/sin(δ) > 1 kPa | Unmodified asphalt |
| G*/sin(δ) > 2.2 kPa | RTFO-aged asphalt |

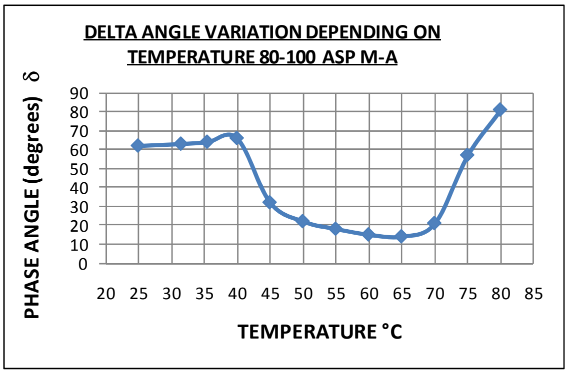
2.4.1 Results of asphalt binders in the DSR for unmodified, modified and aged asphalts, respectively.

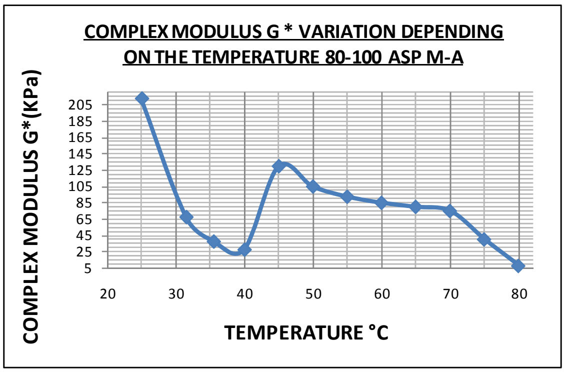
Figure 2: Graphs obtained in the DSR test






From these results it can be observed that in the case of modified and unmodified asphalt as the temperature increases, the δ angle increases, however when comparing the modified asphalt with unmodified asphalt the latter is more susceptible to rutting. This indicates that the modified asphalt could reduce possible plastic deformations that occur in the asphalt mixture.

The complex modulus of unaged modified asphalt is higher than that of unaged and unmodified asphalt. This last aspect is desirable because increasing the mixing module is likely to have a better response to the burdens imposed by the traffic with low distortion. See table 7.

Table 7 Complex shear modulus obtained

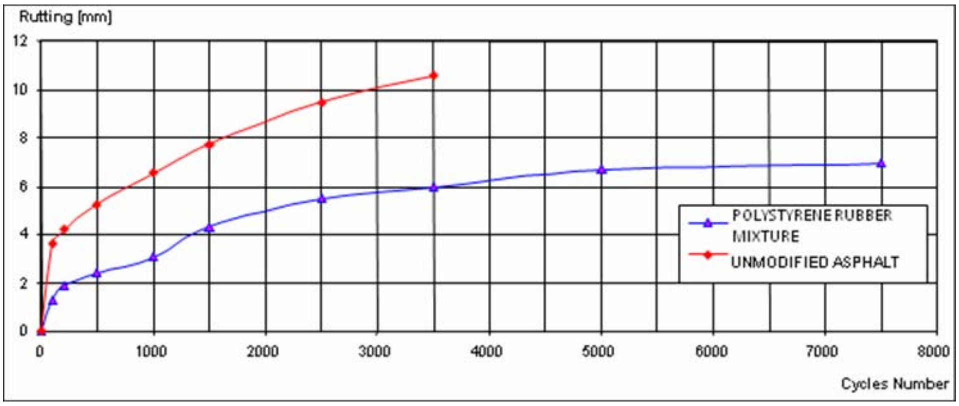
| COMPLEX SHEAR MODULUS | | |
|---|---|---|
| **BINDER** | **T°C** | **\|G*\| Pa** |
| UM-WA | 60 | 1757 |
| UM-A | 60 | 2652 |
| M-WA | 60 | 94249 |
| M-A | 60 | 46362 |

## 2.5. Dynamic Tests

### 2.5.1. Rutting

The plastic deformation obtained for the modified mixture shows a decrease of 4% of relevant aspect for high-traffic, eventually channeled roads and Transmilenio type (articulated buses with a capacity of 160 people in Bogota). The figure below shows the results for a conventional and modified mixture.

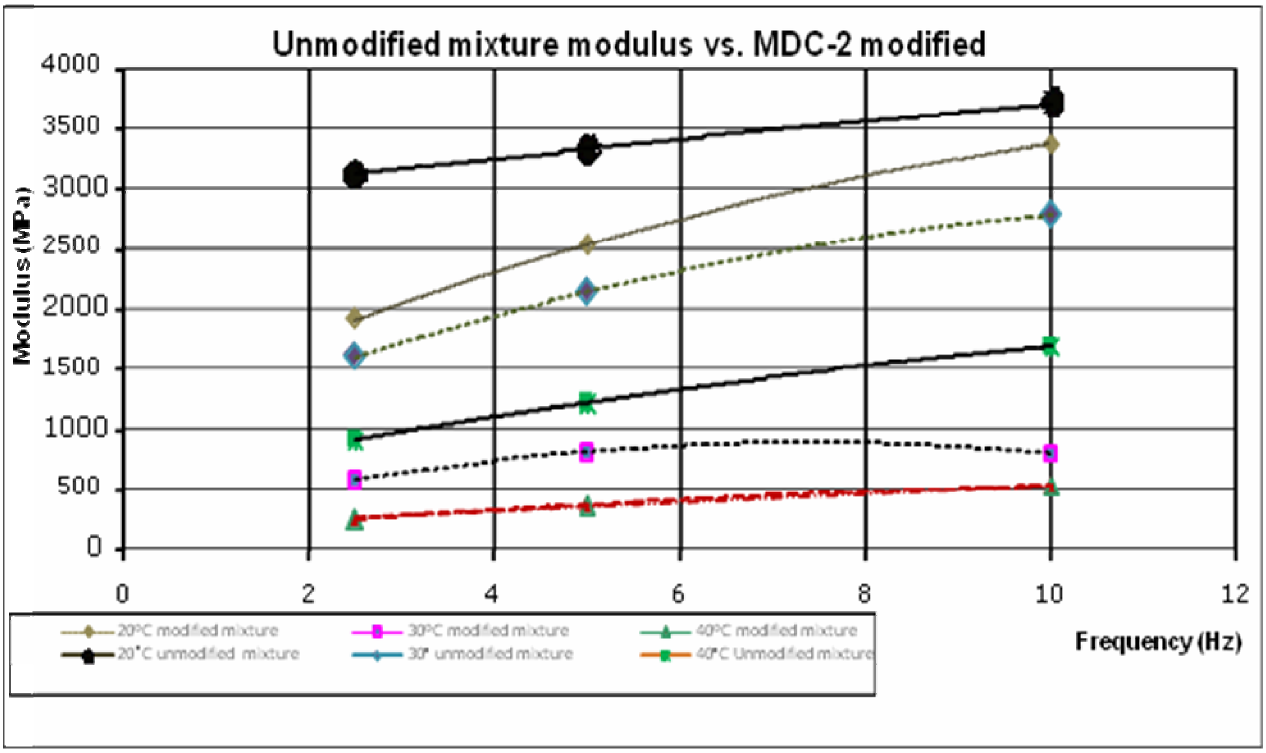
Figure 3: Comparison of results obtained from rutting tests of original and modified CIB asphalt mixtures.




2.5.2. Dynamic Modulus

Comparison between the modulus of the unmodified and modified mixture shows that at 20°C and 10Hz, they are very similar for both types of mixtures. Although the form of modified asphalt did not increase as significantly as expected, it is in the workable range for a climate like that of Bogota. See figure 12.

Figure 4: Comparison of dynamic modulus for a modified and unmodified MDC-2 mixture with tire powder and polystyrene.

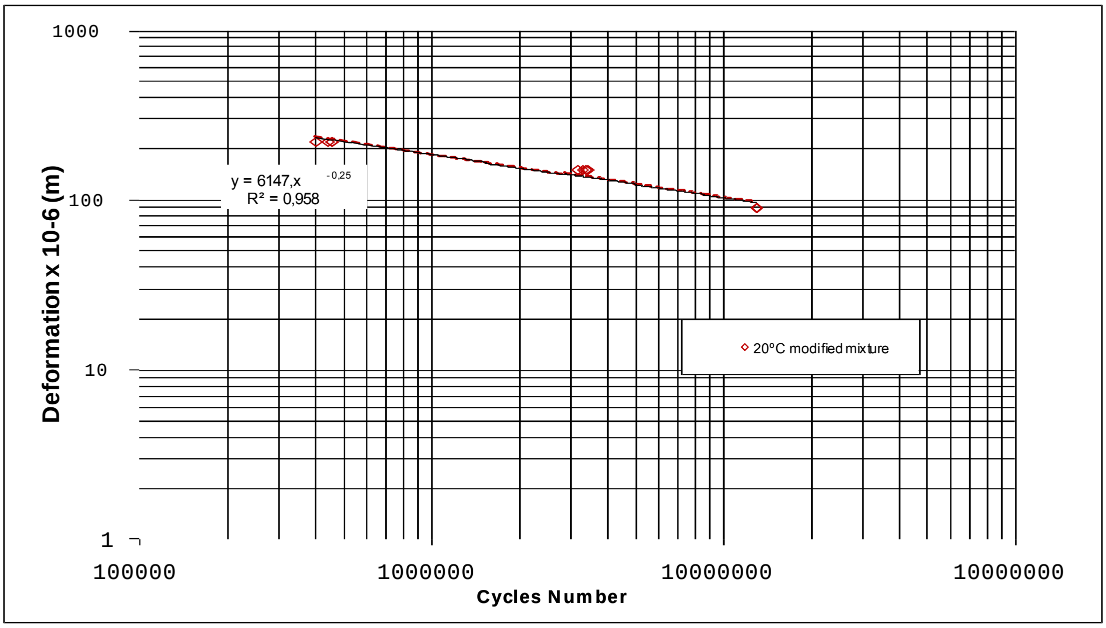



This fatigue test, performed according to the NF P 98-261-1 standard, shows that the fatigue law gives a b slope of -0.25, which is in the normal range for asphalt mixtures. The maximum deflection permitted under this test for the modified mixture is shown in Equation 3.

$\varepsilon_6 = 194x10^{-6}$ (Equation 3)

The deformation obtained for one million cycles for the modified mixture is lower than the one obtained for the same number of cycles for the conventional asphalt mixture. In a conventional mix, $\varepsilon_6 = 120x10^{-6}$ and b = -0,22.

Figure 5: Fatigue law for a modified mixture.




## DISCUSSION AND CONCLUSIONS

It was established that the expanded polystyrene as a polymer maintains and improves the elastic properties of the binder, while the tire powder increases properties like thermal sensitivity, fatigue resistance, flammability and solvent resistance. According to the results of the research, the optimal percentages of each polymer for conventional CIB asphalt modification was found, and this dosage produced a stable modified binder (in regard to binder-polymer interactions), which besides containing an important percentage of tire powder to contribute to solving a serious environmental problem. The results indicated that no significant change was observed in the chemical structure of the asphalt binder, the modified CIB asphalt obtained being a physical asphalt-polymer mixture that is stable and homogeneous. Rheological and calculated flow-activation energy curves let predict a lower thermal susceptibility of conventional CIB asphalt. The fatigue law for the polystyrene and asphalt powder modified CIB mixture showed a fatigue law of $194x10^{-6}$, a value that is consistent with that found in the investigation of IDU for only tire powder, $180x10^{-6}$ and an unmodified mixture of $120x10^{-6}$. The plastic deformation proven through rutting tests had a significant decrease in the modified mixture compared to the conventional. The reduction was about 4%, which is important to avoid rutting or sinking in areas prone to repeated loading and channeling. Finally, one of the most important claims to our results is to contribute information to implement as a norm in this country the use of non-biodegradable waste like tire powder, among others, in asphalt mixtures. Shear rheometer tests determined that the modified, unaged binder is more elastic than the unmodified binder. This condition contributes to the recovery that has a mixture with low cyclic loading. Regarding the performance in the aged condition, new repeatability tests have to be conducted to study the points that are generated in the atypical test. It is worth having in mind that it is a new material and that a new performance should be found for it. The complex modulus of the modified binder is greater than the one of the unmodified binder in the studied temperature range, which was between 25 and 80°C. It is recommended to analyze points in intervals of low (negative) and high (higher than the mixture) temperature and study more repeatedly the results obtained from the dynamic modulus of modified binder aging.

When performing a conventional mixture design and one with modified mixtures, the following structures are received:

| Design traffic | Resilient modulus of subgrade (MPa) | Modulus of conventional asphalt mixture (MPa) | Modulus of modified asphalt mixture (MPa) | $\varepsilon_6 x10^{-6}$ Conventional mixture | $\varepsilon_6 x10^{-6}$ Modified mixture | Thickness conventional mixture cm | Thickness modified mixture cm |
|---|---|---|---|---|---|---|---|
| 500000 | 50 | 3500 | 3540 | 120 | 194 | Asphaltic mixture:24cm | Asphaltic mixture:16cm |

This means that there is a reduction in asphalt thickness of 34% for poor quality soil, such as the one of Bogota.

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