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Optimization of the static mechanical properties of two bituminous concretes modified by partial bitumen replacement with a mass-total of tire powder, plastic bottle powder, and sulfur, depending on the production procedure

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Abstract
This paper examines the effect of the manufacturing process on the static mechanical properties of modified bituminous concrete by partially replacing the bitumen with the mass sum of tyre powder, plastic bottle powder, and sulfur. This optimization is in response to the persistence of pavement degradation despite multiple solutions based on material type and method of obtaining doped bituminous concrete. These solutions are high modulus mixes (EME), bituminous concretes doped with rubber or plastics and cross-linked bituminous concretes on the one hand, and bituminous composites manufactured by dry or wet process (Shaoula; 2008), after partial substitution of conventional materials by dopants or by adding dopants on the other.
To better understand the evolution of the static mechanical properties of neo-bituminous concrete using the Duriez (NF P 98-251-1) and Marshall (NF P 98-251-2) tests, the product was manufactured using the wet process and the dry process (Shaoula; 2008), respectively, after formulation. Formulation translated by 5%, 10%, and 15% substitution of bitumen by the mass sum of PUNR powder, PET powder, and sulfur at 40%, 28%, and 32%, respectively. All of this is preceded by component characterization in accordance with relevant standards. It is discovered that bituminous concretes modified and manufactured using the wet process are quite compact, stable, and resistant than the control composite on the one hand, and clearly preferential to those manufactured using the dry process on the other.

Keywords: Bituminous concrete, tyres, plastic bottles, cross-linking, dry process, wet process

1. Introduction
The aggressiveness of the climate, combined with the constraints associated with the traffic of increasingly intense and slow heavy goods vehicles, provide motivation for improving the properties of the composite used in wearing course. To achieve this shielding, dopants such as fillers, plastic powder, tire powder, palm nut shells, and sulfur are injected. The proposed material can be manufactured using either a dry or a wet process (Shaoula; 2008).
It should be noted, however, that rubbery bituminous concrete deforms more in temperate zones, whereas bituminous concrete enriched with plastics (more than 30%) or sulfur (more than 32%) is shiny. as a result, fewer adherent.
Because elastomer crosslinking allows for a fairly compact, hydrophobic, rigid, and even ductile material, the current work aims not only to capitalize on the aforementioned advantages, but also, and most importantly, to identify the manufacturing process that provides the best properties to the neo-material.
To accomplish this, the Duriez and Marshall parameters of modified bituminous concretes produced using the dry process (Shaoula; 2008) will be compared to those of materials produced using the wet process (Shaoula; 2008). This after partial substitution of 5%, 10%, and 15% bitumen by the mass sum of sulphur, tire powders, and plastic bottles (32%, 40%, and 28%, respectively) on a control bituminous concrete.

2. Materials and Method

2.1 Materials

Traditional materials and partial bitumen substitutes are the two types of components used. Aggregates (gravel and sand) and bitumen are the traditional materials, while partial substitutes include sulphur, tire powder, and powder from transparent and non-opaque plastic bottles.

The base bitumen is manufactured by total in accordance with NF EN 12591 [22], which specifies that the penetrability, softening point, and mass variation fall within the ranges [50; 70, 46; 54], and [0; 0.5]. Granitic aggregates, on the other hand, are sourced from the AKAK ESSE quarry in the South Cameroon region. These materials are used to asphalt the RN 17A Mengong - Sangmelima road in the said region.

The tire powder (fig 1) is produced by screening with a 1 mm sieve and magnetic purification of shredded non-reusable used tire waste (PUNR), which has previously been transformed into cubes washed with plenty of water, spun, and dried.

Fig 1: Obtaining Tire crumbs

Plastic bottle powder, also known as polyethylene terephthalate (PET), is produced by converting bottles into flakes that are wrung out and dried after being thoroughly washed. Sifting with a 1 mm mesh sieve follows melting, cooling, and crushing (fig 2).

Fig 2: PET waste is converted into powder

The sulfur used comes from Nigeria, where it was extracted using the Frash process and then reduced to fines for weighing. This method of extracting sulfur with the fewest impurities involves connecting three (03) pipes to the hearth and then sending a very hot vapor through one of the extremal pipes to finally bombard cold water through the other tube extreme, causing the sulfur to rise through the central channel.

2.2 Method

On the one hand, it entailed characterizing the conventional components and the control bituminous concrete after it had been formulated and manufactured. On the other hand, to determine the properties of modified bituminous concretes after they have been manufactured.

2.2.1 Obtaining bituminous concrete for control

The material from which the partial bitumen substitutions are made is the control asphalt concrete. This partial substitution occurs after the Marshall and Duriez parameters are determined after manufacturing, which is preceded by the formulation and characterization of the conventional components.

2.2.1.1. Characterization of traditional constituents
It entails performing the following tests:

- **Analysis of particle size**
  Particle size analysis, according to standard NF P 94 – 056 [23], is the separation of the elements that comprise a material based on their size using successive sieves with square meshes. These sieves are arranged from bottom to top in increasing mesh order. The material is washed to remove all fines (particles smaller than 80m) before being dried in an oven for 24 hours. The purpose of the test is to represent the size and respective percentages of the different families of grains constituting the material sample using a granulometric curve, which is a representation of the percentages of the sieves or those of the refusals on the sieves. Particle size analysis by sedimentometry is used for particles smaller than 80 microns. The results of said analysis will allow you to determine the percentages of each aggregate that goes into the mixture's composition in order to generate the granular curve, which must fall within the granular zone relating to it to ensure a better formulation.
- The particle size curve yields two (02) parameters. These are the curvature coefficient (C_c) and the uniformity coefficient (C_u), which will provide information on the spread of the granular diameters.

- **The Los Angelès Trial**
  The Los Angeles coefficient (LA) is determined using the NF P 18-573 [24] standard, which is based on the resistance to fragmentation by impact of the elements of a sample of aggregates. The test involves counting the number of elements smaller than 1.6 mm produced after subjecting the material to standardized ball shocks in the Los Angeles machine for 30 minutes. The aggregates are washed and then dried in an oven at 105 °C to remove all traces of water.

- **The Micro Deval Trial**
  It is manufactured in accordance with the NF P 18-572 [25] standard. The MDE parameter that is determined provides information on the wear resistance of the aggregates. This is accomplished by subjecting the aggregates to reciprocal friction with spherical balls (100.5 mm in diameter) in a rotating cylinder. Prior to use, the material is washed and dried in a 105° C oven. The mixture of materials and abrasive filler, which depends on the granular class, is then mixed for 2 hours. Following the test, the whole is washed with water through a 1.6mm sieve, and the oversize (without fillers) is dried in a 105°C oven until the weight is constant.

- **Forma Test**
  It is used to calculate the flattening coefficient (CA) of gravel (sizes ranging from 4 to 50 mm) in accordance with NF P 18 – 561 [26]. A double sieving operation is used in the test. First, using square-mesh sieves, divide the sample into different classes d/D by specifying the mass of each class, which is denoted M g. The second step is to sieve the various granular classes d/D on grids with parallel slots spaced E.

- **The Sand cleanliness Test**
  The sand equivalent (ES) is determined according to standard NF P 18 – 598 [27] on the fraction of the aggregate passing through a 2 mm square mesh sieve, to provide information on the degree of cleanliness of a sand. A dry mass of the sample (120 1g) is placed in a graduated cylindrical test tube containing a washing solution to obtain this parameter. The entire mixture is agitated in 90 cycles 1 cycle for 30 s 1s, and then another quantity of the washing solution is added to clean the edges of the test tube and force the flocculate (the dirt on the sand) to be suspended above the sedimented sand. We notice three distinct parts after 20 minutes of sedimentation (the sedimented sand, the flocculate and the clean washing solution) and we can measure the height of the sedimented sand (h 2') and the height of the sedimented sand with flocculate (h 1) on the graduated cylinder. Finally, a piston is lowered into the test tube until it rests on the sedimented sand, and its height (h 2) is measured using the graduated cylinder.

2.2.1.2 Control asphalt concrete formulation and production
The formulation, which consists in determining the percentage of each granular class, is completed by the calculation of the percentage of bitumen (P bi) using the equation (Eq 1) proposed by S. LALDJI in 2013.

$$P_{bi} = \frac{TG+120}{100} \qquad \text{(Eq1)}$$

Where TG, or total granulometric, is the sum of the percentages of granular mixture passers-by at meshes 16, 12.5, 10, 6.3, 4, 2, and 0.080.

The following seven (07) chronological stages are followed in the production of bituminous concrete in accordance with standard NF EN 13 108-1 [28]:

1. Place the trowel in the tray;
2. Heat the assembly with a continuous flame;
3. Place the aggregates in the heating tank for homogenization by mixing;
4. Set the covered bitumen bowl on top of the aggregates. The cover protects the bitumen from oxidation
5. Create a crater in the center of the heated aggregates;
6. Pour the binder liquefied by heating into the crater;
7. Mix the whole with the trowel in order to homogenize.

2.2.1.3 Control asphalt concrete characterization
The Duriez (NF P 98 251-1) [20] and Marshall (NF P 98 251-2) [21] tests are used.

2.2.2 Production of modified bituminous concretes
The modified bituminous concretes are the result of partial bitumen substitutions at 5%, 10%, and 15%, which are then subjected to the same tests as the control bituminous concrete after being manufactured using the wet and dry processes at equal percentages.

2.2.2.1 Modified bituminous concrete formulation
The preservation of the granular skeleton and partial

substitutions of bitumen at 5%, 10%, and 15% by the mass sum of tire powder, plastic bottle powder, and sulfur at 40%, 28%, and 32%, respectively, result in modified bituminous concrete.

2.2.2.2 Modified bituminous Concrete Manufacture
On the one hand, modified bituminous concretes are produced using the wet process, and on the other, the dry process.

A) Wet process
It entails creating neo-bitumen and then mixing it with aggregates that have already been prepared for mixing.

It is carried out in the following ten (10) steps in chronological order:

1. Place the trowel in the tray;
2. Subject the assembly to continuous flame heating;
3. Place a covered bowl of bitumen in a 150°C oven until liquefaction occurs;
4. Inclusion of partial substituents in pure liquefied bitumen;
5. Steaming + kneading;
6. Removal of the neo-bitumen bowl from the oven for the production of modified bituminous concrete;
7. Placement of the covered bitumen bowl on said aggregates. The cover keeps the bitumen from oxidizing.
8. Make a crater in the center of the heated aggregates;
9. Pour the liquefied neo-binder into the crater;
10. homogenize the whole with the trowel.

B) Dry process
This procedure can be broken down into eight (08) steps, which are listed below in chronological order:
1. Place the trowel in the tray;
2. Heat the assembly with a continuous flame;
3. Place the aggregates in the heating tank for homogenization by mixing;
4. Set the covered bitumen bowl on top of the aggregates.The cover keeps the bitumen from oxidizing.
5. Make a crater in the center of the heated aggregates;
6. Pour the liquefied binder into the crater; and
7. Mix the whole with a trowel to homogenize.
8. Partial addition + mixing for homogenization purposes.

2.2.2.3 Modified bituminous concrete characterization
The Duriez (NF P 98 251-1) [20] and Marshall (NF P 98 251-2) [21] tests are performed on the bituminous concretes produced by the various processes.

3. The findings and their interpretation
Following the completion of the experiments, the results will be analyzed.

3.1 Results
Following the presentation of their formula, the different results are typical of the classic components on the one hand and those of bituminous concretes (control and modified) on the other.

3.1.1 Aggregate characteristics
The composition of the blank mixture is revealed by the particle size analysis (Table 1).

Table 1: The particle size analysis

Mesh diameters	Granular classes and rate			Granular mix	Granular spindle LCPC of BBSG0/10		Mean Values
	6/10	4/6	0/4		Min	Max	
16	100	100	100	100	100	100	100
14	100	100	100	100	100	100	100
10	93.5	97.2	100	99.13	95	100	97,5
6.3	33.5	69.1	97.1	67.9	62	74	68
4	9.1	46.1	89.2	53.4	48	58	53
2	6.8	26.1	68.7	38.9	30	45	37,5
1.25	6.6	8.9	41.2	21.2	20	28	24
0.315	3.8	6.4	27.1	16.55	10	19	14,5
0.2	1.3	3.3	21	9.2	8	15	11,5
0.08	1.1	3.2	13	7.5	5	9	7

The data in Table 1 show that the curve resulting from the granular mixture values fits perfectly into the LCPC granular zone of the BBSG0/10. This allows us to state that the aforementioned aggregates are suitable for the production of the LCPC of BBSG0/10.
Following that, the granular mixture's coefficient of uniformity $(C_u = 23{,}70)$ and coefficient of curvature $(C_c = 2{,}45)$, which confirm the inequalities $1 < C_c < 3$ and $C_u > 4$, highlight a good spread of granular diameters in accordance with standard NF P 18-540.
Furthermore, the aggregates have been subjected to a number of tests in order to determine the essential properties (Table 2).

Table 2: Aggregate essential properties

	0/4	4/6	6/10	Specifications
CA (%)	≠	14.8	15.2	< 20%
LA	≠	32%	34%	< 35%
MDE	≠	16%	19%	< 25%
Equivalence of sand ES (%)	80%	≠	≠	< 40%

The properties of table 2 ensure the use of said aggregates in the manufacture of quality bituminous concrete in accordance with the relevant standards.

3.1.2. Control asphalt concrete formula

Table 3 shows the mass composition of 10000 g of asphalt concretes using BB_i as the asphalt concrete with i% bitumen substitution.

Table 3: Mass composition of 10,000g of BB

	Aggregates			Binder components			
	6/10	4/6	0/4	Bitumen	Plastic	Tires	Sulfur
BB_0	3300	1420	4720	560	0	0	0
BB_5	3300	1420	4720	532	8,4	63	12,6
BB_{10}	3300	1420	4720	504	16,8	73	25,2
BB_{15}	3300	1420	4720	476	25,2	84	37,8

3.1.3 Bituminous concrete characteristics

The Duriez and Marshall parameters define the static mechanical properties. Bituminous concretes manufactured by wet and dry processes will be denoted by BB_{vh} et BB_{vs} in the following

3.1.3.1 Duriez Parameters

The parameters in question are four in number (04), and they are as follows: simple compressive strength, compactness, degradation coefficient, and imbibition rate.

A) Simple compressive strength

Figure 3 depicts the simple compressive strengths of bituminous concretes (pure and modified) on test specimens.

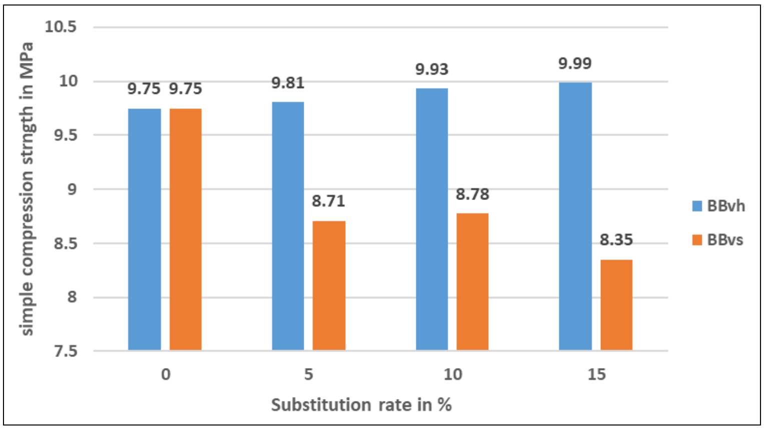

Fig 3: Simple compressive strength variations

It is discovered that

a) The simple compressive strength of the BB_{vh} are greater than those of the control bituminous concrete and increase with the rate of bitumen substitution;
b) The simple compressive strengths of the BB_{vs} are less than those of the control asphalt concrete and decrease with the rate of bitumen substitution;
c) The simple compressive strengths of the BB_{vh} are greater than those of the BB_{vs} of the same composition.

B) Compactness

Figure 4 depicts the compactness of two bituminous concretes (on Duriez specimen) with varying percentages of bitumen.

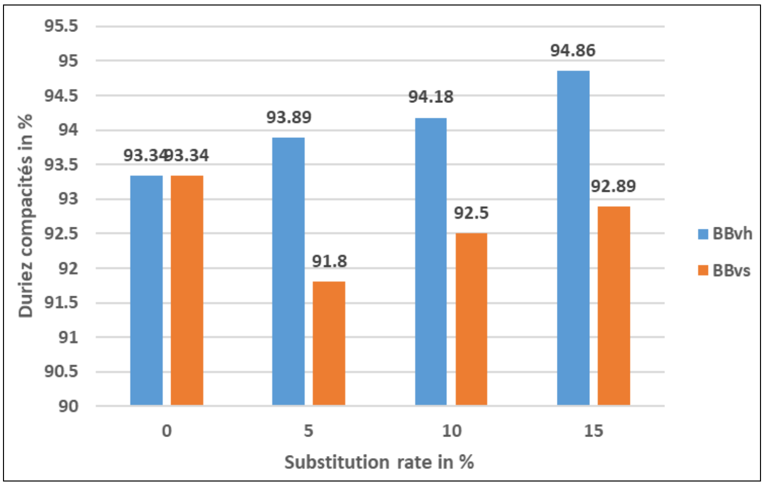

Fig 4: Duriez compactness variations

Figure 4 shows that the compactnesses of the BB_{vh} outclass those of the control asphalt concrete and evolve in accordance with the bitumen substitution rate, whereas the compactness of the BB_{vs} remain lower.

C) Degradation coefficient

Figure 5 depicts the variations in bituminous concrete degradation coefficients.

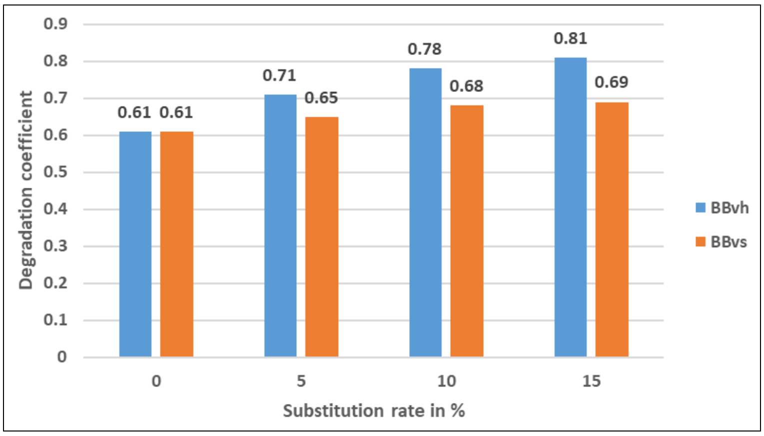

Fig 5: Degradation coefficient variations

The degradation coefficients of the various modified bituminous concretes appear to be higher than those of the reference material. with a rather remarkable evolution of said coefficient in BB_{vh} versus BB_{vs}.

D) Imbibition rate

Figure 6 depicts the rate of soaking of bituminous concretes with varying percentages of bitumen.

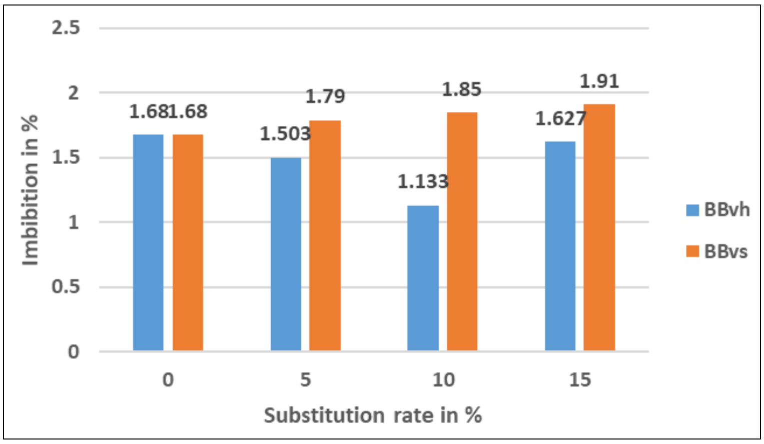

Fig 6: Imbibition rate variations

It has been discovered that the alveolar structure of the BB_{vh} varies inversely with the variation of the bitume rate. Meanwhile, these alveoles intensify for the BB_{vs} as the bitumen rate changes.

3.1.3.2 Marshall parameters

Marshall's three (03) parameters are stability, fluency, and Compacity.

a) Stability

Figure 7 shows the bituminous concrete stabilities at various bitumen concentrations.

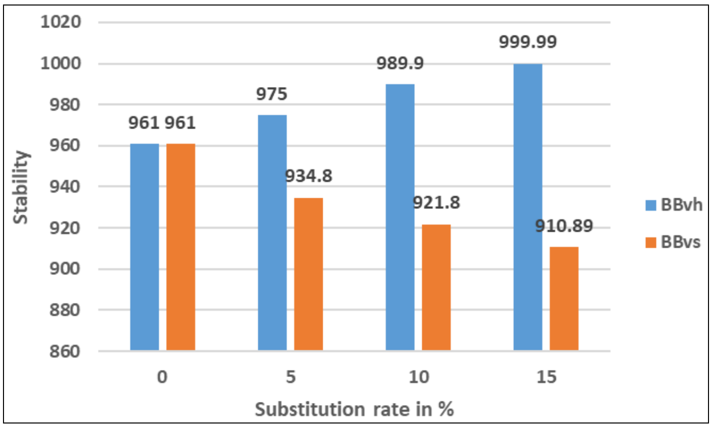

Fig 7: Stability variations

The observation is that the stability of BB_{vh} advances while that of BB_{vs} regresses with the rate of bitumen substitution.

b) Creeps
Figure 8 depicts the variations in creep as a function of bitumen content.

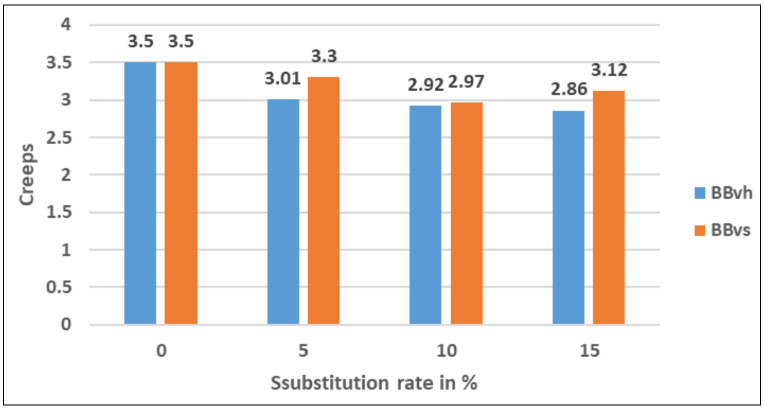

Fig 8: Creeps variations

Figure 8 shows that the modified composites (BB_{vh} et BB_{vs}) fluent less than the reference material. However, only BB_{vh} are more resistant to this phenomenon.

c) Compactness
Figure 9 depicts the variation in the compactness of bituminous concretes (on Marshall specimen) at various bitumen rates.

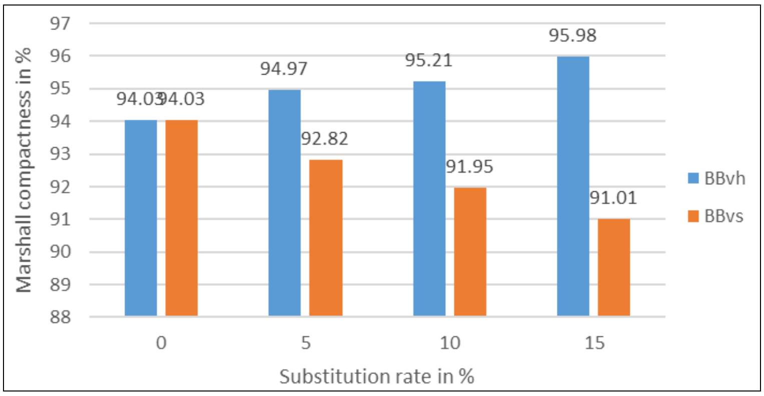

Fig 9: Marshall compactness variations

It is worth noting that the alveolar structure regresses for the BB_{vh} and densifies for the BB_{vs} in response to the bitumen substitution rate.

3.2. Interpretation

Figures 4–9 analysis reveals

1. The compactnesses of the BB_{vh} outperform those of the BB_{vs}, which are less compact than the control asphalt concrete's compactness.
2. The rate of BB_{vh} imbibition is almost inversely related to the evolution of bitumen percentage substitution. While the honeycomb structure of the BB_{vs}, which is emphasized, provides more site for water to lodge in large quantities;
3. The simple compressive strength of the BB_{vh} increases and remains higher than that of the BB_{vs}, which is outclassed by the control asphalt concrete's simple compressive strength.;
4. The BB_{vh} degradation coefficient is so close to 1 that it remains higher than the BB_{vs}., which outperforms the control asphalt concrete;
5. The BB_{vs} are more creep sensitive than the BB_{vh}, which are less sensitive than the control asphalt concrete;
6. The stability of the BB_{vh} changes due to the bitumen substitution rate while remaining within an acceptable range. While we observe a decrease in this parameter in the case of BB_{vs}. These findings highlight:

For bituminous concrete manufactured using the wet process

1. The multiplication of single bonds at the expense of multiple ones, with the formation of three-dimensional sulfur bridges (C-S or S-S) between linear polymers as a result of the destruction of multiple bonds, as explained by Charles Goodyear's work in 1939;
2. The influence of the manufacturing process (wet process), which, on the one hand, allows the PUNR powder to digest heavy oils very well, resulting in a fairly dense vortex;
3. The success of the cross-linking phenomenon that begins during the manufacture of the neo-binders at 150°C, the temperature at which the PET softens and

the PUNR powder absorbs the heavy oils of the liquefied bitumen;

4. The softened PET powder reduces the dominant vacuolar aspect in the bitumen-PUNR vortex near this temperature (150 °C);
5. The significant reduction in the rate of voids caused by crosslinking due to the cementing power of the crosslinking agent, sulphur;
6. The crosslinker's hydrophobicity;
7. The drastic reduction in the alveolar structure of modified bituminous concretes after cross-linking, which is responsible for modified binders' densification;
8. The disappearance of benzene rings and the transition from multiple to single bonds (Charles Goodyear's; 1939). These mechanisms are accompanied by quasi-isotropic molecular aliasing caused by the formation of -S-S-, -C-C-, and -C-S- bridges, which is a true manifestation of cross-linking as demonstrated by Charles Goodyear's work in 1939.
9. Significant increase in atomicity is caused by the formation of a highly entangled molecular network (Charles Goodyear's; 1939) which occurs as a result of interactions between partial substituents and bitumen that begin during the manufacturing of the modified binder.

2. For bituminous concrete manufactured using the dry process

1. The very small amount of free bitumen makes mixing of the conventional composite (aggregates + bitumen) with bitumen partial substituents (sulfur, PUNR, and PET powders) difficult.
2. The proliferation of segregation between the conventional composite and the constituents, particularly the partial bitumen substituents;
3. The formation of islands, clods, or agglomerates due to the difficult to solve homogenization equation on the one hand and the small amount of free binder with the increase in the specific surface formed predominantly partial bitumen substituents on the other.
4. The formation of isolated chemical and physical bridges, which results in the formation of an anisotropic material.

4. Conclusion

Based on the results of the Duriez and Marshall laboratory tests on bituminous concretes (pure and modified), it appears that:

- When compared to modified bituminous concrete produced by the dry process, the control bituminous concrete has clearly superior intrinsic static mechanical properties;
- Modified bituminous concretes produced by the wet process have significantly better intrinsic static mechanical properties than control bituminous concretes and those produced by the dry process.

Furthermore, we note that the recovery of PUNR waste and waste plastic bottles (PET) transparent and opaque allows for environmental cleanup on the one hand. On the other hand, to improve the static mechanical properties of bituminous concretes in order to realize more durable and potentially cost-effective pavements through the rational use of non-biodegradable resources (aggregates). After the neo-product has been cross-linked, we also have a recovery of an ore (sulphur) that was previously considered waste during mining extractions and is always used at a discount when this is the case.

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