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Influence of the Partial Substitution of Bitumen by a Mixture of Sulphur and Tyre and Plastic Bottle Powders on the Behaviour of Bituminous Concrete

Parfait Isidore Mbenkoue Mbida[1], Déodonne Kunwufine[2], Charles Bwemba[3], Michel Mbessa[4]

[1]Laboratory of Civil and Mechanical Engineering, Department of Civil Engineering, National Advanced School of Engineering of Yaounde, Yaounde, Cameroon
[2]Department of Civil Engineering, National Advanced School of Public Works, Yaounde, Cameroon
[3]Department of Civil Engineering, National Advanced School of Engineering of Yaounde, National Advanced School of Public Works, Yaounde, Cameroon
[4]Department of Civil Engineering, National Advanced School of Public Works, National Advanced School of Civil Engineering of Yaounde 1, Yaounde, Cameroon
Email: mbenkoue.fgi@yahoo.com, deokunwu@yahoo.fr, carlbwe@yahoo.fr, michel.mbessa@yahoo

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Abstract

This article deals with the influence of the partial substitution of bitumen by a mixture of sulphur and tyre and plastic bottle powders on the characterization of asphalt concrete. The approach adopted was to subject a control asphalt concrete to level 2 formulation tests as well as those modified at 10%, 20%, 30% and 40% by substituting bitumen with a mixture of tyre powder, plastic bottle powder and sulphur at 40%, 28% and 32% respectively. The results of the PCG, Duriez and rutting tests carried out on the control and modified bituminous concretes (manufactured using the wet process) revealed three (03) major findings, in particular with regard to workability, resistance to simple compression and rutting. The experimental results show an increasing trend in the essential parameters. At 40% substitution, there was a 22.73% increase in compactness, reflecting a significant improvement in the material's workability. With regard to simple compressive strength, the increase is 34.02% at 40% substitution, highlighting the limitation of crack formation and propagation under heavy precipitation. With regard to rutting, the 16% drop in susceptibility at 40% substitution reflects a significant improvement in the behaviour of the material under dynamic mechanical stresses in heavy precipitation. The improvement in these behaviours results from the insertion of the plastic bottle powder into the interstices of the granular skeleton, thus reducing its cellular structure, and also from the interactions between the sulphur with the tyre powder and the sulphur with the plastic bottle powder, *i.e.* cross-linking or vulcanisation.

Keywords

Bituminous Concrete, Tyre Powder, Plastic Bottle Powder, Sulphur

1. Introduction

The deterioration observed on asphalt pavements is often linked either to climatic or traffic stresses, or to the ageing of the material making up the wearing course. The deterioration observed may be stripping, cracking or irreversible deformation [1]. Several proposals have been made to remedy the situation, including asphalt concrete doped with plastics [2] [3], sulphur [4] [5], or rubber, as revealed in the 2008 report by Quebec politicians working with RECY-QUEBEC on the recycling of tyre waste. On the other hand, the persistence of certain pathologies remains a topical issue, in particular thermal susceptibility, cushioning and grip, even though dopants have hitherto only been used in a single phase.

However, it should be noted that sulphur can double certain mechanical properties [6] of plastics and rubber, which are non-biodegradable materials whose abundance of waste destroys the environment. The adhesive power of rubber and its ability to limit the propagation of cracks in an asphalt concrete wearing course [7] and the ability of plastic to make the bituminous matrix denser [8], are assets to be capitalised on at the same time as the added value of sulphur.

In this article, the behaviour of BBSG 0/10, following the substitution of bitumen at 10%, 20%, 30% and 40% by the sum by mass of tyre powder, plastic bottle powder and sulphur at 40%, 28% and 32% respectively, will be evaluated by means of level 2 formulation tests.

2. Materials and Method

2.1. Materials

2.1.1. Components of the Control Asphalt Concrete

The two (02) components used are bitumen obtained from Arab Contractor'S Ltd, a public works company in Cameroon, and aggregates from the AKAK ESSE quarry, in the Mvila department, South Cameroon Region.

2.1.2. Partial Bitumen Substitutes

Three (03) partial bitumen substitutes are used, including sulphur, tyre powder and plastic bottle waste powder.

2.2. Method

This consists of subjecting modified bituminous concrete to level 2 formulation tests in the same way as control bituminous concrete, following the characterization of its components.

2.2.1. Characterisation of Conventional Components

This consists of determining the following parameters in accordance with the relevant standards:

~ Moisture content (NF P 94 - 050);
~ Particle size analysis (NF P 94 - 056);
~ Los Angelès coefficient (NF P 18 - 573);
~ Micro Deval coefficient (NF P 18 - 572);
~ Flattening coefficient (NF P 18 - 561);
~ Sand equivalent (NF P 18 - 598).

2.2.2. Control Asphalt Concrete

1) Formulation and manufacture of control asphalt concrete

The formulation consists of determining the rate of each granular component in accordance with standard NF P 98-150-1, and then determining the percentage of bitumen (P_{bi}) calculated using Equation (1) [9].

$$P_{bi} = (TG + 120)/100 \tag{1}$$

where TG, the total particle size, is the sum of the percentages of passings of the granular mix at mesh sizes 16, 12.5, 10, 6.3, 4, 2 and 0.080.

The control asphalt concrete is manufactured in accordance with standard NF EN 13 108-1.

2) Characterization of the control asphalt concrete

This is carried out by means of level 2 mix design tests which are:

~ PCG test (NF EN-P 12 697 - 31);
~ Duriez test (NF P 98 251 - 1);
~ The rutting test (NF EN-P 12 697 - 22).

2.2.3. Modified Bituminous Concrete

They are produced using sulphur, tyre powder and plastic bottle powder.

1) Obtaining partial substituent of bitumen

Three (03) partial bitumen substituents will be used, namely sulphur, tyre powder and plastic bottle powder. They will be obtained following a very precise procedure.

The sulphur was bought on the local Cameroonian market in the form of carrots before being crushed and sieved through a 1-millimetre mesh sieve to make it easier to weigh. Extracted in neighbouring Nigeria, the carrot shape of the sulphur indicates that it was obtained using the Flash process.

The powdered plastic bottle waste will be obtained in eight (08) consecutive stages, including:

a) Collection of waste plastic bottles (non-opaque, transparent and coloured);
b) Removal of the caps;
c) Cutting into flakes and manual washing;

d) Spinning and drying;

e) Melting;

f) Cooling the paste to room temperature;

g) Manual grinding of the hardened paste;

h) Screening with a 1 mm sieve.

The tyre powder will be obtained in seven consecutive stages, including:

a) Collection of waste tyres;

b) Manual coarse cutting into flakes;

c) Cutting into elements of approximately 1 cm^2;

d) Washing under running water;

e) Dewatering;

f) Shredding;

g) Screening with a 1 mm sieve;

h) Magnetic purification.

2) Formulation of modified bituminous concrete

Modified bituminous concretes are just 10%, 20%, 30% and then 40% bitumen by the sum by mass of tyre powder, plastic bottle powder and sulphur, at a rate of 40%, 28% and 32% respectively.

3) Manufacture of modified bituminous concrete

This is done using the wet process [10] and in accordance with the Guide [11] for the manufacture of asphalt mixes with rubber powder from used tyres in Spain.

4) Characterization of modified bituminous concrete

This is also done by means of level 2 mix design tests.

3. Results and Interpretation

The results to be interpreted are the parameters obtained from tests carried out on aggregates and on bituminous concrete (pure and modified) previously formulated and manufactured.

3.1. Aggregate Parameters

These are the particle size parameters and the essential properties of the aggregates. The particle size parameters are made up of the particle size (**Table 1**) and the curvature (C_c) and uniformity (C_u) coefficients.

Examination of **Table 1** shows that the composition of the granular mix fits well into the LCPC spindle of the BBSG 0/10.

Furthermore, the coefficient of uniformity (C_u = 23.70) and the coefficient of curvature (C_c = 2.45) of the granular mix satisfy the inequalities $1 < C_c < 3$ and $C_u > 4$. This highlights a good spread of granular diameters in accordance with standard NF P 18 - 540.

The essential properties of the said aggregates are given in **Table 2**.

In accordance with the requirements of the relevant standards, these aggregates can be used in the manufacture of bituminous concrete.

Table 1. Granulometry.

Mesh Size Diameters	Granular grades and rates			Granular mix	Granular Spacing LCPC of BBSG0/10		Average 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

Table 2. Essential properties of aggregates.

	0/4	4/6	6/10	Specifications
Water content W (%)	3.60	2.81	1.89	
CA (%)	≠	14.8	15.2	<20%
LA	≠	32%	34%	<35%
MDE	≠	16%	19%	<25%
Sand equivalent ES (%)	80%	≠	≠	>40%

3.2. Formula for Bituminous Concrete

Noting TP as tyre powder, PBP as plastic bottle powder, S as sulphur and BBM_i asphalt concrete with i% bitumen substitution, the consequent variants are shown in Table 3.

3.3. Asphalt Concrete Parameters

These are the PCG, Duriez and rutting parameters. For the following, we note "BBM_i" the bituminous concretes modifies i% substitution.

3.3.1. Duriez Parameters

Two (02) Duriez parameters are presented in Table 4 including the simple compressive strength "R_C" and the degradation coefficient "a".

It is observed that the simple compressive strength increases progressively with an increase of 12.5% for 40% substitution. This gap is identical to that of asphalt concrete modified by the addition of 15% plastics [12]. The strength of BBM_{40} (10.4 MPa) is close to that of some anti-rutting bituminous concretes, in particular REXOVIA (10.2 MPa) [13], and RUFLEX M (9.8 MPa) [14] produced

Table 3. BBM1 variants.

Designations	Granularity			Binder components			
	6/10	4/6	0/4	Bitume	TP	PBP	S
BBM_{10}	33%	14.2%	47.2%	5.04%	0.224%	0.1568%	0.1792%
BBM_{20}	33%	14.2%	47.2%	4.48%	0.448%	0.3136%	0.3584%
BBM_{30}	33%	14.2%	47.2%	3.92%	0.672%	0.4704%	0.5376%
BBM_{40}	33%	14.2%	47.2%	3.36%	0.8960%	0.6272%	0.7168%

Table 4. Duriez parameters.

Average parameters	Samples					Requirements
	BBM_0	BBM_{10}	BBM_{20}	BBM_{30}	BBM_{40}	
R_C (MPa)	7.76	7.9	8.3	9.1	10.4	$6 \leq R_C \leq 11$
α	0.81	0.72	0.78	0.81	0.83	$0.60 \leq \alpha \leq 0.85$

respectively by the laboratories EUROVIA (which is a VINCI company) [13] and COLAS. As a result, BBM_{40} is classified as an anti-rutting bituminous concrete. Furthermore, BBM_{40} is of lower strength than so-called very high-performance bituminous concretes such as ECOFLEX LT (11.3 MPa) [15] and MULTICOL (15 MPa) [16] produced respectively by the SCREG and COLAS laboratories. Therefore, BBM_{40} is not one of the so-called very high-performance bituminous concretes.

All variants have a good ability to resist stripping under mechanical stress in the presence of water depending on the requirement. Only the BBM_{40} has a coefficient close to that of the material whose degradation coefficient is 0.85 [17]. Also, it is improved that, this parameter is by 09% for asphalt concrete modified with 15% plastics whereas the reinforcement is only 01.21% for the present work [12]. Furthermore, the degradation coefficient of BBM_{40} is slightly higher than that of REXOVIA (0.81) [13] while ECOFLEX LT (0.89) [15], MULTICOL (0.9) [16] and RUFLEX M 0/10 (0.98) [14] withstand static mechanical stresses under heavy precipitation better than BBM_{40}.

The increase in simple compressive strength results from the formation of several linear and/or star-shaped bonds [18] [19] that become more intertwined followed by the development of hydrophilic character.

3.3.2. PCG Parameters

Table 5 shows the variations in voids and compactness, PCG parameters.

Examination of **Table 5** reveals that only BBM_{40} has a non-compliant voids rate per 100 gyrations, whereas this specification of standard NF P 98 - 252 is verified by the other variants.

Indeed, the compactness of BBM_i is higher than that of the material by 94% of compactness [17]. But the 01.04% improvement obtained for the present work is

Table 5. Variations in PCG parameters.

Number of revolutions	10	50	80	100	Spécifications
Bituminous concrete at 0% of partial substitution of bitumen (BBM_0)					
Compactness (%)	84.3	91.6	94	95.6	
Voids (%)	15.7	8.4	6	4.4	4 - 9
Bituminous concrete at 10% of partial substitution of bitumen (BBM_{10})					
Compactness (%)	84.9	92.1	94.2	95.8	
Voids (%)	15.1	7.9	5.8	4.2	4 - 9
Bituminous concrete at 20% of partial substitution of bitumen (BBM_{20})					
Compactness (%)	85.3	92.9	94.9	96	
Voids (%)	14.7	7.1	5.1	4	4 - 9
Bituminous concrete at 30% of partial substitution of bitumen (BBM_{30})					
Compactness (%)	85.8	91.6	95	96	
Voids (%)	14.2	8.4	5	4	4 - 9
Bituminous concrete at 40% of partial substitution of bitumen (BBM_{40})					
Compactness (%)	86	92.8	95.4	96.6	
Voids (%)	14	7.2	4.6	3.4	4 - 9
Specifications	A 10 gyrations $V_{\min,Ng1} = 10$; $V_{\min,Ng1} \le V_{Ng1} = 13.8$; % vides $\ge 15\%$		A 80 gyrations $V_{\min,Ng2} = 6$; $V_{Ng2} = 8.5$; $V_{\max,Ng2} = 10$; $V_{\min,Ng2} \le V_{Ng2} \le V_{\max,Ng2}$ $4 \le$ % vides ≤ 7		

lower than the 05% improvement recorded for bituminous concretes manufactured by dry process, obtained by partial substitution of bitumen by rubber powder and those from partial substitution of 0/3 by rubber powder [20]. The same is true for asphalt concretes doped with rubber fines and those doped with rubber granules [21].

Furthermore, at 10 gyrations, the four (04) modified bituminous concretes are more cellular than the anti-rutting bituminous concretes, in particular ECOFLEX LT (11.5%) [15] and COFLEX N (12.6%) on the one hand, and on the other, the very high performance concretes, namely Shell Thiopave and MULTICOL [16], which have a maximum of 11% voids. On the other hand, at 80 gyrations, the compactness of MULTICOL (93%) is lower than that of each BBM_i.

The increasing evolution of workability observed via the progression of compactness is, on the one hand, a consequence of the plastic bottle powder which reduces the cellular structure by melting and cooling [20] of the granular skeleton matrix and, on the other hand, a result of the double sulphuric cross-linking [19] [21].

3.3.3. Resistance to Rutting

Changes in rutting resistance are shown in **Table 6**.

Table 6. Trends in rutting resistance of modified bituminous concretes.

Bituminous concrete at 0% of partial substitution of bitumen (BBM_0)					
Right wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	2.4	3.7	6.5	7.02	[5; 10]
Left wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.6	3.0	5.7	6.9	[5; 10]
Average values	**2**	**3.35**	**6.1**	**7.02**	≤7.5% at 30,000 cycles
Bituminous concrete at 10% of partial substitution of bitumen (BBM_{10})					
Right wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.7	2.8	6.0	6.5	[5; 10]
Left wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	2	3.5	5.7	7.4	[5; 10]
Average values	**1.85**	**3.15**	**5.85**	**6.95**	≤7.5% at 30,000 cycles
Bituminous concrete at 20% of partial substitution of bitumen (BBM_{20})					
Right wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.8	3	5.8	6.2	[5; 10]
Left wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.6	3.2	5.4	7.0	[5; 10]
Average values	**1.7**	**3.1**	**5.6**	**6.6**	≤7.5% at 30,000 cycles
Bituminous concrete at 30% of partial substitution of bitumen (BBM_{30})					
Right wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.8	3	5.2	6.0	[5; 10]
Left wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.4	2.7	5.1	5.82	[5; 10]
Average values	**1.6**	**2.58**	**5.15**	**5.91**	≤7.5% at 30,000 cycles
Bituminous concrete at 40% of partial substitution of bitumen (BBM_{40})					
Right wheel					**Specifications**
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.9	2.5	4.8	6.0	[5; 10]

Continued

	Left wheel				Specifications
Number of cycles	1000	3000	10,000	30,000	Voids (%)
Rut (%)	1.3	2.8	5.0	5.8	[5; 10]
Average values	**1.6**	**1.65**	**4.9**	**5.9**	≤7.5% at 30,000 cycles

Resistance to rutting increases with the rate of substitution and the rut depth rate falls by 19% for 40% substitution. Similarly, another work [22] [23] shows that incorporating plastic into bitumen increases its rigidity at high temperatures and also boosts rutting resistance. This theory of improving resistance to rutting by injecting plastic into the bitumen is corroborated by Nouali [24], while Zhang et al (2018) [25] reached the same conclusions by substituting 1.5% of aggregates with tyre powder.

Furthermore, rutting-resistant bituminous concretes such as REXOVIA [13], ECOFLEX LT [15] and RUFLEX M [14] have rut depths of 5%, 3% and 5.6% respectively. These values, which are fairly close to those of BBM_{30} (5.91%) and BBM_{40} (5.90%), can be used to classify the last two (02) variants as anti-rutting bituminous concretes.

With a susceptibility to rutting of 7.5% at 30,000 cycles, class 2 high modulus asphalt is not preferable to BBM_{40} (5.9%), which is less prone to rutting than MULTICOL [16], which has a maximum rut depth of 3%.

The improvement in the stability of the material under the combined action of dynamic and thermal stresses derives from the interactions between the sulphur and the plastic bottle powder and then between the sulphur and the tyre powder [18] [19].

4. Conclusions

~ Tyres and plastic bottles, as derivatives of crude oil such as bitumen, have chemical affinities with the latter in the same way as sulphur, which is one of the chemical components of this composite. This chemical base guarantees the compatibility of these four (04) materials, namely bitumen, sulphur, tyre powder and plastic bottle powder [19] [23] [24];

~ The plastic bottle powder used is inserted into the matrix of the reference material, reducing the honeycomb structure of the reference composite. This insertion follows the softening of the plastic bottle powder, which forms a film after cooling. This film, which is further densified by the sulphur that interacts with the tyre and plastic bottle powders by cross-linking, helps to increase workability [19] [23];

~ The increase in simple compressive strength and stability for both static (Duriez test) and dynamic (rutting test) mechanical stresses are the result of the double sulphuric vulcanisation with the tyre powder on the one hand and with the plastic bottle powder on the other [24] [25]. This vulcanisation or cross-linking takes the form of linkages or bridging, which is the formation of new chemical bonds following the destruction of certain multiple bonds and benzene nuclei.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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