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Study and valorization of a new bituminous concrete based on natural dune sand for hot and arid environments

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Abstract
The trans-desert road network is exposed to enormous degradation of asphalt concrete pavements due to the high temperatures of these arid regions, which considerably accelerate asphalt ageing. Common bituminous mixes generally use quarry sand fillers, the proportions of which are poorly controlled due to the diversity of rock deposits and their manufacturing conditions. This article responds to this problem by proposing dune sand as a source of filler by grinding it and then introducing it into pure bitumen to obtain the bitumen-filler mix. In this paper, two types of analysis were carried out, one thermal and the other mechanical to study the influence of the substitution of quarry sand filler by dune sand filler in asphalt concrete. In the thermal analysis, the study evaluates the stiffening power (ΔTBA) of three types of fillers incorporated into a pure bitumen, namely quarry sand, dune sand and standardized filler. The results of these analyses reveal that at a normative percentage of 57% filler with 43% pure bitumen, the stiffening power (ΔTBA) of dune sand filler and normalized filler comply with established standards (between 8 and 16°C), unlike quarry sand filler, which does not meet standards. The mechanical analysis carried out on quarry sand filler and dune sand filler revealed an improvement in mechanical performance when dune sand filler was used, with MARSHALL stability values indicating an average increase from 3.9 to 4.9, and better resistance to water with a greater than 99% ratio for the DURIEZ test well above the 75% threshold. These results offer the potential to optimize bituminous mixes by incorporating dune sand fillers, thereby enabling Saharan roads to be built more quickly, at lower cost and, above all, to extend their lifespan, making a positive contribution to the development of road infrastructure in hot, arid environments.
Keywords: Road. Filler. Sand. Dune. Temperature. Bitumen.

1. Introduction and background

In trans-Saharan countries, the trans-desert transport system is the main mode of transport for goods and passengers. The durability and performance of pavements depend mainly on materials, whose characteristics are not constant, but evolve over time like all other organic substances. They are subject to significant changes due to environmental conditions during their various phases of use. Indeed, bitumen is subject to ageing phenomena that modify its mechanical and rheological parameters, as well as its chemical structure.

The trans-desert road network suffers from many types of deterioration, mainly due to climatic aggression, particularly high temperatures which accelerate asphalt ageing. The powders or fillers in common bituminous mixes often come from quarry sand, so their properties and proportions within the mixes are not controllable due to the diversity of rock deposits on the one hand, and on the other, the changing conditions in which aggregates are manufactured, especially sand, which loses its fine part through wind and during transport, causing many problems particularly for wearing courses made of bituminous mix.

A new bituminous concrete based on natural dune sand has been studied and evaluated for hot and arid environments. The scarcity of building materials, especially coarse aggregates, in desert areas has led to the exploration of sand dunes as a potential alternative. Several studies have confirmed that sand can be used in concrete after granular correction (Soleimani *et al*., 2023). The mechanical characteristics of the sand dune have been evaluated, and it has been found that certain mixtures have high mechanical characteristics suitable for road foundations (Akhtar *et al*., 2024). Additionally, the use of modified sand, which includes desert sand, natural crushed sand, and recycled crushed sand, has been proposed as a sustainable solution for concrete manufacturing (Smaida *et al*., 2022). These studies demonstrate that sand dune can be valorized and used effectively in bituminous concrete for hot and arid environments.

Several techniques for improving the properties of asphalt mixes can be found in the literature, such as adding a quicklime filler, filling with organic matter, filling with industrial waste, etc. Mastoras *et al*. (2021) studied the effect of ageing on asphalt concrete using dynamic shear tests and infrared spectroscopy measurements. They reported the existence of an anti-ageing mechanism linked to the physical presence of filler particles in the bitumen-filler mix and their retarding effect on oxygen diffusion. Modarres and Rahmanzadeh (2014) studied the effect of waste coal powder as a filler in hot-mix asphalt. In addition, Sangiorgi *et al*. (2017) carried out laboratory research to analyze the physical characteristics of three different recycled fillers and compare them with those of a traditional limestone filler. Several other types of fillers are found in the literature, including rock extract-based fillers (Fatima *et al*., 2014; Chandra *et al*., 2002; Choudhary *et al*., 2020; Akbulut *et al*., 2012), natural fillers (Tessema *et al*., 2022; Mistry *et al*., 2019), synthetic fillers (Praticò *et al*., 2010; Mistry *et al*., 2016) and mineral fillers (Franesqui *et al*, 2017).

Most of the research articles reviewed, including those mentioned above, report the use of synthetic fillers or materials that are difficult to obtain in certain regions. This has motivated researchers to investigate locally abundant materials, such as natural dune sand, which can be easily obtained in the desert and indeed the background to this research is the continuing quest to improve the quality of road infrastructure in desert areas, taking advantage of abundant local resources, such as dune sand. This research is based on two types of experimentation, the first being the study of the thermal influence of dune sand filler on asphalt concrete by carrying out an in-depth analysis of the thermal properties in order to assess the material's ability to withstand the extreme temperature variations typical of desert environments, with the aim of guaranteeing the structural stability and long-term durability of road surfaces.

The second experiment is to study the mechanical influence of replacing quarry sand filler with dune sand filler by carrying out an in-depth analysis encompassing compressive strength and other essential mechanical properties to ensure that the new bituminous material meets the required standards of mechanical performance under specific environmental conditions. This research is part of an innovative approach to improving the durability of desert roads by exploiting the unique properties of dune sand, and the expected results should help to optimize asphalt concrete formulations, paving the way for more durable road construction solutions adapted to the extreme conditions of desert regions.

2. Physical and chemical analysis of dune sand filler

As part of this comprehensive study into the influence of dune sand filler in hot-mix asphalt concrete, physical and chemical analyses were carried out to provide an in-depth understanding of the characteristics of the materials used. These analyses play a crucial role in defining the intrinsic properties of the fillers, thus contributing to a more complete interpretation of the results obtained in the thermal and mechanical aspects of the research. The dune sand used as a source of filler in this experiment comes from the sand dunes of the city of Ghardaïa (Figure 1).

Figure 1 - Natural dune sand collected from Ghardaïa.

The sand fillers obtained after crushing (Figure 2) were subjected to a particle size analysis, the results of which are summarized in Table 1. This analysis provides a detailed view of the distribution of particle sizes in dune sand fillers and makes it possible to characterize the texture and fineness of the materials, which are crucial factors in the formulation of bituminous mixtures.

Figure 2 - Dune sand fillers DSF after milling

Table 1 - Granularity of bituminous concrete fillers.

Sieve Opening (mm)	Cumulative refusal mass (g)	Cumulative refusals (%)	Cumulative sieve (%)
12,5	0	0	100
10	0	0	100
5	0	0	100
1,25	0	0	100
0,125	22,1	6	94
0,063	108,6	30	70

The results of this granulometric analysis are shown in Figure 3 and indicate a particularly favorable granulometric pattern, with 70% of the elements having a diameter of less than 0.063 mm and 94% of the elements having a diameter of less than 0.125 mm. This specific particle size distribution meets the normative requirements in an exemplary manner, in particular article 5.21 of standard NF EN 13043 (EN 13043, 2002), thus giving dune sand filler a quality that is particularly suitable for use in bituminous mixes.

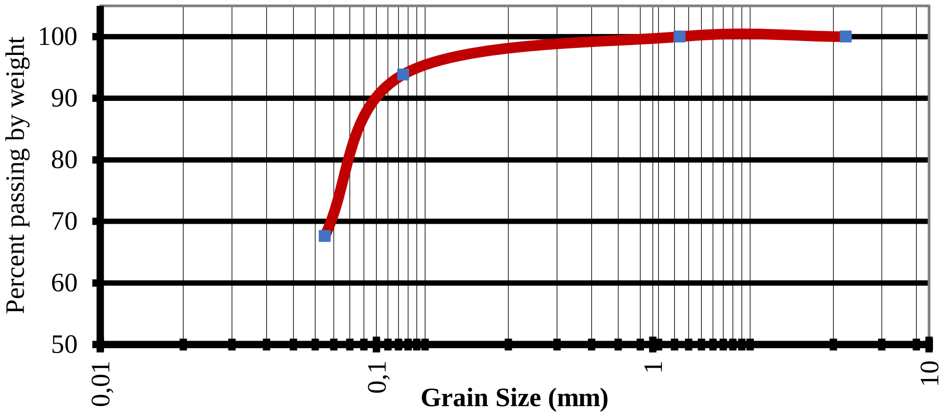

Figure 3 - Grading curves for dune sand filler.

The high concentration of fine elements (less than 0.0632 mm) in dune sand filler suggests a fineness that can play a key role in improving the thermal and mechanical properties of bituminous mixes. These fine particles contribute to an increased contact surface with the bitumen, thus promoting better adhesion and a homogeneous distribution of fillers within the composite material.

In short, the particle size analysis of dune sand filler attests to its compliance with standards, underlining its suitability for use in bituminous mixtures. These results strengthen the scientific basis of our study and provide valuable information for engineers and researchers involved in the formulation of road construction materials adapted to the specific conditions of desert roads. The controlled fineness of dune sand filler is thus positioned as a major asset in the design of high-performance, long-lasting bituminous surfacing. At the same time, the chemical analyses presented in Table 2 provided information on the chemical composition of the fillers. These data are essential for assessing the reactivity of dune sand fillers with bitumen, thus influencing the overall performance of the asphalt concrete. The concentrations of the various components were scrupulously evaluated to gain a better understanding of the physic-chemical properties of the fillers.

Table 2 - Chemical analysis of dune sand fillers.

SAMPLE			
UNSOLVABLE (NF P 15- 461, 1984)	Crucible + precipitate (g)	29.184	
	Vacuum Crucible (g)	28.239	
	Residue weight (g)	0.948	
	Insoluble (%)	94.8	
CARBOONATES (NF P 15- 461, 1984)	$CaCO_3$ (%)	02	
CHLORIDES Mohr's method	pH_i (initial)	7.62	
	pH_i (Titling)	6.75	
	$V_{ag}NO_3$ (ml)	Test 1	Test 2
		0.4	0.3
	V_m (moyen) (ml)	0.25	
	Cl^- (%)	0.004	
	NaCl (%)	0.007	

The in-depth chemical analysis of the dune sand filler presented in Table 2 confirms a composition that meets the essential quality criteria for its use in bituminous mixes. The results reveal a notable percentage of 94.8% of insoluble elements, demonstrating the high chemical stability of the material. This high level of insoluble elements is a crucial indicator of the resistance of dune sand filler to undesirable chemical reactions, thereby enhancing the potential durability of asphalt concrete under a variety of environmental conditions.

In addition, the low chloride concentrations, with only 0.004% Cl^- and 0.007% NaCl, are particularly significant as chlorides can be devastating corrosive agents for road infrastructure. The minimal presence of chloride in dune sand filler is a considerable advantage for the long-term preservation of the integrity of bituminous mixes made from this material.

Another notable feature is the presence of carbonate, representing 0.2% $CaCO_3$. Although modest in percentage terms, this component can provide additional benefits. The presence of carbonate can contribute to the chemical stabilization of the material, potentially reinforcing the internal cohesion of asphalt concrete.

In summary, the chemical analysis of dune sand filler reveals a favorable composition, characterized by high chemical resistance, low chloride content and a moderate presence of carbonate. These results confirm the relevance of dune sand filler in the formulation of bituminous mixes for road construction, highlighting its intrinsic properties that favor the durability and resilience of the material in various environments. These combined physical and chemical analyses provide a solid basis for interpreting the results of thermal and mechanical tests, and enable a correlation to be established between the intrinsic characteristics of fillers and the performance observed in bituminous mixes.

3. Experimental plan

Two types of experiment were carried out in this study, namely the influence of dune sand filler on the thermal and mechanical properties of pure bitumen.

The influence of dune sand filler on the thermal properties of pure bitumen

The fillers used in this article are prepared in accordance with EN. 13043 (EN 13043, 2002) and their particle size meets the requirements given in Table 1. In the remainder of this work, dune sand fillers are referred to as DSF, quarry sand fillers as QSF, standard fillers as NSF and pure bitumen as PB.

The aim is to explore the thermal influence of three types of filler on hot mix asphalt concrete, particularly in the context of desert roads. The fillers studied are quarry sand filler, obtained by sieving quarry sand, dune sand filler, obtained by crushing dune sand, and finally the standard filler used as a control. These fillers, characterized by a diameter of less than 0.063 mm, with a limited percentage of elements between 0.063 mm and 0.125 mm, are essential in the composition of bituminous mixes. Carefully determined proportions of 50%, 57% and 60% filler to pure class 35/50 bitumen, commonly used on desert roads, have been used to create representative mixes. These filler/bitumen mixes are essential for assessing the thermal response of the bituminous material and ensuring its stability under extreme conditions.

The second step involves introducing the three types of fillers into the pure bitumen PB, obtaining the bitumen/filler mixture (Figure 4). The final step consisted of appropriately mixing the bitumen/filler mixture used in this experiment (Figure 5).

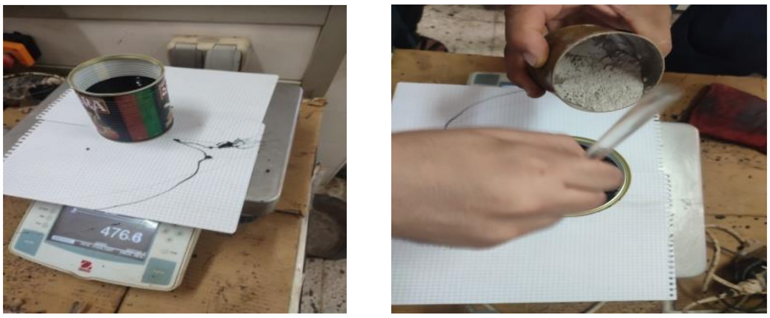

Figure 4 - Preparation of bitumen/filler


Figure 5 - Mixing the bitumen/filler.

The ring and ball softening point test (TBA), in accordance with EN 1427 (EN 1427.,2015), was chosen as the main thermal indicator. This test is carried out iteratively on pure bitumen and on different filler/bitumen mixtures in order to capture subtle variations due to filler variations. The TBA makes it possible to observe the temperature at which bitumen reaches a specific consistency, which provides crucial information about the material's resistance to the high temperatures to which it may be exposed in desert regions.

The rigorous methodology implemented in this part of the study aims to reveal the specific thermal properties induced by the use of dune sand as a filler material. The expected results will make it possible to refine asphalt concrete formulations, thereby optimizing resistance to high temperatures and, by extension, the durability of desert roads. This methodical approach will enable us to make informed decisions to improve the performance of road surfaces in extreme environmental conditions.

A series of tests was carried out on DSF, QSF and NSF using the softening point apparatus (Figure 6). This experiment carried out on pure bitumen and pure bitumen with fillers gives the ball-ring temperature (TBA), which is used to define the quality of the filler in bituminous concretes in accordance with standard EN 1427 (EN 1427,2015).

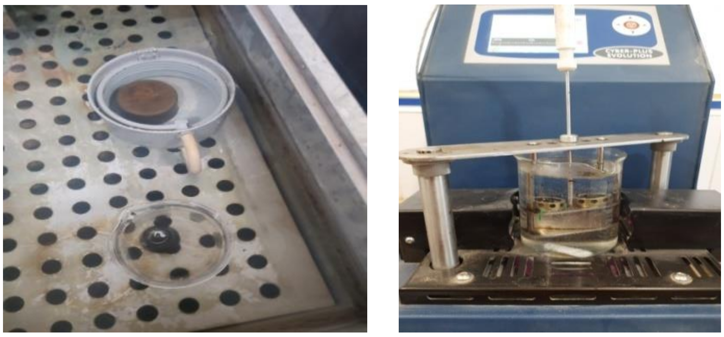
Figure 6 - Testing the softening point of the PB+DSF mixture.

The difference between the ball-ring temperatures of pure bitumen with fillers ($\mathrm{TBA_{PBF}}$) and pure bitumen ($\mathrm{TBA_{PB}}$) is denoted by ΔTBA. It characterizes the rigidifying power of fillers mixed with bitumen and the standard value of ΔTBA ought to be between 8°C and 16°C according to EN 13043 (EN 13043, 2002). The ΔTBA is defined according to EN 13179 (EN 13179, 2013) as:

$$\Delta\mathrm{TBA} = \mathrm{TBA}_{\mathrm{PBF}} - \mathrm{TBA}_{\mathrm{PB}} \tag{1}$$

To check the quality of the filler with regards to the rigidifying power of DSF compared with QSF, comparative tests were carried out between the values of ΔTBA for the two cases using the ΔTBA value of NSF as a control.

The percentage of pure bitumen in semi-grained bituminous concrete (BBsg 0/14) is between 5.1% and 5.9%. In our experiment, it is taken to be equal to 5.4%. Hence, the mass percentage of fillers in relation to pure bitumen is required to be in the interval 54 to 60%, with 57% being the exact target. In our experiments, we chose the extended interval 50 to 60%. Three points were chosen within this interval: 50, 57 and 60%.

Pure bitumen and pure bitumen samples with prepared fillers are cast in brass rings placed on replica disks. These rings are heated in a water bath at a controlled rate, while serving as a steel ball support. Then, the temperature at which the disks soften sufficiently to allow the steel ball to sink (25.0 ± 0.4) mm is recorded. The temperatures of the PB rings and the PB with fillers are collected, and the average temperature values and ΔTBA's are calculated.

The influence of dune sand filler on the mechanical properties of asphalt concrete

The second part of the experiment focused on an in-depth analysis of the mechanical properties of hot-mix asphalt concrete, highlighting in particular the influence of the substitution of quarry sand filler by dune sand filler. In this crucial stage, two separate samples were prepared to assess the impact of this substitution on the mechanical strength of the material.

The first sample, constituting our control group, is made up of a mixture of sand (with its original filler) and gravel of different fractions. The second sample is identical to the first, with the exception of the substitution of quarry sand fillers (fraction 0/0.125 mm) by dune sand filler, while retaining the same proportions. These samples represent realistic formulations of bituminous concrete, likely to be used in road construction in a desert environment.

Both samples were mixed with the same percentage of pure class 35/50 bitumen, in accordance with the standards commonly used in desert roads. Specimens were made for two major tests: the water resistance test, also known as the DURIEZ test, and the MARSHALL test, designed to assess the mechanical behavior of bituminous mixtures.

The DURIEZ (Figure 7) test is chosen to assess the material's resistance to water. This test examines the ability of bituminous concrete to maintain its mechanical properties under the effect of water, simulating the damp conditions to which roads may be exposed. The substitution of quarry sand filler for dune sand filler is of particular interest in this context, as it can influence the material's response to water.

Figure 7 - Equipment for DURIEZ water resistance test.

At the same time, the MARSHALL test (Figure 8) was selected for its ability to provide detailed information on the mechanical behavior of bituminous mixes. This test measures the stability, deformation and breaking strength of samples, providing a comprehensive assessment of the material's mechanical performance. Comparison of the results obtained with the two types of filler will make it possible to determine the specific impact of substitution on the mechanical properties of hot bituminous concrete.

In summary, this second part of our research offers a holistic approach to understanding how the substitution of quarry sand filler by dune sand filler can influence the mechanical properties of hot-mix asphalt concrete. The results obtained will guide our formulation choices, aimed at optimizing the mechanical performance of road surfaces in the specific conditions of desert roads.

Figure 8 - The equipment for the MARSHALL test.

4. Results and discussions

4.1 Results and discussion of the thermal study

The results obtained from tests to determine the temperature of softening by the ring-ball method on pure bitumen (PB) in accordance with EN 1427 (EN 1427, 2015) and on the mixture of PB with dune sand fillers (PB/DSF) in accordance with EN 13179 (EN 13179, 2013) are summarized in Table 3.

Table 3 - Summary table of ΔTBA values for PB and PB/DSF.

	Pure Bitumen 35/50 (PB)	PB /DSF		
Ratio of DSF to PB (%)	0	50	57	60
Softening point test temperatures TBA (°C)	56	63,15	64,6	64,95
ΔTBA (PB /DSF) (°C)		7,15	8,6	8,95
ΔTBA Max required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		16	16	16
ΔTBA Min required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		8	8	8

The results shown in Table 3 are presented graphically in Figure 9 illustrates the increasing variation in ΔTBA in relation to the variation in the percentage of DSF to PB. It is evident that the curve passes through two different zones, the first being the zone where the ΔTBA is below 8°C corresponding to a filler percentage less than 54%, and the second being the zone where the ΔTBA is between 8°C and 16°C corresponding to a filler percentage in the interval 54 to 60%.

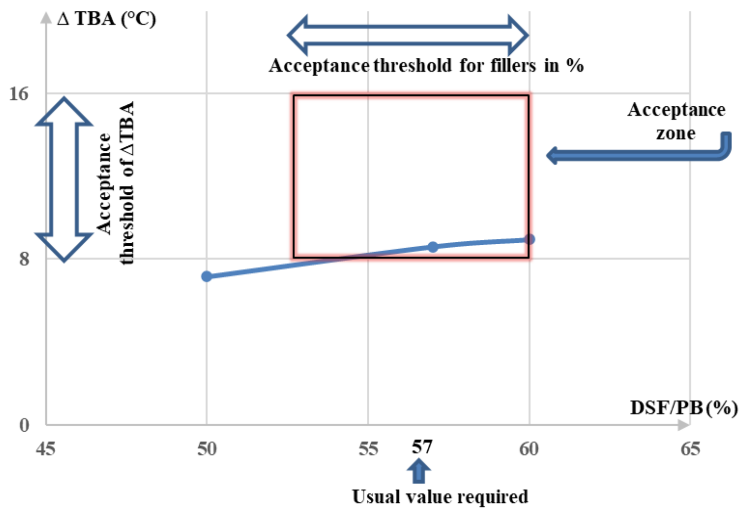

Figure 9 - Variation in ΔTBA as a function of the ratio of DSF to PB.

The ΔTBA results are acceptable if the filler ratios in the bituminous mix comply with the requirements of the standards used, which recommend a filler to bitumen percentage between 54% and 60% (57% is the usual value).

The results obtained from tests on PB in accordance with standard EN 1427 (EN 1427, 2015) and on the mixture of PB and QSF in accordance with standard EN 13179 (EN 13179, 2013) are summarized in Table 4 and shown in Figure 10.

Table 4. Summary table of ΔTBA values for PB and PB/QSF.

	Pure Bitumen 35/50 (PB)	PB /QSF		
Ratio of QSF to PB (%)	0	50	57	60
Softening point test temperatures TBA (°C)	56	61,1	61,8	62,1
ΔTBA (PB /QSF) (°C)		5,1	5,8	6,1
ΔTBA Max required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		16	16	16
ΔTBA Min required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		8	8	8

Figure 10 illustrates the increasing variation in ΔTBA in relation to the variation in the percentage of QSF to PB. The curve where ΔTBA is below 8°C corresponds to complete filler percentage interval under study (54-60%). This curve shows that the ΔTBA test results are unacceptable, even if the filler ratios in the bituminous mix comply with current standards.

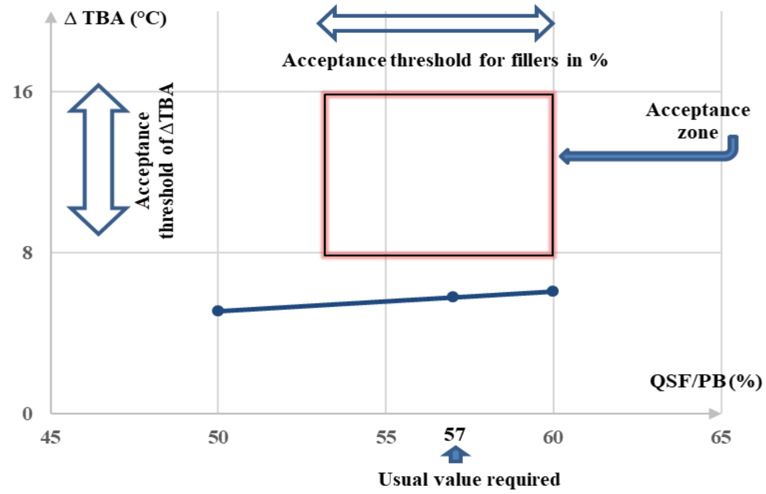

Figure 10 - Variation in ΔTBA as a function of the ratio of QSF to PB.

The results obtained from tests on PB in accordance with standard EN 1427 (EN 1427, 2015) and on the mixture of PB with NSF in accordance with standard EN 13179 (EN 13179, 2013) are summarized in Table 5 and depicted in Figure 11.

Table 5 - Summary table of ΔTBA values for PB and PB/NSF.

	Pure Bitumen 35/50 (PB)	PB /NSF		
Ratio of NSF to PB (%)	0	50	57	60
Softening point test temperatures TBA (°C)	56	65,9	66,53	66,8
ΔTBA (PB /NSF) (°C)		9,9	10,53	10,8
ΔTBA Max required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		16	16	16
ΔTBA Min required by article 5.3.3.2 of the standard (EN 13043, 2002) (°C)		8	8	8

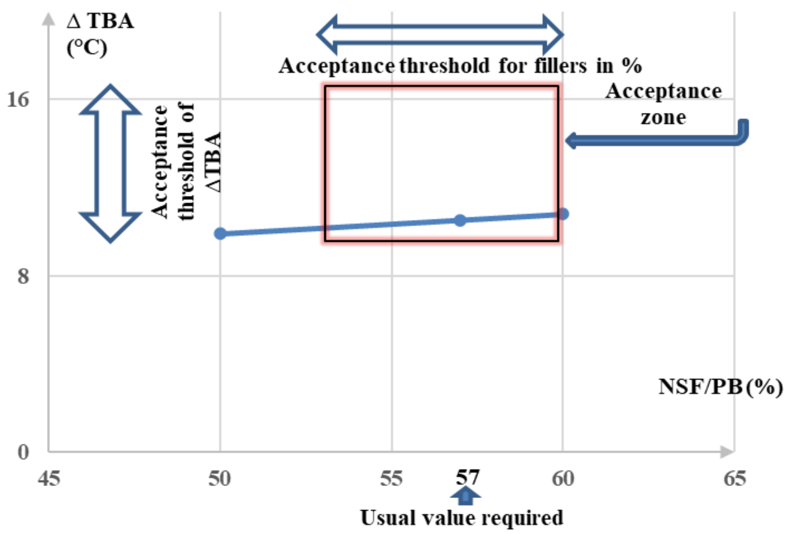

Figure 11 - Variation in ΔTBA as a function of NSF to PB ratio.

The curve in Figure 11 shows that the ΔTBA test results are acceptable if the ratios of fillers in the bituminous mix comply with current standards.

In order to compare the performance of each mix in terms of the rigidifying power of the fillers characterized by ΔTBA in the filler/bitumen mix, the ΔTBA results of the three mixes, bitumen with dune sand fillers (PB/DSF), bitumen with quarry sand fillers (PB/QSF) and bitumen with standardized sand fillers (PB/NSF) were considered. Generally, the filler percentage in bitumen follows a direct proportional relationship with respect to the rigidifying power. However, the values of ΔTBA for the same percentage vary according to the type of filler as shown in Figures 9 to 11. According to the obtained results, the ΔTBA for the PB/QSF is totally out of range (5.1°C to 6.1°C), while that of PB/DSF fully meets the requirements of the standardized filler percentage, with an improvement of around 70% in the ΔTBA.

Figure 12 depicts the variation in ΔTBA in relation to the variation in the filler proportion. It is clear that for the standardized filler percentage (57% ± 3%), the ΔTBA of the PB/QSF is completely outside the accepted threshold. Hence, this type of filler is probably the cause of the rapid ageing degradation observed on Saharan roads. On the other hand, the ΔTBA values for PB/DSF are completely above the acceptance threshold, and the results are close to those of PB/NSF. Consequently, it can be said that PB/DSF perfectly meets the requirements and offers a major advantage in terms of the ageing resistance of Saharan roads.

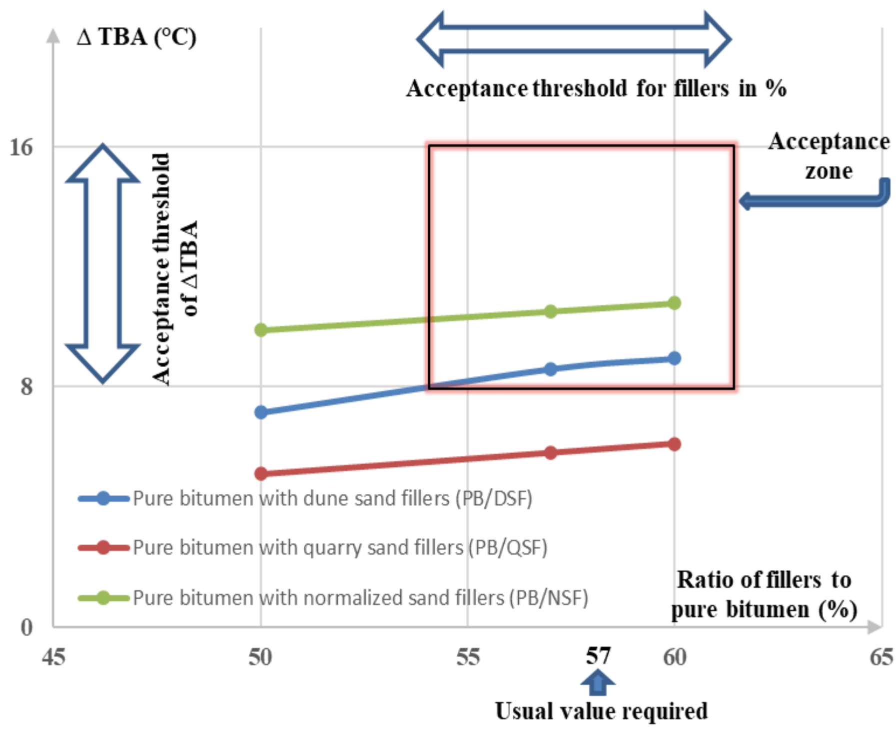

Figure 12 - Variation in ΔTBA as a function of the proportion of DSF, QSF and NSF to PB.

4.2 Results and discussion of the mechanical study

The results of the mechanical tests are summarized in Table 6.

Table 6 - Results of mechanical tests.

	Absolute density (g/cm^3)	Apparent density (g/cm^3)	Apparent density of bituminous sample (g/m^3)	MARSHALL stability (kN)	Creep (mm)	MARSHALL quotient (kN/mm)	Water sensitivity DURIEZ on hydrocarbon mix
Normative reference	NF EN 1097-7 (2022)	NF EN 1936 (2007)	NF EN 12697-6 (2020)	NA 5227/EN 12697-34 (2020)	NA 5227/EN 12697-34 (2020)	NA 5227/EN 12697-34 (2020)	NA 5226/NF P 98-251-1 (2002)
Quarry sand filler QSF (1st sample)			2.32	11.67	3.25	4.944	0.887
Dune sand filler DSF (2nd sample)	2.64	1.25	2.31	12.54	2.56	3.616	1.133

The MARSHALL quotient, measured in units of kN/mm, emerges as a fundamental indicator of the mechanical strength of the material. The data reveal that the average MARSHALL quotient value for the first sample, containing quarry sand filler, is 3.616 kN/mm, while the second sample, incorporating dune sand filler, has an average MARSHALL quotient value of 4.944 kN/mm. It is important to note that higher MARSHALL quotient values indicate improved mechanical performance of the material.

The DURIEZ test, which assesses the water resistance of the material, reveals an interesting aspect: the comparison of the R/r ratio between the two samples offers significant conclusions, where R is the compressive strength in air and r is the compressive strength after immersion in water. The first sample has an average R/r ratio of 0.887, while the second sample has an average R/r ratio of 1.133%. According to standards, an R/r ratio greater than 0.75 is desirable, indicating better performance of the material against the effects of water. This observation confirms that the dune sand filler helps to improve the material's resistance to water, thereby enhancing its durability in harsh environmental conditions.

In summary, the results of the second part consistently demonstrate that dune sand filler has mechanical advantages over quarry sand filler. The higher MARSHALL quotient indicates improved mechanical strength, while the higher R/r ratio in the DURIEZ test highlights better water resistance. These findings will guide our recommendations for the optimal use of fillers in the formulation of bituminous mixes designed to reinforce road infrastructure in demanding environments.

5. Conclusions

Dune sand fillers can be obtained easily through the mechanical milling of dune sand, which is abundantly available in the great Sahara and is very easy to collect. The in-depth study devoted to the influence of dune sand filler on hot mix asphalt concrete in the context of desert roads has provided significant results and essential insights. The two parts of the research, focusing respectively on thermal and mechanical aspects, shed valuable light on the performance of the material as a function of the type of filler used.

The quarry sand filler (calcareous – QSF) often used in the desert does not respect the required value of ΔTBA (8/16 °C) according to clause 5.3.3.2 of standard EN 13043 (EN 13043, 2002). According to the results of laboratory experiments, the bitumen mixture with dune sand fillers complies with the required ΔTBA (8/16°C) unlike bitumen with quarry sand fillers, whose results are totally out of bounds, which may explain why the use of quarry sand fillers is the main cause of the rapid ageing deterioration observed in Saharan roads. The dune sand fillers improve the rigidifying power characterized by ΔTBA of the bitumen/filler mix, making it conform to European standards such as EN 13043 (EN 13043, 2002) and the LCPC's asphalt mix formulation manual (Manuel, L. P. C.,2007), with ΔTBA between 8% and 16%, thus correcting the non-conformity of the rigidifying power of quarry sand fillers and solving the problem of the uncontrollable quantity of fillers in bituminous mixes.

Stiffening capacity analysis (ΔTBA) revealed that dune sand filler, as well as standardized filler, met established thermal standards, offering a stable response to temperature variations. In contrast, quarry sand filler demonstrated inferior thermal performance, highlighting its limited potential under elevated temperature conditions.

The second part, focusing on mechanical properties, corroborated these findings by showing that dune sand filler improves MARSHALL stability, a crucial indicator of mechanical strength, compared with quarry sand filler. Furthermore, the R/r ratio in the DURIEZ test highlighted a better resistance to water when dune sand filler is used, thus enhancing the durability of the material.

Consequently, it is possible to draw a general conclusion in favor of using dune sand in bituminous mixtures for desert roads, as this material has demonstrated superior thermal and mechanical performance, meeting the required standards and offering a promising solution for improving the durability of road infrastructure in arid environments. These findings provide a solid basis for guiding formulation choices in desert road construction, paving the way for more resilient solutions adapted to the extreme conditions encountered in these specific regions.

The optimization of bituminous mixes by incorporating dune sand fillers offers useful prospects for road engineers and decision-makers in directing their choices towards the use of this material in the construction and maintenance of desert roads, and can thus make a significant contribution to the creation of more durable roads adapted to the particular challenges of deserts.

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