

Study of the Effect of Compaction Rate on the Thermal Diffusivity of an Unbound Granular Road Material: The Case of Lateritic Gravel

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Abstract In the context of road construction in the intertropical zone, lateritic gravel is a predominant material due to its availability and geotechnical characteristics. This article examines the influence of compaction rate on the thermal diffusivity of lateritic gravel. For this study, samples of lateritic gravel from Cana Atchia, Zogbodomey commune, Zou department in Benin, were compacted to rates of 90%, 95%, 97%, and 100% in PVC cylinders. For each of these specimens, thermal diffusivity was determined using a numerical method that solves the heat equation in quasi-steady state based on data collected via an experimental setup comprising a heating lamp as the heat source and a data acquisition system with Type K thermocouples to monitor temperature changes within the material. At the same time, the CBR was measured at the various targeted compaction rates, both on unheated specimens and on those used to measure thermal diffusivity. The results obtained demonstrate a direct correlation between an increase in the compaction rate and an improvement in the material's thermal properties. The average thermal diffusivity increased from $4.834 \times 10^{-7} \text{ m}^2/\text{s}$ at 90% compaction to $5.774 \times 10^{-7} \text{ m}^2/\text{s}$ at 100%. This increase is explained by the reduction in the material's porosity, which facilitates better heat propagation through the densified particles. Additionally, it was noted that heating caused the CBR values to drop. However, the CBR increases with the compaction rate regardless of the type of specimen. This study confirms that optimizing the compaction of lateritic gravel is an effective means of improving its thermal performance, which reduces its strength performance. Better control of heat diffusion is essential for designing more stable and durable road infrastructure in tropical climates, thereby helping to reduce damage and long-term maintenance costs.

Keywords: Lateritic gravel, compaction rate, thermal diffusivity, CBR, road infrastructure

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1. Introduction

In tropical regions, road infrastructure is subjected to extreme climatic conditions, characterized by high temperatures and intense rainfall. These climatic conditions strongly influence the thermal properties of pavement materials, including thermal diffusivity, which determines the rate at which heat propagates through a material [1]. Controlling thermal diffusivity is essential in these environments, as it directly affects the thermal stability, resistance to deformation, and durability of road infrastructure [2,3]. Indeed, uneven heat propagation can generate internal stresses, contributing to the development of premature degradation such as cracking or creep [4].

The nature of the materials used in pavements, particularly granular materials that are insensitive to variations in temperature and humidity. Kumar and Singh [5] have shown that in a tropical environment, an uncompacted granular material exhibits low thermal diffusivity, which leads to heat accumulation at the surface and accelerates pavement aging. Conversely, optimal compaction of granular materials can improve their resistance to thermal cycles and reduce the risk of plastic deformation under repeated loads [4,6].

This study therefore aims to explore the influence of the compaction rate on the thermal diffusivity of unbound lateritic gravel, following Berraha's approach [7], which emphasizes that knowledge of thermal properties is essential for preventing pavement degradation related to heat flow. To this end, we characterized the lateritic gravel

and then measured its thermal diffusivity at different compaction rates using a method based on solving the heat equation.

2. Materials and Methods

• Material

In Table 1 the material studied in this research comes from the Cana Atchia quarry, specifically in the municipality of Zogbodomey, Zou Department, Republic of Benin. Its characteristics [8], listed below, clearly indicate that it is a road construction material.

Table 1. Major characteristics of the lateritic gravel from Cana Atchia

Features	Valeurs de grave latéritique	CEBTP1984 thresholds, revised in 2019	
		Foundation layer	Base layer
Percentage passing 80µm sieve	13,00	< 35	< 20
Liquidity limit (%)	32,67	<50	<35
Plasticity Index (%)	13,67	<25	<15
Plasticity Index (%)	2,28	≥ 1.8-2	≥ 2
Linear swelling index (%)	0,04	<1	<1
CBR index at 95% OPM	106,00	≥ 30	≥ 80

Source: Houanou et al. [8]

Materials

The materials used to conduct this study are classified into three categories, namely:

- Modified Proctor test materials in accordance with standard NF P 94-093 [9];
- Thermal diffusivity test materials as presented by Houanou et al. [10];
- CBR (California Bearing Ratio) test materials in accordance with standard NF P 94-078 [11].

Method

To achieve the desired result, the methodological approach used is divided into three phases, namely:

- Modified Proctor test method in accordance with standard NF P 94-093;

To determine the number of blows as a function of the compaction rate, Equation 3 is established.

The scientific origin of the logarithmic relationship, Equation 1, in compaction dates back to the work of G.P. Boutwell in [12]:

$$\gamma_d = a \log n + b \quad (1)$$

Where

$a=0.2864$ et $b=1.7654$

n represents the number of strokes

give that the compactness is given by equation 2:

$$C(\%) = 100 \frac{d}{(d)_{Opt}} \quad (2)$$

Equation 3 is derived by substituting (1) and (2):

$$(d)_{Opt} \frac{C}{100} = a \log n + b \quad (3)$$

With $(d)_{Opt} = 2,28t / m^3$ taken from Houanou et al. [8].

This gives:

$$\frac{C}{100} = 0.1256 \log n + 0.7743 \quad (4)$$

$$\text{Let } \rightarrow n = 10^{\frac{\left(\frac{C}{100}\right) - 0.7743}{0.1256}} \quad (5)$$

Based on equation 5, we determined the number of blows as a function of the compaction rate (see Table 2).

Table 2. Compaction as a function of the number of blows

Compactness C%	Number of strokes n
90	10
95	25
97	36
100	63

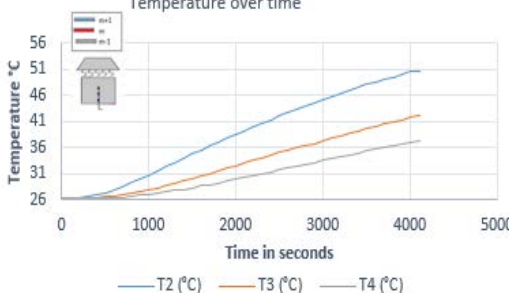
The modified Proctor test is performed using these different numbers of blows corresponding to the compaction level.

- Thermal diffusivity test method as presented by Houanou et al. [10];
- CBR (California Bearing Ratio) test method in accordance with standard NF P 94-078.

3. Results and Discussion

The results of the thermal diffusivity tests are presented in Table 3, Table 4, Table 5, and Table 6 below:

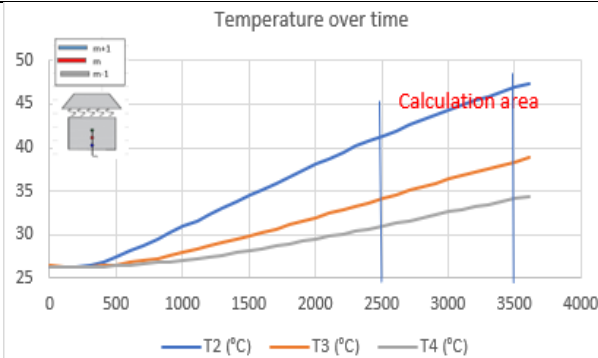
Table 3. Results of the thermal diffusivity test at 90% compaction

Temperature change over time	
Sample 1	
Temperature over time  — T2 (°C) — T3 (°C) — T4 (°C)	
Formula	

$$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$$

Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 5.103 \times 10^{-7} \text{m}^2/\text{s}$

Sample 2

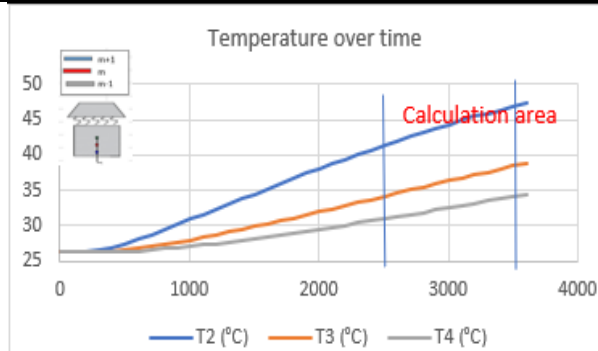


Formula

$$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$$

Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.482 \times 10^{-7} \text{m}^2/\text{s}$

Sample 3



Formula

$$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$$

Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.4916 \times 10^{-7} \text{m}^2/\text{s}$

Table 4. Results of the thermal diffusivity test at 95% compaction

Temperature change over time
Sample 1
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.853 \times 10^{-7} \text{m}^2/\text{s}$
Formula
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$

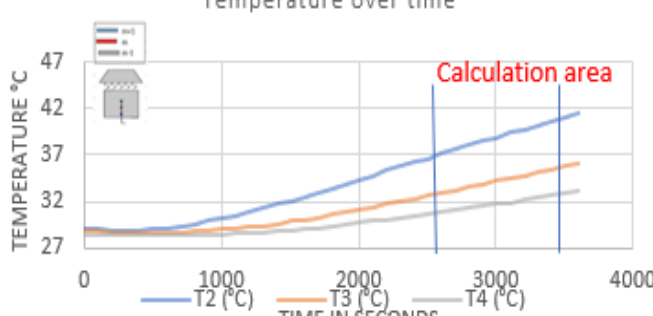
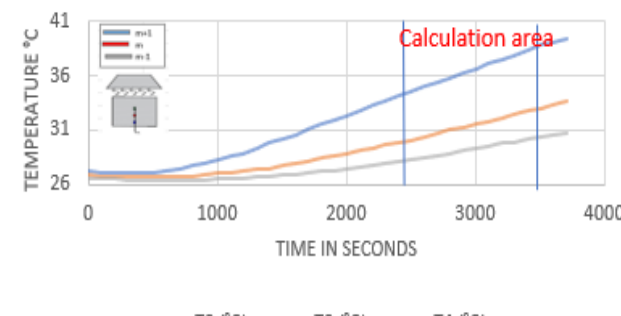
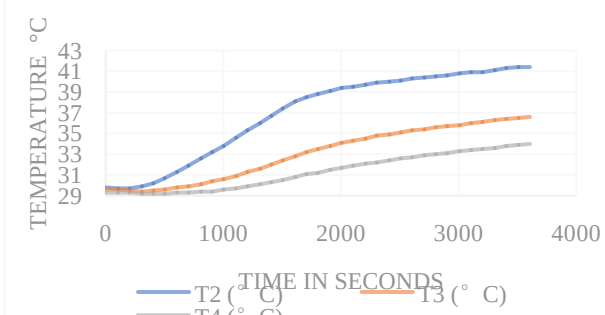
Sample 2	
Temperature over time 	
Formula	
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$	
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 6.138 \times 10^{-7} \text{m}^2/\text{s}$	
Sample 3	
Temperature over time 	
Formula	
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$	
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.501 \times 10^{-7} \text{m}^2/\text{s}$	

Table 5. Results of the thermal diffusivity test at 97% compaction

Temperature change over time	
Sample 1	
	
Formula	
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$	
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 2.556 \times 10^{-7} \text{m}^2/\text{s}$	
Sample 2	

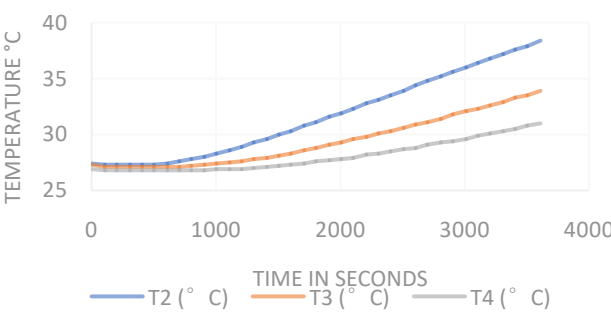
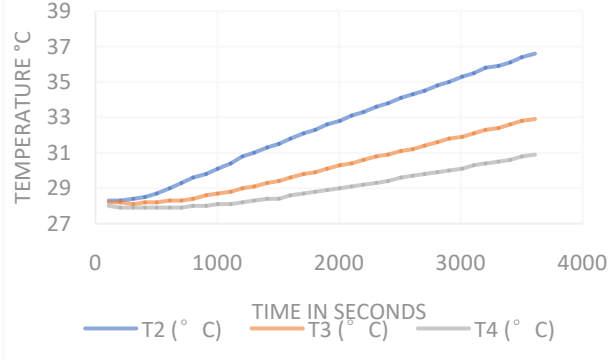
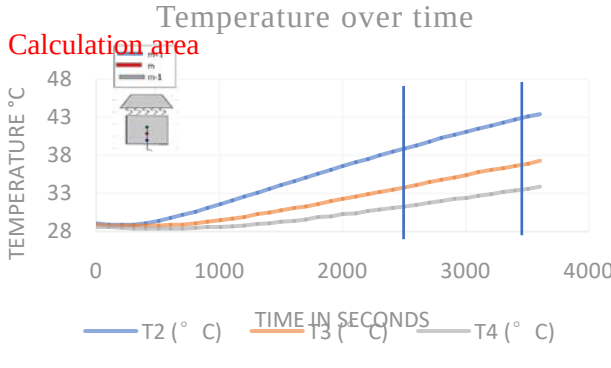
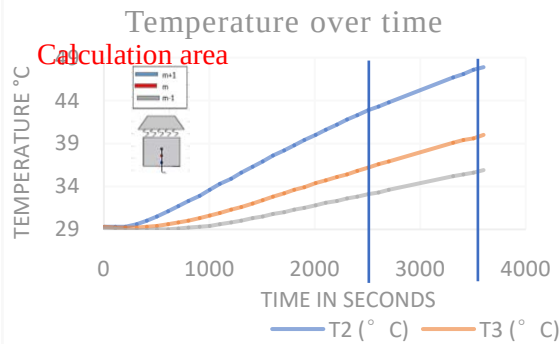
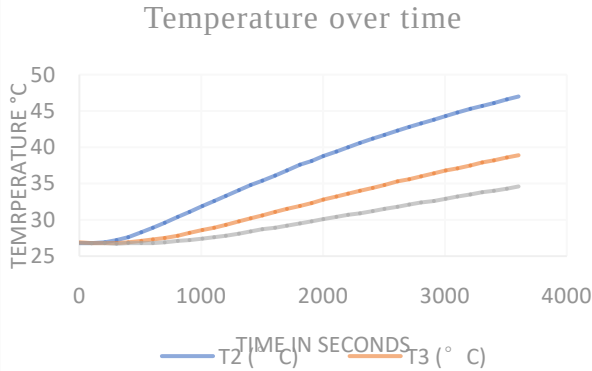
		
Formula		
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$		
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 8.351 \times 10^{-7} \text{m}^2/\text{s}$		
Sample 3		
		
Formula		
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$		
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.663 \times 10^{-7} \text{m}^2/\text{s}$		

Table 6. Results of the thermal diffusivity test at 100 % compaction

Temperature change over time		
Sample 1		
		
Formula		
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$		
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 5.164 \times 10^{-7} \text{m}^2/\text{s}$		
Sample 2		

	
Formula	
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$	
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 7.685 \times 10^{-7} \text{ m}^2/\text{s}$	
Sample 3	
	
Formula	
$\alpha = \left(\frac{T_m^{i+1} - T_m^i}{T_{m+1}^i + T_{m-1}^i - 2T_m^i} \right) \cdot \frac{(\Delta z)^2}{\Delta t}$	
Calculation of thermal diffusivity based on the numerical solution of the heat equation: $\alpha = 4.474 \times 10^{-7} \text{ m}^2/\text{s}$	

Based on thermal diffusivity tests conducted on the lateritic gravel from Cana Atchia as a function of CBR, we have compiled Table 7 and the bar chart (Table 8) below:

Table 7. Thermal diffusivity test as a function of compaction rate

Test of thermal diffusivity as a function of compaction rate					
Compaction	Sample	Diffusivity (10^{-7})	Average diffusivity (10^{-7})	CBR with diffusivity	CBR without diffusivity
90	1	4,482	4,834	29	32
	2	5,103			
	3	4,9163			
95	1	4,853	5,164	62	72
	2	6,138			
	3	4,501			
97	1	2,556	5,190	66	75
	2	8,351			
	3	4,663			
100	1	5,164	5,774	85	128
	2	7,685			
	3	4,474			

Table 7 shows that the average thermal diffusivity increases gradually with the compaction rate. For example, the average thermal diffusivity increases from $4.834 \times 10^{-7} \text{ m}^2/\text{s}$ at 90% compaction to $5.774 \times 10^{-7} \text{ m}^2/\text{s}$ at 100%. Furthermore, the **CBR value measured by taking diffusivity into account is consistently lower** than that of the standard CBR (“without diffusivity”). This proves that the material’s thermal properties—specifically its ability to diffuse heat—have a negative impact on its mechanical bearing capacity. This phenomenon is due to the decrease in the material’s porosity, a consequence of increased densification of the solid particles. Indeed, as compaction intensifies, the spaces between the grains shrink, thereby facilitating better heat propagation through the material’s particles. Nancy Hamieh et al. [13,14,15,16].

The reduction in load-bearing capacity is explained by the behavior of the interstitial water present in the material. When the material is subjected to a heat flux, the water contained in the pores heats up and expands.

- At lower compaction rates, the pores are more numerous and better connected, allowing water pressure to dissipate more easily.
- At **100% compaction**, the material is very dense,

and the pores are reduced in size and poorly connected. Heat propagates faster (higher diffusivity), the water expands, and generates an **increase in pore pressure**. This excess pressure reduces the effective stresses between the solid grains, which **decreases the material's shear strength and causes its bearing capacity (CBR) to drop**.

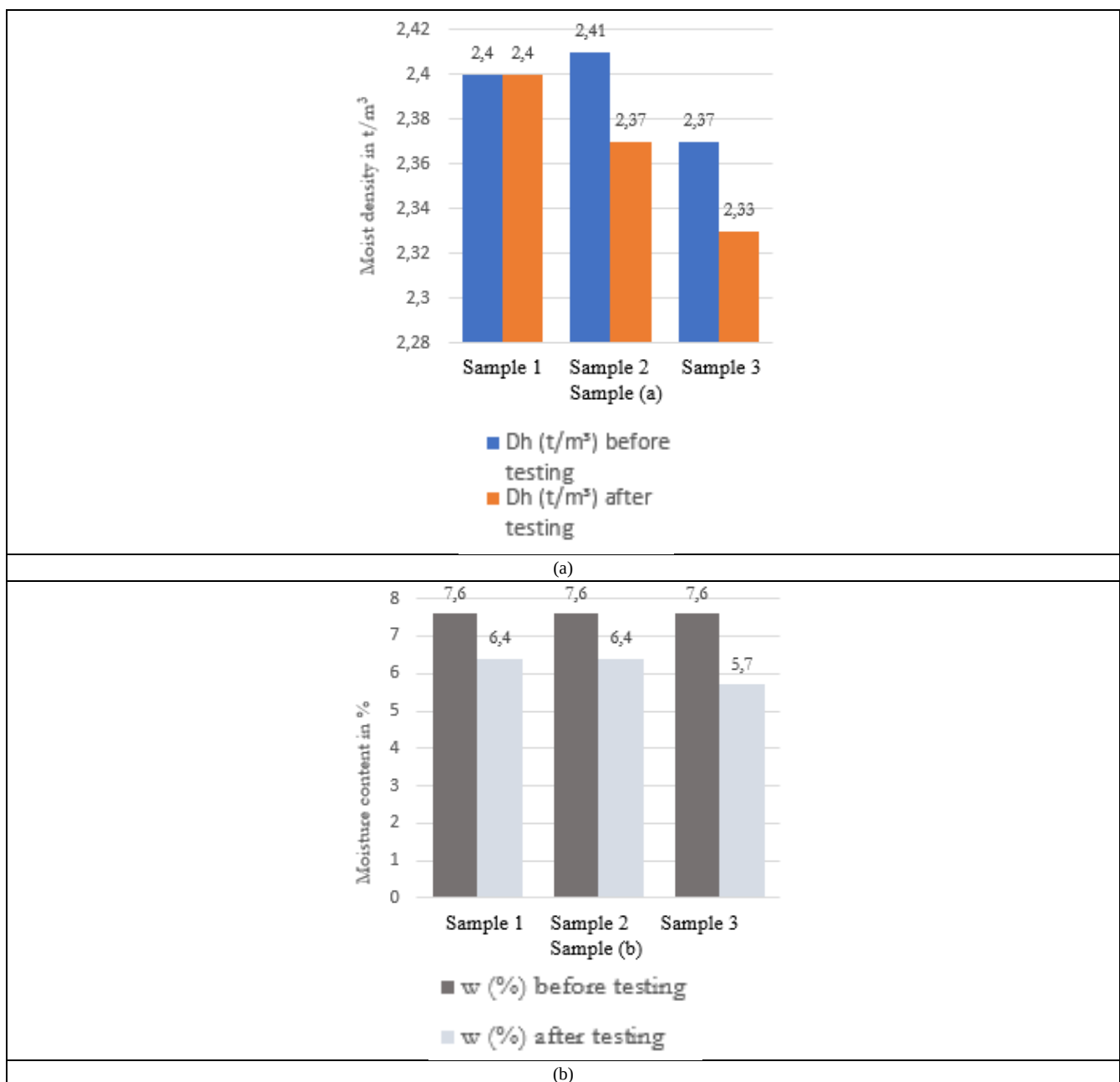
A comparative analysis of CBR values reveals a crucial point: ignoring a material's thermal properties can lead to a **dangerous overestimation of its bearing capacity**, especially when it is highly compacted. The "CBR without diffusivity" test provides an optimistic picture of the material's mechanical performance, whereas the "with diffusivity" test reveals potential vulnerability under thermal stress—a critical factor for pavement applications

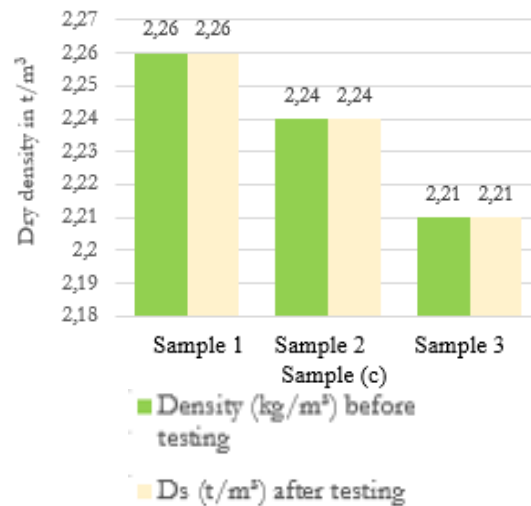
exposed to sunlight and temperature fluctuations.

The values for dry density, wet density, and moisture content measured before and after the thermal diffusivity test were used to generate the following graphs:

Table 8 shows three graphs (a), (b), and (c). It can be seen that the dry density values, before and after the tests, did not show any significant difference. However, the wet densities and moisture contents decreased significantly. This change indicates that a material compacted at its optimal moisture content experiences a decrease in its wet densities and optimal moisture content over time due to the effects of heat. This phenomenon results from the evaporation of water contained within the material, which alters its physical properties, particularly regarding its water retention capacity and compactness.

Table 8. Variation in D_h , w , and D_s values before testing compared to those after testing of thermal diffusivity specimens





(c)

4. Conclusion

This study establishes a direct and positive correlation between the compaction rate of lateritic gravel and its thermal diffusivity. The results demonstrate that the average thermal diffusivity increases from $4.834 \times 10^{-7} \text{ m}^2/\text{s}$ at 90% compaction to $5.774 \times 10^{-7} \text{ m}^2/\text{s}$ at 100% compaction. This improvement in thermal performance is due to the reduction in the material's porosity, which facilitates more efficient heat transfer through the densified particles.

Beyond this observation, the major contribution of this research is the demonstration of the direct impact of these thermal properties on the material's mechanical performance. It was found that the bearing capacity, as measured by the CBR (California Bearing Ratio), decreases significantly when the material is subjected to a heat flux. For example, at 100% compaction, the CBR drops from 128 (standard measurement) to 85 when the effect of heat is factored in, representing a 33% reduction. This phenomenon is explained by the increase in interstitial water pressure due to heat in a densified medium, which reduces the effective stress between the grains and weakens the material's shear strength.

This finding has major implications for road engineering in tropical environments: ignoring thermal effects can lead to a dangerous overestimation of the bearing capacity of pavement layers. While optimizing compaction is beneficial for thermal stability, it must therefore be approached with caution, as it can mask mechanical vulnerability under thermal stress.

This study highlights the need to integrate the analysis of thermal properties into design and quality control standards for road materials. A coupled thermo-mechanical approach is essential to ensure the design of more reliable and durable road infrastructure capable of withstanding the extreme climatic conditions of tropical regions and thereby reducing long-term maintenance costs.

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