Comprehensive Study on Thermal Variability of 50/70 Bitumen: An Examination of Fatigue Testing Outcomes

ANNOUAR DJIDDA Mahamat, OUMAR IDRISS Hamid, KENMEUGNE Bienven

Abstract: The primary methodology for this research involves conducting a series of fatigue tests on 50/70 bitumen to assess its behaviour under varying thermal conditions. The tests will be carried out using a Dynamic Shear Rheometer (DSR), a widely used apparatus in bitumen testing. The DSR allows for measuring bitumen's rheological properties, such as viscosity and elasticity, under controlled temperature and stress conditions. The 50/70 bitumen samples will be carefully prepared according to standard testing procedures to ensure uniformity. The bitumen will be heated to a specified temperature for testing, and samples will be taken at different thermal conditions to simulate varying environmental scenarios. The bitumen samples will be placed in the DSR and subjected to cyclic loading to simulate the stresses experienced in real-world road conditions. The tests will be conducted at a range of temperatures, typically from low temperatures (to simulate cold weather) to high temperatures (to simulate hot weather). This will allow for the study of the temperature-dependent behaviour of bitumen. The DSR will measure the *complex shear modulus (G)**, which provides information on the stiffness of the material, and the phase angle (δ), which reflects the material's ability to recover after deformation. These parameters are crucial for assessing the fatigue resistance of bitumen. The fatigue behaviour of the bitumen will be evaluated under repeated loading conditions. The dynamic shear rheometer will apply cyclical stress to the bitumen samples and measure the resulting strain. The number of cycles to failure, defined by a significant decrease in stiffness or an increase in phase angle, will be recorded. The focus will be on understanding how the fatigue resistance of the bitumen is affected by temperature fluctuations. By subjecting the bitumen to these varying conditions, it will be possible to determine at which. Temperatures the material exhibits optimal durability or fails prematurely.

Keywords: Bitumen, Temperature, Modeling, Frequencies

I. INTRODUCTION

In this work, the 50/70 bitumen sample was obtained through the Arab Contractors company.

Manuscript received on 22 November 2024 | Revised Manuscript received on 28 November 2024 | Manuscript Accepted on 15 December 2024 | Manuscript published on 30 December 2024.

*Correspondence Author(s)

Dr. ANNOUAR DJIDDA Mahamat, Department of Technology / University of N'Djamena, Chad. Email ID: mahaboubdjidda@gmail.com, ORCID ID: 0009-0005-7595-0451

OUMAR IDRISS Hamid*, Department of Technology / University of N'Djamena, Chad. Email ID: oumaridriss1@gmail.com, ORCID ID: 0000-0003-3136-2402

KENMEUGNE Bienvenu, Department of Industrial and Mechanical Engineering University of Yaoundé I, Yaoundé, Cameroon. Email ID: kenmeugneb@gmail.com ORCID ID: 0000-0002-2587-3698

The needle penetration tests, softening points, and experimentation were conducted at the CGCOC Group company in collaboration with the ENSTP laboratories in N'Djamena and the LERTI laboratory at the University of N'Djamena.

II. MODELING OF THERMAL TRANSFER EFFECTS

Bituminous mixtures are highly heterogeneous materials containing three main phases:

- The matrix, composed of bitumen, exhibits a thermally activated viscoelastic behaviour described as thermodynamically simple, with relatively low thermal conductivities.
- Aggregates, ranging from a few tenths of a millimetre to several tens of millimetres and potentially having complex angularity, exhibiting elastic behaviour and higher thermal conductivity.
- Finally, the voids, with a relatively low percentage [1]. In most modelling studies, bituminous mixtures are considered as homogeneous materials [2]. The drawback of this simplifying assumption is that it does not allow for the study of local phenomena occurring within the material due to its heterogeneity (such as stress and strain states in the thin film) [3]. Using a heterogeneous approach, many authors have observed a higher level of local strain and stress within the thin film in the matrix during mechanical loading.

The Dissipated Energy Density (DED) resulting from the viscoelastic behaviour in the matrix is a function of the level of strain and stress. Therefore, in the thin film where these values are higher, the amount of dissipated energy will be greater. The wasted energy acts as a heat source that increases the temperature of the material.

$$\mathrm{DED} = \int_{t_1}^{t_2} \sigma \frac{\partial \varepsilon}{\partial \tau} d\tau \qquad (1)$$

This effect is more noticeable during a fatigue test where a significant number of loading cycles are applied to the material. The heating causes a reduction in the modulus of the thermosensitive matrix. Numerous studies on bituminous materials, such as pure binder, mastic, and bituminous concrete, have highlighted the self-heating phenomenon at different scales.

III. ESTABLISHING THE HEAT EQUATION

Heating the material is essential for understanding its behaviour under cyclic loading. To account for these effects, it is necessary to include viscous dissipation as the heat source term (DED) in the heat equation.

$$\begin{cases} \rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = DED \quad In\ a\ Medium\ \Omega \\ n \cdot (k \nabla T) = h(T_{ext} - T) \end{cases} \quad (2)$$

The source term DED is equal to the viscous deformation energy, which, according to the calculation assumption, is fully dissipated as heat [4]. Specifically, the expression for DED in the case of tension-compression is given by the following equation [5]:

$$DED = \omega \cdot Im[E^*] \cdot W_e + \omega |E^*| \sin\varphi \cdot W_e \quad (3)$$

Where W_e correspond to the usual deformation energy for a unit modulus (E = 1).

This is a strong assumption, as part of the viscous energy may correspond to plasticity. However, we choose to assume that all the viscous energy is converted into heat. According to this coupled model, it is possible to account for this heating and analyze its effect on the evolution of temperature and the complex modulus of the bituminous mixture as a function of the number of applied cycles. In the case of uniaxial tension-compression, the deformation energy function and the pulsation can be written as follows:

$$\begin{cases} W_e = \frac{1}{2} \sigma_a \cdot \varepsilon_a \\ \omega = 2\pi f \end{cases} \quad (4)$$

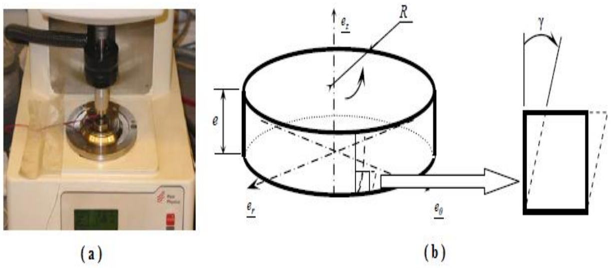
where indices σ_a and ε_a are the stress and strain tensors, respectively, with amplitudes corresponding to their maximum values reached during the cycle.

The equation (3) becomes:

$$DED = \pi \cdot f \cdot \sigma_a \cdot \varepsilon_a \cdot \sin\varphi \quad (5)$$

A. Heat Transfer Equation: Case of the Cylindrical Shear Test Geometry

Thermal conduction is assumed to be unidirectional along the radial direction from the centre (r = 0) to the boundary surfaces of the cylinder (r = R) [6]. The variation of temperature with height is neglected, and the temperature is considered a function of the radius r. However, thermal exchanges with the surfaces are accounted for. To do this, an additional term is introduced to correct the heat source to consider these exchanges. The complete set of equations is given by the following expressions:



[Fig.1: (a) Bitumen Rheometer (b) Schematic of the Cylindrical Sample]

From Figure 1, the thermal conduction equation is as follows:

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \pi \cdot f \cdot \left(\frac{r}{R}\gamma_a\right) \cdot |G^*(T)| \cdot \sin(\varphi(T)) - \frac{2\lambda_{th}}{k} e(T - T_{ext}) \quad (6)$$

Thermal Boundary Conditions and Initial Conditions

$$\begin{cases} \frac{\partial T}{\partial r}(0, z) = 0 \\ k \frac{\partial T}{\partial r}(R, z) = -\lambda(T - T_{ext}) \\ T(r, z, t = 0)_{t=0} = T_{ext} \end{cases} \quad (7)$$

Mechanical Loading and Boundary Condition at the Top of the Specimen:

$$U_\theta(r, H) = \frac{e}{R}\gamma_a \cdot r \cdot sin(\omega t) \quad (8)$$

Mechanical Loading, Boundary Condition at the Base of the Specimen:

$$\begin{cases} U_r(r, 0) = 0 \\ U_\theta(r, 0) = 0 \\ U_z(r, 0) = 0 \end{cases} \quad (9)$$

These equations lead to a purely radial problem [8]. Under these conditions, numerical implementation is performed using MATLAB to solve the initial boundary value problems for the system of parabolic and elliptic partial differential equations in one time-dependent variable [9].

To evaluate the thermal variations of bitumen, fatigue tests were conducted with a thermocouple attached to the surface of the bitumen [10]. This setup allowed for the measurement of temperature increases within the material and the monitoring of its variations [11]. Two types of bitumen, 50/70A and 50/70B, were used, and the test conditions were set at 25 Hz and 15°C.

Indeed, the 50/70A and 50/70B classes are bitumens modified at certain percentages for the preparation of the surface layer (50/70A) and the base layer (50/70B), respectively. Samples were prepared with these modified bitumens to determine their thermophysical properties [12]. These types of bitumen are intended for typical road applications, including the construction of foundation, base, binder, and surface layers of pavements. They are suitable for all technical assemblies implemented in road construction.

B. Rheological Parameters

For the thermomechanical simulation, it was necessary to adapt the parameters of the rheological model in equations (10) and (11) to match the shear modulus measurements. These tests were conducted within the linear viscoelastic range for a low-strain level.

($\gamma_a = 5 \cdot 10^{-4}$). The tests were performed over the following ranges:

- Loading frequencies: [0.01; 0.1; 1; 4.65; and 10] Hz.
- Temperatures : [-5; 5; 15; 25; 35; and 45] °C.

$$E^*(\omega) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i \cdot 2\pi f \cdot a(\theta))^{-k} + (i \cdot 2\pi f \cdot a(\theta))^{-k}} \quad (10)$$

$$Log(a_T) = -\frac{C_1(T - T_0)}{C_2 + (T - T_0)} \quad (11)$$

C. Thermophysical Parameters of Bitumen

The identification of thermophysical parameters, according to the Shell bitumen manual, is as follows:

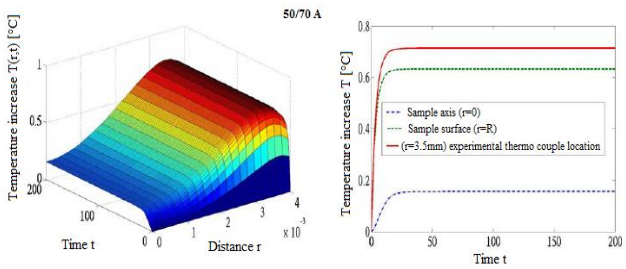
- Specific heat $\rho C = 1.710 \cdot 10^6\ W/m^{3\circ}C$.
- Thermal conductivity: $k = 0.157\ W/m^{3\circ}C$.

These parameters play a significant role at the sample surface but are challenging to evaluate precisely. Different values were assigned for the two contact surfaces: one modelling the exchange between bitumen and steel, and the [7] lateral surface modelling the heat exchange between bitumen and air. Heat exchanges within the test chamber of the steel testing machine are relatively high, with a thermal conductivity of $\lambda_{bt} = 50\ W/m^{2\circ}C$, and for the free surface in contact with air, $\lambda_{bt} = 20\ W/m^{2\circ}C$.

These values were chosen to be close to standardized values for bitumen mixtures used in fatigue tests. The accuracy of these values can be assessed as a posteriori by comparing the calculated temperature to the measured temperature.

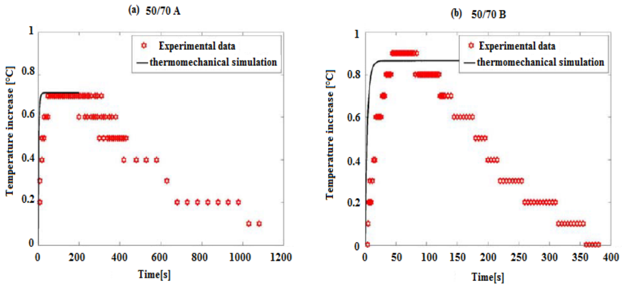
IV. SIMULATION RESULTS AND FATIGUE MEASUREMENTS

The fatigue test results presented below were conducted at 15°C with a frequency of 25 Hz. The same load level was applied to each sample (50/70A and 50/70B), resulting in a shear strain of, $\gamma_a = 18 \cdot 10^{-3}$.



[Fig.2: 3D Representation of Temperature as a Function of Time and Radius]

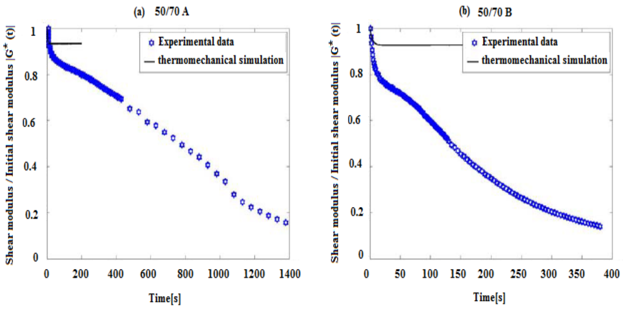
The figures illustrate the variation in temperature rate during the dissipation process until the sample reaches a steady-state temperature [7]. This state is governed by the balance between the energy produced within the sample and the energy, exchanged through the surface [8]. We will see later that the temperature reaches a steady regime throughout the bitumen fatigue process.



[Fig.3: Thermomechanical Simulation and Experimental Data]

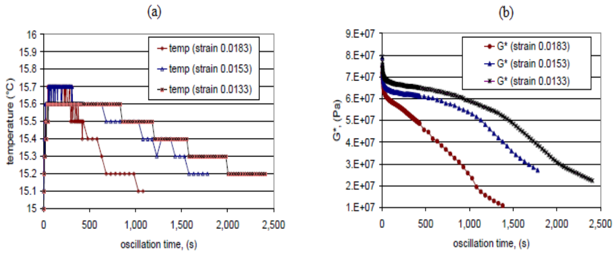
The temperature values obtained can be compared to those measured on the surface of the sample. Figure 3 shows the evolution of temperature as a function of time, which occurs in two phases:

1. In the first phase, the temperature increases from its initial value to reach a stationary zone. In this phase, the measured temperatures and the thermomechanical simulation show a good agreement, considering the thermal precision of ± 0.1°C.
2. In the second phase, the measured temperature decreases in a stationary, stepwise manner. This decrease is the main factor driving the fatigue mechanism, which leads to a reduction in the dissipation term. This temperature decrease is not implemented in this model, but it has already been modelled and validated for bituminous mixtures by coupling thermal dissipation with a damage model.



[Fig.4: Shear Modulus Simulation]

In this model, the displacement is controlled in such a way that the thermal variation reaches a steady state at its maximum value. The stiffness modulus follows the thermal variation up to its maximum value, then decreases to reach a steady state. Qualitatively, the stiffness obtained at the end of the simulation is overestimated due to the thermal effect, and the thermal variation is overestimated during the second phase of the test. Nevertheless, the value of this overestimation is small (less than 5% for both simulations). The thermal effects do not account for the entire loss of stiffness at the beginning of the fatigue test.



[Fig.5: Temperature, Deformations, and Shear as a Function of Oscillation Time]

Figure 5 shows the evolution of temperature and stiffness modulus during fatigue tests at various levels of deformation. The significant decrease in stiffness at the beginning of the test should not be considered in the rupture criterion, as it is due to the rapid temperature rise.

V. CONCLUSION

The results of the experimental campaign presented in this work lead to the determination of the linear viscoelastic properties using the complex modulus test conducted over a wide range of temperatures (from -25°C to approximately 65°C) and frequencies (from 0.01 Hz to 10 Hz). The Following point can be drawn:

- The thermal conductivity of the aggregates is higher than that of the matrix, which promotes the rapid diffusion of heat produced within the matrix.
- For a thin matrix (thin film), the generated heat diffuses quickly to the aggregates surrounding the film, while the temperature of the film increases gradually.
- At the level of a thick film, the insulating properties of the matrix cause a temperature rise.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. Bodin, D., Pijaudier-Cabot, G., de La Roche, C., Piau, J.-M., & Chabot, A. (2004). Continuum. « Damage Approach to Asphalt Concrete Fatigue Modeling. Journal of Engineering Mechanics, 130(6), 700-708. Doi: https://doi.org/10.1061/(ASCE)0733-9399(2004)130:6(700)
2. Alexis Kemajou, L. Mba (2023). « Matériaux de construction et confort thermique en zone chaude Application au cas des régions climatiques camerounaises ». Journal of Renewable Energies. Doi : https://doi.org/10.54966/jreen.v14i2.256
3. Annouar D. M. Oumar I. H. Moussa A. A. and Kenmeugne B. « Complex modulus testing of bitumens 50/70 and 10/20 using the 2S2P1D model» International Journal of Materials Engineering and Technology. Vol. 23, Number 2, 2024, Pages 119-131. Doi: https://doi.org/10.17654/0975044424007
4. M.R.M. Aliha, H. Fazaeli, S. Aghajani, and F. Moghadas Nejad. «Effect of temperature and air void on mixed mode fracture toughness of modified asphalt mixtures». Journal Construction and Building Materials Vol 95 (2015) 545-555. Doi: https://doi.org/10.1016/j.conbuildmat.2015.07.165
5. Ruolin Gao, Gaowei Yue, Zihao Li and Yanwen Zhang. « Optimisation and numerical study of forced convection heat transfer design for glass tempered cooling grille» International Journal of Thermal Sciences. Vol. 210, April 2025, 109569. Doi : https://doi.org/10.1016/j.ijthermalsci.2024.109569
6. Annouar D. M., Kenmeugne B., Moussa A. A. and Fogue M. « Degradation of phenomenon pavement in zone Sahel: Case of Chad» International Journal of Materials Engineering and Technology 14(2):79-91. Doi: https://doi.org/10.17654/IJMETOct2015_079_091
7. F. Fakhari Teheran. Absi F. Allou, and C. Petit «Investigation into the impact of the use of 2D/3D digital models on the numerical calculation of the bituminous composites' complex modulus» Computational Materials Science Vol 79, (2013), Pages 377-389. Doi: https://doi.org/10.1016/j.commatsci.2013.05.054
8. BODIN D., SOENEN H., DE LA ROCHE C., « Temperature Effects in Binder Fatigue and Healing Tests », Actes des 3rd Eurasphalt Eurobitume Congress, Vienne, 12-14 mai 2004, Book II, Paper 136. https://trid.trb.org/View/743984
9. Singh, H., Chopra, T., Kamotra, S., Jain, S., & Kaur, A. (2019). Performance Evaluation of Bituminous Concrete Mixes Modified with SBS Polymer and Warm mix Additive. In International Journal of Recent Technology and Engineering (IJRTE) (Vol. 8, Issue 3, pp. 441–450). Doi: https://doi.org/10.35940/ijrte.c4219.098319
10. Shah, P. R. (2024). Partial Replacment of LDPE in Bituminous Pavement. In International Journal of Emerging Science and Engineering (Vol. 12, Issue 7, pp. 20–26). Doi: https://doi.org/10.35940/ijese.h2578.12060724
11. Abdulrahman, S., Hainin, M. R., Satar, M. K. I. M., Hassan, N. A., & Usman, A. (2019). Rutting and Moisture Damage Evaluation of Warm Mix Asphalt Incorporating POFA Modified Bitumen. In International Journal of Engineering and Advanced Technology (Vol. 9, Issue 1, pp. 90–98). Doi: https://doi.org/10.35940/ijeat.a1052.109119
12. Saini, M., Aggarwal, Dr. P., & Chauhan, S. (2019). Behaviour of Bituminous Concrete Mixes with addition of Waste Plastic Bottle via Dry Process. In International Journal of Innovative Technology and Exploring Engineering (Vol. 2, Issue 9, pp. 732–736). Doi: https://doi.org/10.35940/ijitee.b7834.129219

AUTHOR'S PROFILE

Dr. Annouar Djidda Mahamat is a young academic and researcher, specializing in mechanics and energy. He is the Head of the Department of Teaching Monitoring at the Faculty of Exact and Applied Sciences at the University of N'Djamena. His area of expertise includes the mechanical behaviour of materials, material characterization, material properties, material testing, fracture mechanics, and high-temperature materials. He has supervised several master's theses and has published works in this field.

***Annouar Djidda Mahamat**, Oumar Idriss Hamid, Moussa Ali Abdoulaye and Kenmeugne Bienvenu «Complex modulus testing of bitumens 50/70 and 10/20 using the 2SP2P1D Model ». International Journal of Materials Engineering and Technology 23(2024) 119-13*

***Annouar Djidda Mahamat**, Kenmeugne Bienvenu, Tchikdje K. Marthe P. Kalameu Alain; Djeumako Bonaventure «Improved Particle Swarm Optimization for the Determination of Chaboche Model Parameters of the Elastoplastic Behavior Railway Steel». Journal of Applied Mechanical Engineering, International Journal of Innovative Science and Research Technology, ISSN No:-2456-2165*

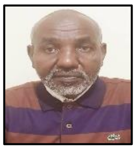
***Annouar Djidda Mahamat**, Kenmeugne Bienvenu, Moussa Ali Abdoulaye, and Fogue Medard «Degradation Phenomenon of Bituminous Pavement in Sahel zone case of Chad» International Journal of Materials Engineering and Technology, volume 14, Dec 2015, Issue 2, pp 79 to 91*

***Annouar Djidda Mahamat**, Kenmeugne Bienvenu, Moussa Ali Abdoulaye, and Fogue Medard «Measuring the Thermomechanical Fatigue of Asphalt Coatings» International Journal of Engineering and Technical Research, volume 3, Nov 2015, Issue 11, pp 9 to 15*

*Ngargueudedjim K., Bassa B., Nadjitonon N., Allarabeye N., **Annouar D. M.**, Abdel-Rahim M., B. Soh Fotsing, Fogue M., J.-F. Destrebecq, Rm Pitti, Jerome D «Mechanical Characteristics of Tall-Palm (Borassus Aethiopum Mart., Arecaceae) Of Chad / Central Africa» International Journal of Engineering and Technical Research, volume 3, Sep 2015, Issue 9, pp 125 to 128*

*Ngargueudedjim K, **Annouar D. M.**, G.E. Ntamack, S. Charif Douazzane, and Bianpambe H. W. «Anisotropic Behaviour of Natural Wood Palmyra (Borassus Aethiopium Mart) of Chad» International Journal of Mechanical Engineering and Technology, volume 6, Sep 2015, Issue 9, pp102 to 111*

*Ngargueudedjim K., Bassa B., Nadjitonon N., Allarabeye N., **Annouar D. M.**, Abdel-Rahim M., B. Soh Fotsing and Fogue M « Caracteristiques physiques du bois Ronier du Tchad» International Journal of Innovation and Applied Studies, volume 13, Nov 2015, pp 553 to 560*



Dr. Oumar Idriss Hamid is a teacher-researcher specializing in thermal engineering, energy systems, and the environment. He is the Head of the Department of Technology at the Faculty of Exact and Applied Sciences at the University of N'Djamena. He has supervised several master's students and has published works in this field.

***Oumar IDRISS Hamid**, Nadjitonon NGARMAIM, Mahmoud Youssouf Khayal, Abdallah DADI Mahamat, Mohammed GAROUM, Salif GAYE, Yacine ELHAMDOUNI « Thermophysical characterization of an environmental construction material made by clay and wheat » INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY (IJESRT) [4(12): December 2015]*

*Abdallah DADI Mahamat, **Oumar IDRISS Hamid**, Malloum Soultan, Mahmoud Youssouf KHAYAL, Yassine Elhamdouni, Mohammed GAROUM, Salif GAYE; « Effect of cow's dung on thermophysical characteristics of building materials based on clay » **RJASET, 2015***

*Azibert Oumar Abdelhakh, **Oumar Idriss Hamid**, Malloum Soultan, Mahamat Barka, Mamadou Adj and Salif Gaye «Improvement of the Thermal Conductivity of a Composite Material has Clay Base ». Res. J. Appl. Sci. Eng. Technol. 11(9): 962-968, 2015*

Yassine Elhamdouni, Abdelhamid Khabbazi, Chaimaa Boneyard, Abdallah Dadi, **Oumar Idriss Hamid** « Effect of fibre alfa on thermophysical characteristics of a material based on clay », Energy Procedia 74 (2015) 718 – 727*

*Annouar Djidda Mahamat, **Oumar Idriss Hamid**, Moussa Ali Abdoulaye and Kenmeugne Bienvenu «Complex modulus testing of bitumens 50/70 and 10/20 using the 2SP2P1D Model ». International Journal of Materials Engineering and Technology 23(2024) 119-131*

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

KENMEUGNE Bienvenu Doctor of Philosophy, Professor, Group Leader at the University of Yaoundé I Skills and Expertise Design Engineering, Engineering Optimization, Stress Analysis, Solid Mechanics, Research Methodology in Engineering, Materials Mechanics, Applied Mechanics, Mechanical Behavior of Materials Computational Mechanics, Damage Mechanics Finite Element, Micromechanics, Homogenization, Multiscale Analysis.