International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 41 No. 1 Nov. 2023, pp. 368-376

http://www.ijias.issr-journals.org/

Behavior of pavements with a base layer made up of Unbound Granular Material (UGM) in Côte d'Ivoire

Bakary Kone[1], Athanas Konin[1], and Augustin Toure[2]

[1]Laboratory of Civil Engineering, Geosciences and Geographical Sciences, National Polytechnic Institute Houphouët-Boigny (INP-HB), PO BOX 1093 Yamoussoukro, Côte d'Ivoire

[2]Laboratory of Mathematics and New Information Technologies, National Polytechnic Institute Houphouët-Boigny (INP-HB), PO BOX 1093 Yamoussoukro, Côte d'Ivoire

ABSTRACT: Roads are essential to the development of a nation, as they facilitate transportation and economic growth. Pavements, which provide a durable surface for vehicle traffic, depend on a variety of factors, including the quality of Unbound Granular Material (UGM) used in their base layers.
The main objective of this review article was to review recent studies on the characterization of UGM in pavements. To do this, a bibliometrics study was carried out to confirm the scientific interest of the subject by revealing a large number of publications on pavements and gravels not treated on the subject since 2000.
It appears that various empirical and theoretical approaches are used in pavement design and that UGM properties play a crucial role in the structural integrity of pavements.
Indeed, the study showed that UGM cleanliness is crucial to avoid contaminants that can affect the quality and performance of building materials. Various methods, including digital image analysis, have been used to quantify the characteristic shape of UGM. Additionally, UGM resistance is achieved using tests such as the Los Angeles abrasion test, which measures impact resistance. The researchers also underline the importance of taking into account cyclic stresses and permanent deformations in the design of the pavement to improve its longevity. In conclusion, the article highlights the growing scientific interest in pavements with UG base layers and discusses various methods for characterizing UGM properties, which are essential for the design of durable and resilient road pavements.

KEYWORDS: Unbound Granular Material (UGM), bibliometrics, pavement.

1 INTRODUCTION

The road network is a key element of a country's transport infrastructure, facilitating the movement of people and goods across the territory [1]. The construction of roads is of paramount importance for the socio-economic progress of a country, in the sense that it promotes the development of exchanges between populations, generates employment thanks to the economic activities it generates, and also facilitates the exploitation of abundant natural resources in the region where it is deployed [2], [3].

Roads have several components among which designate pavements that play a crucial role in transport infrastructure, offering a durable and safe surface for the circulation of vehicles thanks to their structures that allow them to resist over time [4], [5].

Road pavement structures are sized taking into account certain input parameters such as the nature of the supporting soil, its thickness or the traffic and the materials constituting the sofas [6]. Throughout its existence, the pavement is mainly exposed to mechanical and climatic stresses which affect its quality of service [7], which leads to various degradations such as cracks, potholes and rutting. Among the constituents entering into the structure of the pavements which allow it to last, we can cite the unused gravels used as a base course [8].

Several studies have shown the preponderant role played by Unbound Granular Material (UGM) in the life of pavements. Indeed, according to some authors [8], when the shape of these granular materials conforms with exactness, it influences to some extent the structure and the mechanical behavior as well as several properties of the pavement. UGM serve as a structural support by providing a strong and resilient platform on which the roadway is built. They distribute vehicle loads over a larger area and thus transmit the stress to the upper layers. In addition, UMG allow water to drain through the pavement layers [9], [10]

The material characteristics of the unbounded layers are therefore of great importance for the performance of the pavement [4]. The literature reveals numerous studies on unperceived bass as well as on their characterization. Indeed, several authors have proposed different models for characterizing the shape of UGM in order to better predict their behavior on pavements. Other authors [11] proposed a method for modeling coarse aggregates based on the morphological characteristics of particles using the Aggregate Image Measurement System (AIMS). As shape is not the only parameter for characterizing UGM, other studies have focused on a method for correcting parameters embedded in semi-rigid asphalt pavements combining numerical simulations and laboratory tests, as well as on the evolution of permanent deformations of UGM as a function of the number of cycles and the stress level applied to better assess the resistance of UGM under more real conditions [12], [13]. In view of these numerous works, it seems obvious that the characterization of UGM is a problem that arises acutely in the perspective of producing more durable and rutting-resistant pavements. It is with this in mind that this summary article has set itself the objective of reviewing recent studies on the characterization of unpowered gravel in pavements. In this review, we will first examine the bibliometrics in order to show the scientific interest in pavements and Unbound Granular Materials, then we will review the studies carried out on pavements and we will end with the characterization of Unbound Granular Materials.

2 BIBLIOMETRICS

The bibliometrics was carried out from the "SCIENCEDIRECT" database on the theme "behavior of pavements with a base layer made up of unbound granular material (UGM) in Côte d'Ivoire".

Since the year 2000, many publications have been made, including 42,639 publications relating to the terms “pavement” and “carriegeway” and 59,245 relating to the terms “crushed aggregates”. Figures 1 and 2 show us the number of publications made by year since the year 2000.

With regard to the keywords "pavement" and "carriegeway", Figure 1 below shows us that the number of publications relating to these keywords is increasing from 454 to 5,219 from the year 2000 to 2022.

Regarding the keyword "crushed aggregates", we see in Figure 2 that the number of publications relating to this keyword is also changing, going from 551 to 7589 during the same period.

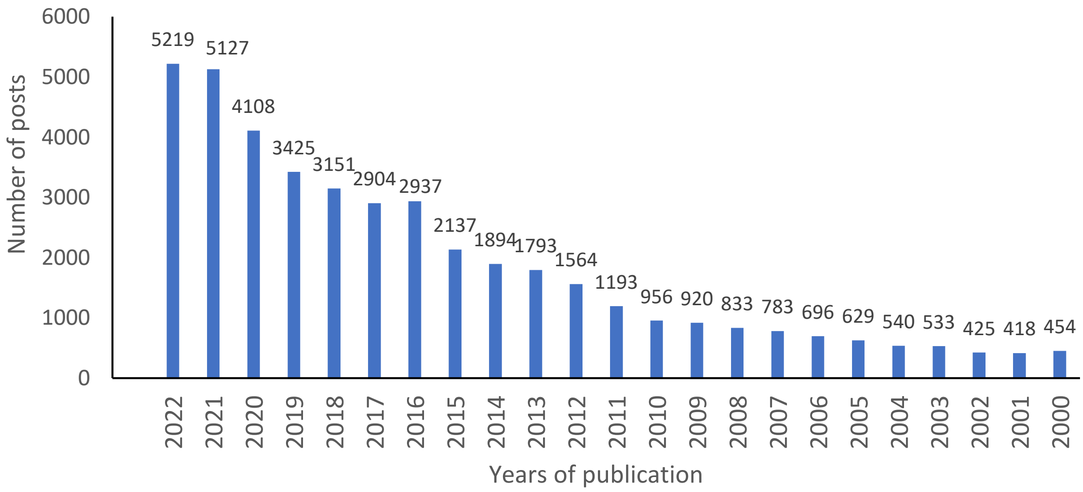

Fig. 1. Number of publications according to the years of publication on the keywords "pavement" and "carriegeway"

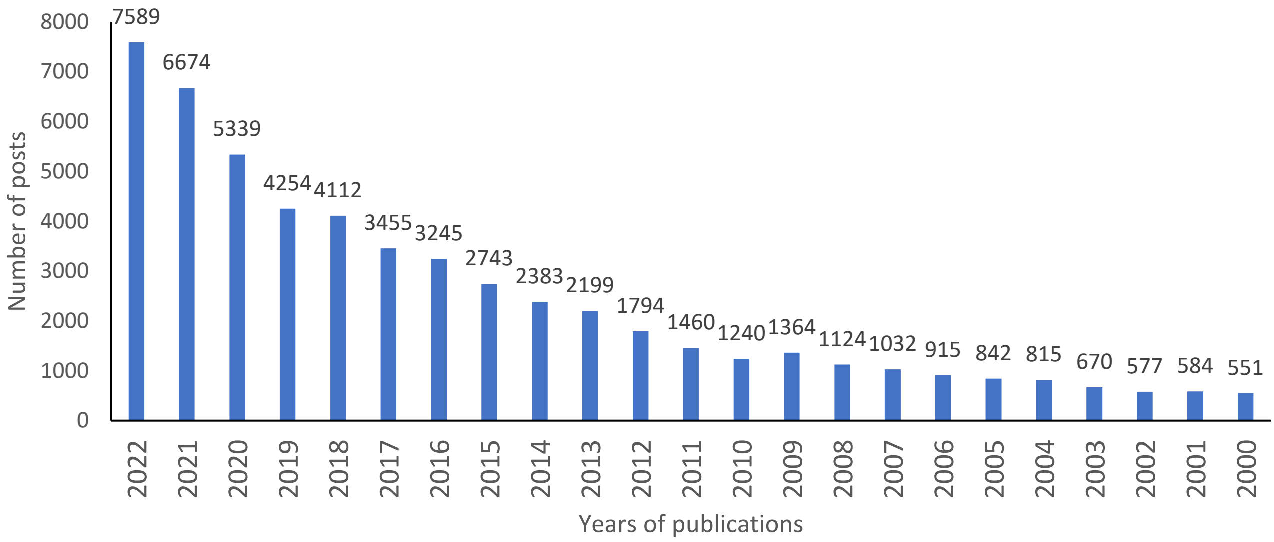

Fig. 2. Number of publications according to the years of publication on the keywords "Crushed aggregates"

This bibliometrics allows us to ensure that the theme "behavior of pavements with a base layer made up of untbound granular material (UGM) in Côte d'Ivoire" is topical in scientific publications and is of growing interest. Furthermore, it should be noted that several types of publications have been produced, including review articles, research articles, book chapters, conference abstracts, short communications and patent reports.

Figures 3 and 4 respectively present the distribution of the types of publications relating to the different keywords.

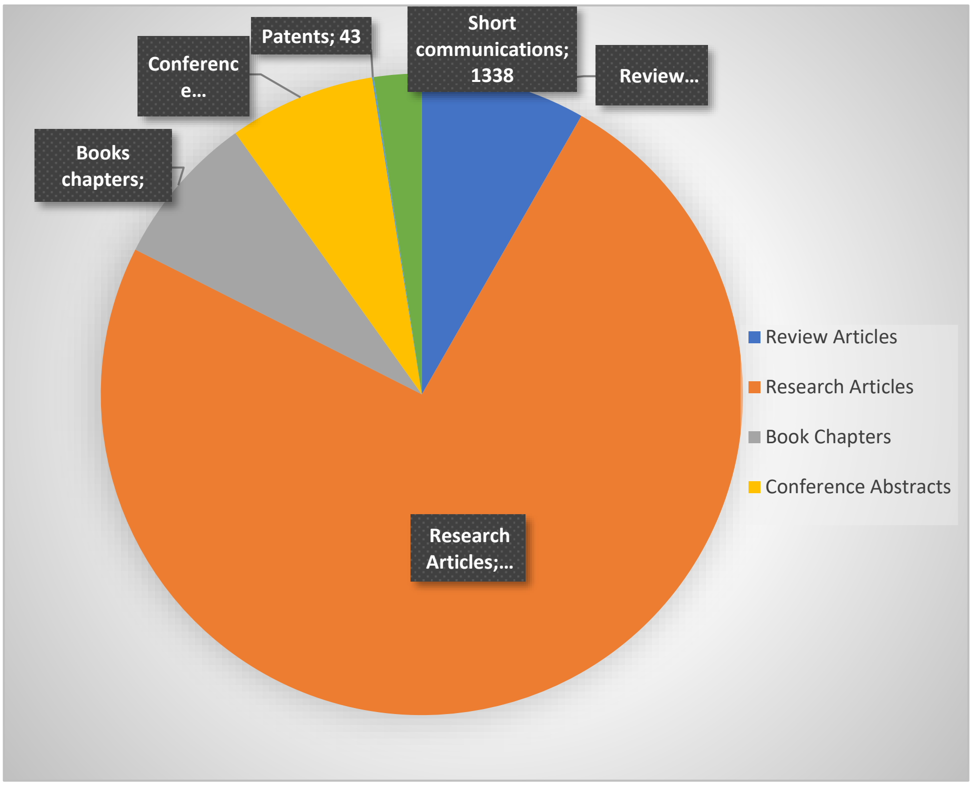

Fig. 3. Post type on keywords "pavement" and "carriegeway"

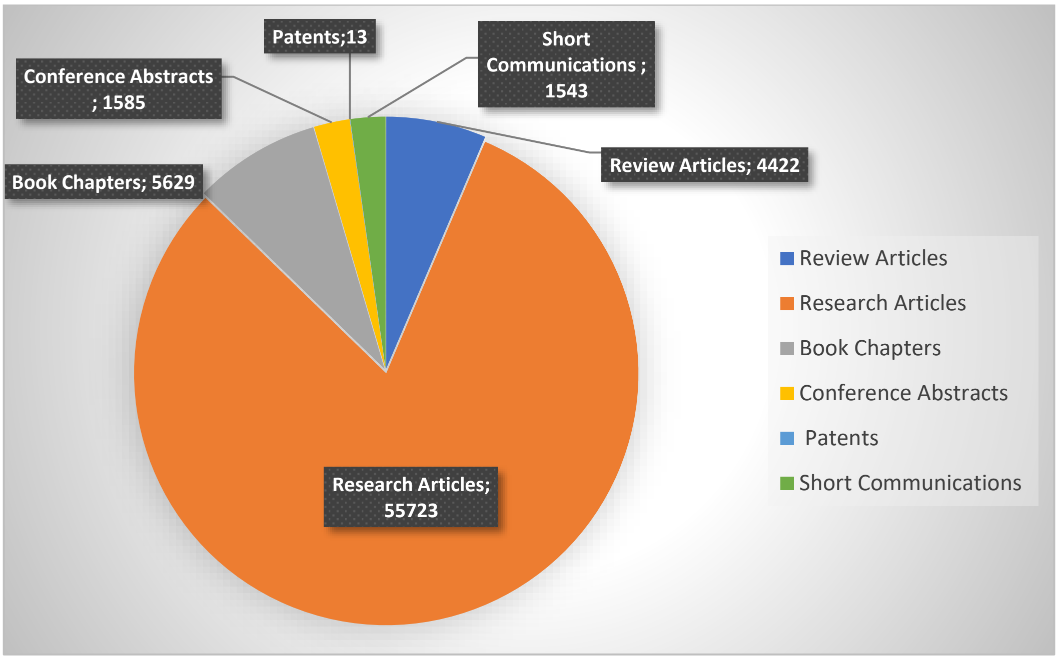

Fig. 4. Types of publications on the keyword "crushed aggregates"

In figures 3 and 4, it appears that research articles are the most present scientific publications. However, we note the low number of patents compared to research articles. Indeed on the keywords "pavement" and "carriegeway" we have 43 patents for more than 44,000 research articles. On the keyword "crushed aggregates" we have 55,723 research articles and 13 patent reports.

3 Pavement

3.1 Composition of pavement structures

A road pavement is a composite structure made by successively piling a sub-base layer, a base layer and a surface layer consisting of an intermediate binder course and a wearing course on top of the sub-base layer [14], [15].

Figure 5 below shows a typical cross-section of a pavement structure and the terminology used for the different layers. Depending on the nature of the materials, their location in the pavement structure and the level of traffic, different types of structure can be identified.

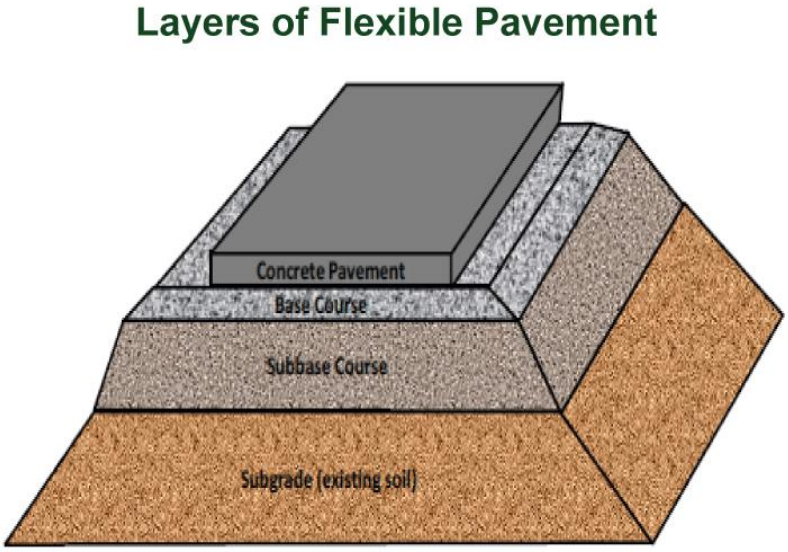

Fig. 5. Typical cross-section of a pavement structure and terminology of the different layers

There is a wide variety of pavements. Flexible, rigid, thick bituminous, semi-rigid, mixed pavements, and reverse pavements. Thus, the choice of a type of pavement can be a function of the lifespan of the road, the stresses to which the said pavement will be subjected after commissioning, and/or construction cost [14]. Pavement structures are designed and constructed to support loads and provide adequate service capacity. The strength of pavements largely depends on the materials used in the base layers. Among these materials, we can cite UGM [16].

Among the pavements, a distinction is made between pavements with treated bases for which the grain size of the materials is also continuous but in which to improve stability and mechanical resistance, a binder, either hydraulic or hydrocarbon, is added and pavements with untreated bases made up of materials with continuous grain size called unbound granular material [1], [17], [18].

In addition to the main types of pavement structures mentioned above, there are pavements with a composite structure combining the durability of cement concrete with the flexibility and adaptability of bituminous materials.

The design of a pavement structure involves a problem of technical and economic optimization, the recipe for which differs depending on the country.

3.2 Design method for pavement structures

Under the effect of external stresses (environmental, loading conditions, etc.), pavement structures are subject to complex phenomena (mechanical, thermal, physical and chemical) which often appear in a coupled manner.

The purpose of pavement design is to design a structure capable of supporting traffic for a fixed lifespan. Several approaches have been developed for this purpose, namely: the empirical approach and the theoretical approach. The empirical design methods developed are based on empirical rules drawn from the observation of the behavior in service of pavement structures or experimental sections. This method has limits which are all the more visible as new types of structures and more efficient materials are developed and traffic is constantly increasing [19], [20].

In the theoretical approach, the first step is to experimentally establish the laws of behavior of the materials and to deduce their mechanical characteristics which will be used in the mathematical formulation of the problem posed. Then, in a second step, to determine the stresses and strains in the pavement materials and the supporting soil, these are then compared to the admissible stresses and strains [21].

4 Unbound Granular Material (UGM)

UGM are granular mixtures composed solely of aggregates and water (no hydraulic or hydrocarbon binder is included in their composition). Their grain size is continuous and the size of the largest aggregates does not exceed 31.5 mm. There are two categories of UGM, UGM A obtained in a single fraction, and UGM B recomposed from at least two granular fractions.

In general, there are essentially two sources of aggregates based on origin: a distinction is thus made between artificial aggregates and natural aggregates.

Artificial aggregates are essentially recycled aggregates: These are aggregate products that include crushed concrete, bituminous or demolition debris, taconite residues (iron ore), coal mining residues, geopolymers which are inorganic materials produced naturally or artificially and resulting from the alkaline activation of aluminosilicates [22], [23].

Natural aggregates, they are composed of aggregates deposited by rivers (alluvium) or glaciers (sand, gravel), aggregates from rocks such as granite, basalt, quartzite, gabbro, limestone, etc [22]. Rock-based UG refer to crushed stone produced in quarries present in areas where natural sand and gravel and aggregate deposits are insufficient to meet local demand. Large stones are processed in an impact crusher to create rock aggregates [17].

4.1 CHARACTERIZATION OF UGM

The service life of pavements essentially depends on the characteristics or properties of the UGM. The shape properties of UG produced by the different crushing techniques influence the performance properties of pavements [4].

The mechanical performance of UGM is usually estimated from several characteristics, including the hardness of the aggregates which is determined by the Los Angeles and Micro-Deval tests, carried out on the 10/14 fraction), the cleanliness of the gravels, and the angularity of the aggregates (crushing index, flattening coefficient) [15].

4.2 CLEANLINESS OF GRAVELS

The cleanliness of the gravels is an important factor in various construction applications, especially in bituminous mixtures, concretes, flooring, drainage works, etc. Gravel cleanliness refers to the presence of unwanted particles, such as dirt, clay, dust, organic matter or other contaminants, which could affect the quality and performance of the material [9], [24]. To assess the cleanliness of chippings, the washing test and visual cleanliness can be used.

Particle size analysis makes it possible to determine the distribution of the different sizes of particles present in the gravel. When the particle size is uneven or there are too many fine particles, it may indicate poor cleanliness [25].

As for the washing test, it is used to assess the content of fine particles present in the bass. The samples are washed with water to remove fine particles, then these particles are dried and weighed. A high fine particle content may indicate a lack of gravel cleanliness [25], [26].

Regarding the visual cleanliness test, it should be noted that it is a visual inspection of the gravel that can be carried out initially to detect the presence of visible contaminants such as soil, organic debris, foreign materials, etc. This method is subjective but can provide a general indication of the cleanliness of the chippings.

In addition, the cleanliness criteria for gravel may vary depending on its use and local standards because good gravel cleanliness is essential to ensure the quality and performance of construction materials. Unwanted particles can affect the stability, durability, strength and other properties of the final material. Therefore, it is important to monitor and control the cleanliness of UGM used in construction projects [27], [28].

4.3 ANGULARITY OF AGGREGATES

Aggregate angularity refers to the shape and geometry of the particles that make up a granular material, such as gravel or sand. It is determined by the arrangement of the edges and faces of the particles [29].

Many studies have focused on determining the angularity of UGM. We will review the most recent methods.

One of his studies focused on the characterization of UGM of several shapes (spherical, flat, elongated and flat and elongated), coming from two sources and different crushers (impact crushers and jaw crushers) by calculating parameters such as the form factor, sphericity and angularity index. This characterization was carried out by determining the morphological properties in the standards, followed by capturing images of the top and front of the UG and digital processing of the images of the aggregated particles [4]. A digital image analysis was performed to obtain the shape parameters of the UG. Furthermore, other authors developed [30] a digital image processing (DIP) scheme to quantify the sphericity, aspect ratio, aspect ratio and particle flatness ratio of coarse aggregates. The system had been standardized using ordinary objects such as marble and coins.

For digital image processing, several algorithms have been used to detect grain boundaries from thin-section images. One of the most commonly used software is ArcGIS for edge detection [31]. This software detects the boundaries of each UGM as abrupt changes of interference colors in the thin section image of the UGM [32].

These interesting studies allowing to model the shape of the particles with precision, only give two-dimensional characteristics. Thus further studies have combined X-ray tomography and the Sobel-Feldman operation to quantify the morphological characteristics of aggregates by measuring the three-dimensional surface of aggregates [8], [33], [34]. For this, various devices such as the CPA (Computerized Particle CPA (Computerized Particle Analysis), the Princeton gamma-tech (PGT) image analysis system, the image analyzer of aggregates from the University of Illinois (UIAIA), to determine the morphological characteristics of UG [32], [35].

4.4 WEAR AND IMPACT RESISTANCE

The repeated passage of vehicles leads to the blunting and progressive polishing of the aggregates and thus to the reduction of the grip of the tires on the road surface. Thus the resistance capacity of aggregates is one of their characteristics which makes it possible to estimate their quality. One of the parameters measuring the resistance of GNTs is the Los Angeles abrasion test [36].

The Los Angeles test makes it possible to measure the combined resistance to impact and progressive deterioration by reciprocal friction of the elements of an aggregate. This method, which applies to the aggregates used for the constitution of the pavements, consists in measuring the quantity of elements lower than 1.6 mm produced by subjecting the material to the shocks of balls and the reciprocal frictions of the Los Angeles machine [37].

The granularity of the material tested is chosen from six granular classes varying between 4 and 50 mm according to the European standard. Depending on the type of granularity, the mass of the pebble charge varies. The Los Angeles LA coefficient is then defined, which is a percentage by mass of the ratio of the elements passing through the sieve of 1.6 and the initial dry mass [38].

Recent methods of determining the Los Angeles have determined mathematical equations to reduce the test by 24 hours, in addition to reducing the resources required for the test [37].

However, it should be noted that this road design method used in the majority of West African countries associates rutting with excessive elastic vertical deformation at the top of the roadbed. Therefore, attributing mechanical performance to UG mainly from the hardness measurements of their aggregates is reductive and not always satisfactory [13], [19].

Indeed, this approach does not take into account cyclic stresses and is only based on static stresses and elastic deformations. Moreover, this method does not take into account the characteristics of the material because it clearly appears that the total permanent deformation of a pavement results from the sum of the permanent deformations which have accumulated in the different layers of the pavement [13], [39]. In order to overcome this lack, the approach based on the results of laboratory tests carried out with the triaxial device with repeated loadings (RLT) is increasingly used.

The principle of this technique is to subject a material to thousands of loading cycles along a specific stress path, without conditioning. This summary method easily demonstrates the impact of stress levels on deformations [14].

Several researchers have thus studied the importance of the number of loading cycles on the evolution of permanent deformations [40]. Various models have been proposed to study the effect of the number of cycles on the development of the permanent set [5].

Some authors [13] showed that during triaxial tests with repeated loading, low shear levels lead to permanent deformations which stabilize with the number of cycles until the behavior becomes reversible. However, when the shear rate is high, the permanent deformations are accentuated until the eventual rupture of the sample. This shows the importance of maintaining a relatively low stress ratio in flexible pavements in order to limit deterioration by rutting.

5 CONCLUSION

This review article reviewed recent studies on the characterization of pavement made up of UGM. Bibliometrics has confirmed the growing scientific interest in pavements and UGM, with numerous publications on the subject since the year 2000. Publications mainly focus on research and review articles, demonstrating a strong scientific commitment to this domain.

In addition, various methods for characterizing UGM have been proposed, such as the modeling of coarse aggregates based on the morphological characteristics of the particles or the study of the evolution of the permanent deformations of UGM as a function of the number of cycles and the level of stress applied.

REFERENCES

[1] H. H. Titi, M. Dakwar, M. Sooman, et H. Tabatabai, « Long term performance of gravel base course layers in asphalt pavements », *Case Stud. Constr. Mater.,* vol. 9, p. e00208, déc. 2018, doi: 10.1016/j.cscm.2018.e00208.

[2] L. Seprillina, E. Yusida, B. S. Narmaditya, et Y. Y. C. Chung, « NEW ROAD INFRASTRUCTURE DEVELOPMENT AND LOCAL COMMUNITY WELFARE: EVIDENCE FROM TOLLER DOOR IN MALANG OF INDONESIA », *J. Ekon. Dan Pendidik.,* vol. 18, nº 1, Art. nº 1, avr. 2021, doi: 10.21831/jep.v18i1.39298.

[3] K. Petrov, « Geo-economic perspectives for construction on speed roads in Bulgaria », *Espaço E Econ. Rev. Bras. Geogr. Econômica,* nº 20, Art. nº 20, nov. 2020, doi: 10.4000/espacoeconomia.18097.

[4] G. Yaseen, W. S. Alaloul, I. Hafeez, et A. H. Qureshi, « Shape Characterizing of Aggregates Produced through Different Crushing Techniques », *Coatings,* vol. 11, nº 10, p. 1199, sept. 2021, doi: 10.3390/coatings11101199.

[5] Y. Dinegdae, A. Ahmed, S. Rahman, et S. Erlingsson, « Evaluation of ERAPave PP permanent deformation models using APT », *Road Mater. Pavement Des.,* vol. 0, nº 0, p. 1-17, mars 2023, doi: 10.1080/14680629.2023.2191733.

[6] A. K. Singh et J. P. Sahoo, « Rutting prediction models for flexible pavement structures: A review of historical and recent developments », *J. Traffic Transp. Eng. Engl. Ed.,* vol. 8, nº 3, p. 315-338, juin 2021, doi: 10.1016/j.jtte.2021.04.003.

[7] M. E. Al-Atroush, « Structural behavior of the geothermo-electrical asphalt pavement: A critical review concerning climate change », *Heliyon,* vol. 8, nº 12, p. e12107, déc. 2022, doi: 10.1016/j.heliyon.2022.e12107.

[8] X. Ding, T. Ma, et W. Gao, « Morphological characterization and mechanical analysis for coarse aggregate skeleton of asphalt mixture based on discrete-element modeling », *Constr. Build. Mater.,* vol. 154, p. 1048-1061, nov. 2017, doi: 10.1016/j.conbuildmat.2017.08.008.

[9] M. A. Mehdi, « Analysis of structural and surface deteriorations of a flexible pavement, based on inspection results using the MCA method | Request PDF ». https://www.researchgate.net/publication/350014769_Analysis_of_structural_and_surface_deteriorations_of_a_flexible_pavement_based_on_inspection_results_using_the_MCA_method (consulté le 29 août 2023).

[10] N. Penna, E. Padhi, S. Dey, et R. Gaudio, « Statistical characterization of unworked and water-worked gravel-bed roughness structures », *J. Hydraul. Res.,* vol. 59, nº 3, p. 420-436, mai 2021, doi: 10.1080/00221686.2020.1780496.

[11] H. Zhu, H. Fang, Y. Cai, et N. Lv, « Development of a rapid measurement system for coarse aggregate morphological parameters », *Particuology,* vol. 50, p. 181-188, juin 2020, doi: 10.1016/j.partic.2019.06.006.

[12] Zhen Liu, Xingyu Gu, Hua Ren a, b, Xiang Wang, et, Qiao Dong, « Three-dimensional finite element analysis for structural parameters of asphalt pavement: A combined laboratory and field accelerated testing approach », *Case Stud. Constr. Mater.,* vol. 17, p. e01221, déc. 2022, doi: 10.1016/j.cscm.2022.e01221.

[13] O. A. Sall, « Évaluation des déformations permanentes des graves non traitées de chaussées souples sous chargement cyclique par palier », 2019.

[14] R. Baadiga et U. Balunaini, « Evaluation of pavement design input parameters of biaxial and triaxial geogrid stabilized flexible pavements overlying soft subgrades », *Clean. Mater.,* vol. 9, p. 100192, sept. 2023. doi: 10.1016/j.clema.2023.100192.

[15] A. El-Ashwah, E. Mousa, S. El-Badawy, et M. Abo-Hashema, « Advanced Characterization of Unbound Granular Materials for Pavement Structural Design in Egypt », *Int. J. Pavement Eng.,* vol. IF 2.298 (2018), avr. 2020. doi: 10.1080/10298436.2020.1754416.

[16] Q. Yuan, Z. Liu, K. Zheng, et C. Ma, « Chapter 7 – Asphalt », in *Civil Engineering Materials,* Q. Yuan, Z. Liu, K. Zheng, et C. Ma, Éd., Elsevier, 2021, p. 287-325. doi: 10.1016/B978-0-12-822865-4.00007-6.

[17] M. I. Souliman, H. Gc, et Z. Mohammed, « Enhanced Flexible Pavement Performance Using Treated Compared to Untreated Aggregate Bases: A Comparative Case Study in the Southern United States », *Infrastructures,* vol. 6, nº 8, p. 110, août 2021, doi: 10.3390/infrastructures6080110.

[18] M. Sukhija et N. Saboo, « A comprehensive review of warm mix asphalt mixtures-laboratory to field », *Constr. Build. Mater.,* vol. 274, p. 121781, mars 2021, doi: 10.1016/j.conbuildmat.2020.121781.

[19] M. Su, J. Liu, J. Lu, J. Ren, et Y. Zhu, « Study on the vibration evaluation method and allowable differential settlement of road-bridge transition section with full-car model », *Int. J. Pavement Eng.,* vol. 24, nº 1, p. 2090557, déc. 2023. doi: 10.1080/10298436.2022.2090557.

[20] E. S. K. Mensahn, S. A. Wada, et L. Lugeiyamu, « Roadway Pavement Design Methods, Structural Approaches and Relevant Computer Algorithms: A Critical Review », *Int. J. Transp. Eng. Technol.,* vol. 8, nº 1, Art. nº 1, févr. 2022. doi: 10.11648/j.ijtet.20220801.12.

[21] A. Vaitkus, R. Kleizienė, et M. Karbočius, « Viastructura – A New Way Of Pavement Structure Design », *IOP Conf. Ser. Mater. Sci. Eng.,* vol. 1202, n° 1, p. 012018, nov. 2021, doi: 10.1088/1757-899X/1202/1/012018.

[22] K. Opara, H. Okeke, C. Ejiogu, et njoku o, Production and Uses of Crushed Rock Aggregate from Intrusive Igneous Rocks: A Review. 2021.

[23] Z. Liu, X. Gu, H. Ren, X. Wang, et Q. Dong, « Three-dimensional finite element analysis for structural parameters of asphalt pavement: A combined laboratory and field accelerated testing approach », *Case Stud. Constr. Mater.,* vol. 17, p. e01221, déc. 2022, doi: 10.1016/j.cscm.2022.e01221.

[24] O. Omotayo, S. Akingbonmire, et C. Ikumapayi, « SUSTAINABLE APPLICATION OF MATERIALS FROM CONSTRUCTION AND DEMOLITION WASTE: A REVIEW », févr. 2019.

[25] U. Ulusoy, « A Review of Particle Shape Effects on Material Properties for Various Engineering Applications: From Macro to Nanoscale », *Minerals,* vol. 13, n° 1, p. 91, janv. 2023, doi: 10.3390/min13010091.

[26] B. Li, C. Zhang, P. Xiao, et Z. Wu, « Evaluation of coarse aggregate morphological characteristics affecting performance of heavy-duty asphalt pavements », *Constr. Build. Mater.,* vol. 225, p. 170-181, nov. 2019. doi: 10.1016/j.conbuildmat.2019.07.092.

[27] W. Langer, « 9 - Sustainability of aggregates in construction », in *Sustainability of Construction Materials (Second Edition),* J. M. Khatib, Éd., in Woodhead Publishing Series in Civil and Structural Engineering. Woodhead Publishing, 2016, p. 181-207. doi: 10.1016/B978-0-08-100370-1.00009-3.

[28] R. Vagtholm, A. Matteo, B. Vand, et L. Tupenaite, « Evolution and Current State of Building Materials, Construction Methods, and Building Regulations in the U.K.: Implications for Sustainable Building Practices », *Buildings,* vol. 13, n° 6, Art. n° 6, juin 2023, doi: 10.3390/buildings13061480.

[29] N. Govender, « Study on the effect of grain morphology on shear strength in granular materials via GPU based discrete element method simulations », *Powder Technol.,* vol. 387, p. 336-347, juill. 2021, doi: 10.1016/j.powtec.2021.04.038.

[30] Z. Sun, Y. Li, L. Pei, W. Li, et X. Hao, « Classification of Coarse Aggregate Particle Size Based on Deep Residual Network », *Symmetry,* vol. 14, n° 2, Art. n° 2, févr. 2022, doi: 10.3390/sym14020349.

[31] L. P. Leon et D. Gay, « Gene expression programming for evaluation of aggregate angularity effects on permanent deformation of asphalt mixtures », *Constr. Build. Mater.,* vol. 211, p. 470-478, juin 2019. doi: 10.1016/j.conbuildmat.2019.03.225.

[32] X. Yang, S. Chen, et Z. You, « 3D Voxel-Based Approach to Quantify Aggregate Angularity and Surface Texture », *J. Mater. Civ. Eng.,* vol. 29, n° 7, juill. 2017, Consulté le: 30 août 2023. [En ligne]. Disponible sur: https://trid.trb.org/view/1461054.

[33] S. Chen, X. Yang, Z. You, et M. Wang, « Innovation of aggregate angularity characterization using gradient approach based upon the traditional and modified Sobel operation », *Constr. Build. Mater.,* vol. 120, p. 442-449, sept. 2016, doi: 10.1016/j.conbuildmat.2016.05.120.

[34] S. Gupta, J. Sarkar, A. Banerjee, N. R. Bandyopadhyay, et S. Ganguly, « Grain Boundary Detection and Phase Segmentation of SEM Ferrite-Pearlite Microstructure Using SLIC and Skeletonization », *J. Inst. Eng. India Ser. D,* vol. 100, p. 203-210, oct. 2019, doi: 10.1007/s40033-019-00194-1.

[35] J. G. Behnsen, K. Black, J. E. Houghton, et R. H. Worden, « A Review of Particle Size Analysis with X-ray CT », *Materials,* vol. 16, n° 3, p. 1259, févr. 2023, doi: 10.3390/ma16031259.

[36] H. Cherifi *et al.,* « Physico-mechanical characterization of schists in Tazzeka complex [Taza Province, Eastern Morocco] », *Case Stud. Constr. Mater.,* vol. 15, p. e00692, déc. 2021, doi: 10.1016/j.cscm.2021.e00692.

[37] T. Umar, C. Egbu, et M. Saidani, « A Modified Method for Los Angeles Abrasion Test », *Iran. J. Sci. Technol. Trans. Civ. Eng.,* vol. 44, n° 3, p. 941-947, sept. 2020, doi: 10.1007/s40996-019-00268-w.

[38] R. Alves, S. Rios, E. Fortunato, A. Viana da Fonseca, et B. Guimarães Delgado, « Mechanical Behaviour of Steel Slag–Rubber Mixtures: Laboratory Assessment », *Sustainability,* vol. 15, n° 2, Art. n° 2, janv. 2023, doi: 10.3390/su15021563.

[39] D. A. Mishra et I. Janeček, « Laboratory Triaxial Testing – from Historical Outlooks to Technical Aspects », *Procedia Eng.,* vol. 191, p. 342-351, janv. 2017, doi: 10.1016/j.proeng.2017.05.190.

[40] M. Rahman et S. Erlingsson, « Modelling the Moisture Dependent Permanent Deformation Behavior of Unbound Granular Materials », *Procedia Eng.,* vol. 143, p. 921-928, déc. 2016, doi: 10.1016/j.proeng.2016.06.072.