

Experimental Characterization of Shape of an Aggregate by a Numerical Value—Application to Senegalese Basaltic Aggregates for Rail Transport

Abdoulaye Diedhiou, Libasse Sow* , Ndeye Mareme Diop

Civil Engineering Department, Higher Polytechnic School, Cheikh Anta Diop University of Dakar, Dakar, Senegal

Email: *libasse.sow@esp.sn

How to cite this paper: Diedhiou, A., Sow, L. and Diop, N.M. (2020) Experimental Characterization of Shape of an Aggregate by a Numerical Value—Application to Senegalese Basaltic Aggregates for Rail Transport. *Open Journal of Civil Engineering*, 10, 131-142.

<https://doi.org/10.4236/ojce.2020.102012>

Received: April 24, 2020

Accepted: May 16, 2020

Published: May 19, 2020

Copyright © 2020 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

This article first talks about railways in general and ballast in particular. An inventory is then made on the modernization of the Senegalese ballast railways. In the second phase, an experimental work of characterization of basaltic aggregates of Diack (Locality of Ngoundiane, Thiès region, Senegal) is presented. The grain size studied is 25/50 mm as for any material studied for use as railway ballast. Experimental work presented consists of the characterization of the shape of an aggregate using the NF P 18-301 standard. The test consists of comparing the volume of the aggregate to that of an equivalent sphere with the largest diameter of the aggregate, by calculating the average volume coefficient. With a Representative Elementary Volume (REV) of 6 aggregates, the volume coefficient “ C_v ” fluctuates between 0.27 and 0.49 with an average volume coefficient of 0.39 which is well above 0.15. The grains studied are polyhedral and therefore have a high mechanical resistance.

Keywords

Ballast, Rail Transport, Basalt, Shape, Volume Coefficient

1. Introduction

Senegal is a West African country bordering the Atlantic Ocean to the west, Mauritania to the north, Mali to the east, Guinea and Guinea-Bissau to the south. The railway sector is both an activity sector and a support sector for other economic or socio-economic sectors. Rail transport is a sector that has reached a level of maturity in developed countries. He knows a remarkable return after a

period of decline. The renewed interest in this mode of transport can be explained by its ability to transport huge volumes of goods or a large number of passengers with energy efficiency and in a very environmentally friendly way. In Senegal, rail traffic ranks second after road transport in terms of satisfaction with domestic travel and relations with Mali. However, the current public transport system in the Dakar region is made up of buses, Rapid Coaches, taxis and the “Petit Train de Banlieue” (PTB). This system does not satisfactorily meet the travel needs of estimated 124,000 passengers during the morning rush hour in Dakar. It is therefore essential to replace the PTB with the Regional Express Train (TER) to ensure, through an omnibus and possibly semi-direct service, the service to the greater Dakar suburbs. This project is articulated with the project of Bus Rapid Transit (BRT) lines and other existing and/or planned public transport modes. The TER project consists of the creation of a double-track “passenger” line:

- in phase 1, 38 km in the existing railway right-of-way between Dakar and Diamniadio;
- in phase 2, on 19 km of line between Diamniadio and Blaise Diagne International Airport (AIBD).

This line is:

- standard gauge UIC (1435 mm) in UIC 54 rails on monoblock or bi-block sleepers;
- electrified in 2×25 kV;
- equipped with ERTMS (European Rail Traffic Management System) rail signalling system level 2.

The project also includes the redevelopment of the existing metric track by shifting it and which will require normative compliance. The cross section is designed in this phase 1, with 3 lanes, and will eventually evolve to 4 lanes in phase 2. The said profile consists of:

- dimensioning the engineering structures carrying the 4 lanes;
- reserving the land for 4 lanes;
- securing the platform by: 1) a fully fenced right-of-way; 2) removing crossings (except 2 industrial); 3) restoration of continuities by road works and uneven pedestrians. **Figure 1** shows the cross-sectional profile selected [1].

In Senegal, the building and public works sector and roads are booming. The construction of buildings, bridges and road infrastructure requires large quantities of quality materials. Aggregate is intended to be used in the composition of materials for the manufacture of public works and building structures. Among these materials, we find aggregates, which are used in very large quantities. It is therefore imperative that it be able to meet certain minimum quality requirements. Their production in Senegal is quite large and varied. Aggregate deposits are found just about everywhere in the territory. The main aggregates used for construction are: basalt, limestone and sandstone. The characteristics of

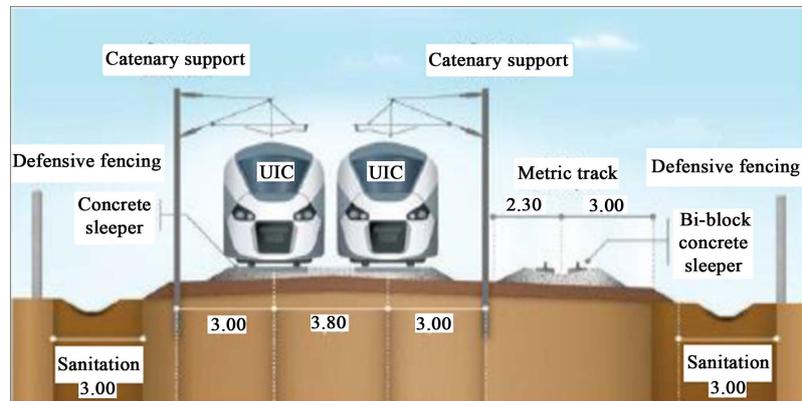


Figure 1. Typical transverse profile adopted for Regional Express Train (TER) in Senegal [1].

the materials that make up the foundations of pavements must meet certain minimum quality requirements.

The study of the mechanical behaviour of materials used in public works in general has been of interest to the scientific community for a very long time ([2]-[19], among others). The case of materials used as railway ballast is also a branch of public works that attracts a lot of interest. Ballast is the top layer of a ballasted track structure on which the ties supporting the rail rest. It is a hard, elastic, calibrated, hollow and compact rock crushed mat blocking the sleepers, which can be levelled to the millimetre by interlocking 25 to 50 mm sized aggregates. The ballast grain size can vary according to use. It can be 25/40 mm when the ballast is intended for ordinary turnout tracks; as it can be up to 40/63 mm in the case of tracks subject to high stress from loaded high-speed trains. As an example, the class of new ballast currently used in high-speed lines (LGV) in France is 31.5/50 mm [20]. **Figure 2** shows a cross-section of a railway track with the location of the ballast layer. Conventional ballasted railway track is made up of a set of elements that enable trains to be guided and the loads induced by them to be supported. A distinction is made between the superstructure comprising the rails, fasteners, footings, sleepers, ballast, any sub-ballast layer, and the substructure consisting of the support platform. Ballast often comes from the crushing of rocks extracted from hard stone quarries (granite, diorite, rhyolite, basalt, quartzite, sandstone, gneiss, etc.) and is a track support element and part of the superstructure. The ballast elements must interlock to form a compact but permeable mass. The quarries where these materials are extracted and processed are called ballast pits. The thickness of the ballast layer under the sleepers, between 150 mm and 400 mm, depends on the type of sleeper, the speed of the trains and the UIC group of the railway line. The ballast thickness on high-speed lines (LGV) is generally 30 cm under the sleepers [8]. The image in **Figure 3** shows the ballast layer for an LGV line.

In recent decades, ballast has been increasingly studied in order to better understand its behaviour and degradation modes. These studies make it possible to

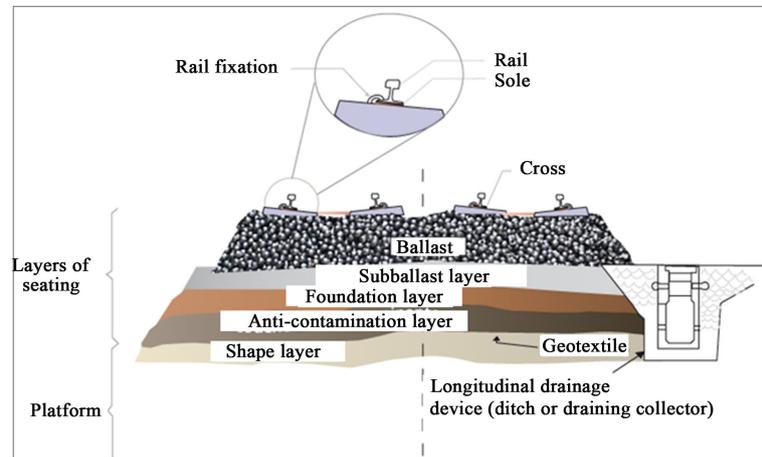


Figure 2. Description of a new generation ballasted track ([21], modified).



Figure 3. Ballast photography on an LGV track [11].

prescribe increasing quality and performance criteria, and to be able to anticipate maintenance before the degree of degradation reaches a critical threshold likely to cause insecurity and discomfort to users.

Good ballast reduces the rate of deformation, maintains track geometry by limiting the movement of ballast particles, and the horizontal and vertical alignment of the rails can be maintained for a very long time. An important characteristic of good ballast is the grain shape of the material. Studies on the effect of aggregate shape have been carried out by authors on aggregates in general ([22] [23] [24] [25], among others). But for the case of ballast, studies on this subject are only numerous in the literature. One can quote the works of [26] which provided an accurate description of grain morphology for the numerical study of the mechanical behaviour of railway ballast.

Therefore, we considered that it is necessary to characterize the shape of an aggregate by a numerical value by applying it to a material intended for Senegalese railway ballast. This study focuses on basalt from Diack (Locality of Ngoundiane, Thiès Region, Senegal). This interest concerns class 25/50 mm for its use

in Senegalese railways. Experimental work is also presented and consists of the characterization of the shape of an aggregate. The idea is to characterize experimentally Diack basaltic aggregates by a numerical value representing their absolute volume.

2. Geometrical Characteristics of Ballast Aggregates

The shape of the ballast elements used for the track must be polyhedral and sharp-edged. A ballast layer with cuboid or angular aggregates of mixed dimensions normally gives the track a very high degree of elasticity and strength. The aggregates should therefore be neither too long nor too flat. Good angularity of the aggregates increases inter-granular friction. The surface condition (degree of roughness and friction) of the aggregates has an influence on:

- The aptitude for the mechanical resistance of the ballast;
- The compactness of underlayers and form layers;
- The adhesion with the sleepers.

Figure 4 gives the geometrical characteristics of an aggregate which must comply with the requirements of **Tables 1-3** [20] [21].

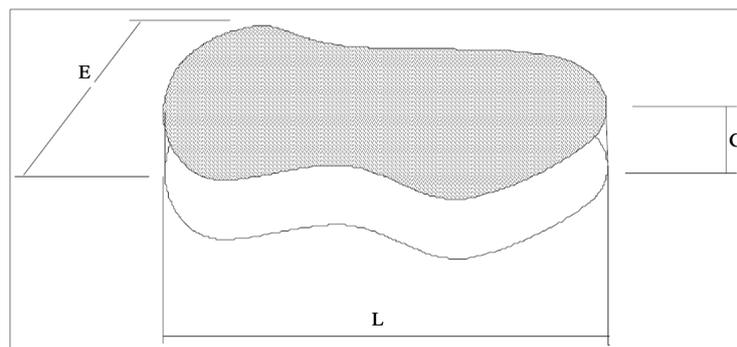


Figure 4. Geometrical characteristics of an aggregate.

Table 1. Dimensions of control meshes and normal tolerances of restraints.

Singular point of the spindles	Square mesh sizes (mm)	Normal tolerances
$D_{\max} = 1.25D$	63	Retentions: 0%
D	50	Retentions $\leq 10\%$
Intermediate sieve	40	$26\% < \text{Retentions} \leq 60\%$
d	25	Retentions $\geq 10\%$
$D_{\min} = 0.63d$	16	Retentions $\leq 98\%$

Table 2. Square mesh dimensions and normal restraint tolerances for maximum diameter.

Material	D (mm)	D_{\max} (mm)	L (mm)	Normal tolerances
Ballast	50	63	92	The percentage by mass of aggregates of length greater than L , must not exceed 4%.

Table 3. Square mesh dimensions and normal restraint tolerances for minimum diameter.

Material	d (mm)	d_{\min} (mm)	E (mm)	Normal tolerances
Ballast	25	16	16	Percentage by mass of aggregates passing through the grids of which the slots have a width of “E”, shall not exceed 4%.

“L” represents the largest spacing of a pair of parallel tangent planes.

“E” is the smallest spacing of a pair of parallel tangential planes.

“G” is the minimum square mesh size through which the element passes.

The ballast grains are polyhedral in shape and have sharp edges. Sharp edges are a characteristic of high angularity and ensure good shear strength. Elongated grains impair the stability of the compacted layer, as they are susceptible to breakage and thus disturb the stability of the ballast: needles and flat elements should not exceed 92 mm [11] [25]. The mass percentage of needles must not exceed 7%.

Flat elements are characterized by an overall flattening coefficient which represents the total mass percentage of passing through all grids and shall not exceed 12% [27]. The flattening coefficient and the shape coefficient make it possible to characterize the more or less massive shape of the aggregates.

3. Experiments

The absolute volume coefficient of a material is determined using the NF P 18-301 standard. The aim is to characterize the shape of an aggregate by a numerical value. The absolute volume coefficient “ C_v ” of a grain is the ratio of the absolute volume “ v ” of the grain to the volume “ V ” of the sphere of diameter “ d ”. With d the largest dimension of the grain, *i.e.* the diameter of the smallest sphere circumscribed to the grain. The relation of the Equation (1) makes it possible to obtain this volume coefficient for one aggregate.

$$C_v = \frac{v}{V} = \frac{v}{\frac{\pi d^3}{6}} \quad (1)$$

The average absolute volume coefficient of an aggregate is the average of the volume coefficients of the tested aggregates (Equation (2)). It is also determined by the ratio between the absolute volume of the grains of the material under consideration and the volume of the corresponding circumscribed spheres (Equation (3)).

$$C_{moyen} = \sum_{i=1}^n \frac{C_{v_i}}{n} = \frac{C_{v_1} + C_{v_2} + C_{v_3} + C_{v_4} + C_{v_5} + C_{v_6} + \dots + C_{v_n}}{n} \quad (2)$$

$$C_{vmoy} = \frac{\sum v}{\sum V} = \frac{\sum v}{\sum \frac{\pi d^3}{6}} \quad (3)$$

The test consists of comparing the volume of the aggregate to that of an

equivalent sphere with the largest diameter of the aggregate, by calculating the average volume coefficient. The experimental procedure followed in this work is as follows:

- Taking a sample by quartering on 2 kg of gravel in order to have a Representative Elementary Volume (REV);
- Screening to recover the 25/50 mm class sample in order to take a ballast grain;
- Pouring into a graduated cylinder of a given volume of water “ v_1 ”;
- Presentation one by one of the ballast grains in the notches of the gauge;
- Notation of the volume of the sphere corresponding to each diameter;
- As the grain passes through the grain size, the ballast is placed in the test tube containing the water; the reading is then taken.

The use of the method of characterizing the shape of an aggregate by a numerical value gives very precise results in the case of a healthy material. This is the case when the material studied has a very low absorption coefficient. On the other hand, if the material is hydrophilic, the method can be false in the measurement or the volume of water in the specimen will be badly appreciated if the immersion time is long. The method cannot therefore be applied to all types of materials. Studies conducted by [2] [18] have shown that Diack Basalt has a very low absorption coefficient and is a good material that is not hydrophilic.

In this work, 6 representative grains have been sandblasted. The images in **Figure 5** show the experiment carried out on an aggregate and the image of **Figure 6** shows the 6 aggregates tested in water test tubes.

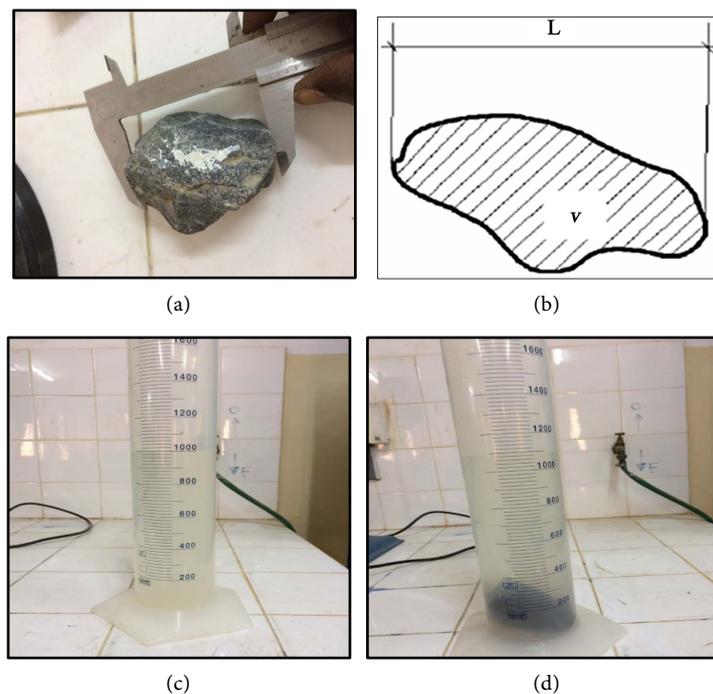


Figure 5. Experiment on an aggregate to determine its absolute volume. (a) Aggregate number 1; (b) $L = 78$ mm; (c) $v_1 = 1000$ cm³; (d) $v_2 = 1100$ cm³.

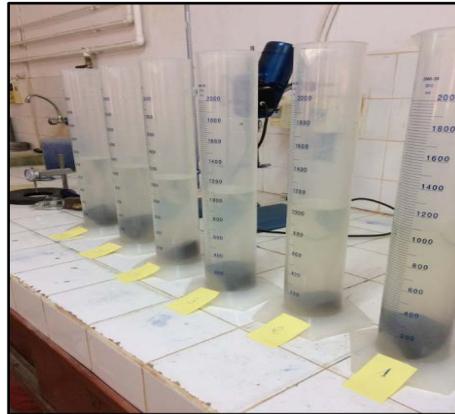


Figure 6. Samples tested in water test tubes.

Using the experimental example shown in **Figure 5**, the absolute volume of the tested aggregate can be calculated by applying Equation (4).

$$v_i = v_2 - v_1 \quad (4)$$

4. Results

The results obtained by applying the experimental procedure described above are given in **Table 4**.

5. Discussions

The volume coefficient “ C_v ” fluctuates between 0.27 and 0.49 with an average volume coefficient of 0.39. This value is well above 0.15. The lower the volume coefficient of the ballast (less than 0.15), the higher the proportion of plates and needles in the material. Referring to the work presented in [2], the flattening coefficient that was determined for the same basaltic aggregates is 5%. The flattening coefficient and the volume coefficient make it possible to characterize the more or less massive shape of the aggregates. An aggregate of unfavourable shape (flat or elongated), has a high flattening coefficient (20% to 40%). An aggregate of favourable shape has a flattening coefficient generally between 5 and 20%. Among the experimental studies on the effect of shape, there were no studies on ballast. Nevertheless, it is possible to give the example of the studies carried out by [22] or [23] on granular assemblies in general.

Firstly, [22] was interested in the measurement of the stress response of grain assemblages of 14 different shapes: spheres, convex shapes (tetrahedrons, triangular bipyramids) as well as more complex non-convex geometries (hexapods). Then, using 3D printing, 5500 particles of each shape are printed. By measuring the stress-strain relationship under quasi-static compression, the authors focused on the overall macroscopic response. For each different shape, triaxial tests were carried out for different containment pressures. By calculating several parameters such as Young’s modulus etc., the authors draw the following conclusions about the effect of the shape:

Table 4. Intrinsic characteristics of Bandia Limestone and Diack Basalt.

Samples	L (cm)	v_1 (cm ³)	v_2 (cm ³)	v_f (cm ³)	$V = \frac{\pi d^3}{6}$	$C_v = \frac{v}{V}$
1	7.8	1000	1100	100	248.47	0.40
2	7.5	1000	1060	60	220.89	0.27
3	7.1	1000	1090	90	187.40	0.48
4	7.3	1000	1100	100	203.69	0.49
5	8.5	1000	1100	100	321.56	0.31
6	7.7	1000	1100	100	239.04	0.41
				$\sum_{i=1}^6 v_i$		
					550	
				$\sum_{i=1}^6 V$		
					1421.05	
				$C_v = \frac{\sum_{i=1}^6 v_i}{\sum_{i=1}^6 V_i}$		0.39

- The shape can change the effective Young's modulus and the yield stress of the grain by about an order of magnitude;
- High confining pressures reduce the dependence of Young's modulus on shape;
- Interactions between faceted polyhedral are made through several types of contacts whose surfaces vary under compression. On the other hand, for other types of particles such as hexapods and spheres, interactions are only through point contacts;
- Finally, highly faceted polyhedral seem to provide higher resistance than other forms, which are less sensitive to confinement.

These studies highlight the effect of shape on the macroscopic mechanical behaviour of the grains.

On the other hand, [23] focused on the flow of spherical grains then elongated by a hopper. The test was modelled experimentally (the silo was filled by closing the orifice, then the orifice was opened to release the grain flow). Then, using a camera, the configuration of the clogged hopper was explored. The system was then disrupted to generate the flow again, and so on for 30 times for each particle shape. The authors were interested in the orientation, density distribution and rearrangement of the grains, as well as the number of grains forming the last layer blocking the flow. The authors' conclusions regarding shape can be summarized in two points:

- There is a preferred orientation of the particles, and thus a better arrangement in the flow area of the silo;
- The number of grains forming the blocking layer of the silo is higher in the silo flow area. The case of grains which are elongated in relation to spherical grains of the same volume.

6. Conclusions

- Based on the conclusions of [22] [23] [26], the experimental campaign presented in this work proves that basaltic granular material in the Diack quarries has good mechanical characteristics when used as railway ballast.
- The result obtained in this work confirms the results obtained in [2] [5] [18].
- The scientific interest of this study is to contribute to the identification and choice of quality materials that can be used as ballast. It finally made it possible to take stock of the modernization of the Senegalese railway network.

Acknowledgements

Authors to Companies Transrail, Sodevit and Mapathé Ndiouck for their technical assistance and materials supply.

Conflicts of Interest

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

References

- [1] Regional Express Train (TER) Dakar (2016) Summary of the Strategic Environmental and Social Study. African Development Bank Group.
https://www.afdb.org/fileadmin/uploads/afdb/Documents/Environmental-and-Social-Assessments/Senegal-Projet_de_Train_Express_Regional_de_Dakar-Resume_EE_SS-Novembre_2016.pdf
- [2] Sow, L. (2019) Ballasted Railways in Senegal-Characterization of Bandia Limestone and Diack Basalt for Use as Ballast Materials. *International Journal of Applied Engineering Research*, **14**, 3396-3405.
https://www.ripublication.com/ijaer19/ijaerv14n15_10.pdf
- [3] Kansango, M.P., Kavula, N.E., Sow, L. and Lunda, H.J.M. (2019) Cartographie Géotechnique par Deep Learning Approche par Réseaux de Neurones Artificiels. *European Scientific Journal*, **15**, 233-251.
<https://doi.org/10.19044/esj.2019.v15n12p233>
- [4] Deiros, I., Voivret, C., Combe, G. and Emeriault, F. (2016) Quantifying Degradation of Railway Ballast Using Numerical Simulations of Micro-Deval Test and *in-Situ* Conditions. *Procedia Engineering*, **146**, 1016-1023.
<https://doi.org/10.1016/j.proeng.2016.06.096>
- [5] Diedhiou, A., Sow, L. and Dione, A. (2020) Contribution to Comparative Study of Physical-Chemical Characteristics of Diack Basalt and Bandia Limestone for Use in Railway Engineering. *Geomaterials*, **10**, 25-34.
<https://doi.org/10.4236/gm.2020.102002>
- [6] Deiros, I., Combe, G., Emeriault, F., Voivret, C. and Ferellec, J.F. (2019) X-Ray CT Analysis of the Evolution of Ballast Grain Morphology along a Micro-Deval Test: Key Role of the Asperity Scale. *Granular Matter*, **21**, 1-12.
<https://doi.org/10.1007/s10035-019-0881-y>
- [7] Sow, L. (2018) Approche couplée expérimentation-modélisation multi-échelle pour la détermination du comportement mécanique des graves routières traitées aux liants. Application à la valorisation des Mâchefers d'Incineration de Déchets Non

- Dangereux. PhD Thesis, INSA Rennes, France, 200.
<https://www.theses.fr/2018ISAR0001>
- [8] Sow, L., Bernard, F., Kamali-Bernard, S. and Kébé, C.M.F. (2018) Experiment-Based Modelling of the Mechanical Behaviour of Non-Hazardous Waste Incineration Bottom Ashes Treated by Hydraulic Binder. *MATEC Web of Conferences*, **149**.
<https://doi.org/10.1051/mateconf/201814901038>
- [9] Sow, L., Bernard, F., Kamali-Bernard, S. and Kébé, C.M.F. (2018) Mesoscale Modeling of the Temperature-Dependent Viscoelastic Behavior of a Bitumen-Bound Gravels. *Coupled Systems Mechanics*, **7**, 509-524.
- [10] Azéma, É. (2007) Digital Study of Granular Materials with Polyhedral Grains: Quasi-Static Rheology, Vibration Dynamics, Application to the Ballast Stuffing Process. PhD Thesis, Montpellier University, Montpellier, France.
- [11] Saussine, G. (2004) Contribution à la modélisation de granulats tridimensionnels: Application au ballast. PhD Thesis, Montpellier University, Montpellier, France.
<https://tel.archives-ouvertes.fr/tel-00077519>
- [12] Ricci, L. (2006) Discrete and Continuous Modelling of the Ballasted Railway Track. PhD Thesis, Navier-Laboratory Institute Material Analysis and Identification (LCPC/ENPC), France.
- [13] Guérin, N. (1996) Experimental and Numerical Approach to the Behaviour of Railway Ballast. PhD Thesis, National School of Bridges and Roads (ENPC), France.
- [14] Calon, N., Lambert, L., Robinet, A., Trinh, V.N., Cui, Y.J., Canou J., Dupla, J.C., Tang, A.M. and Schoen, O. (2010) Hydromechanical Characterization of Materials Used in Old Railway Platforms.
- [15] Sow, L., Kamali-Bernard, S., Bartier, O., Mauvoisin, G. and Bernard, F. (2018) Experimental Estimation of the Elastic Modulus of Non-Hazardous Waste Incineration Bottom Ash Aggregates by Indentation Tests-Microanalysis of particles by Scanning Electron Microscopy. *Advanced Materials Research*, **1145**, 80-84.
<https://doi.org/10.4028/www.scientific.net/AMR.1145.80>
- [16] Sow, L., Kamali-Bernard, S., Mauvoisin, G., Bartier, O. and Bernard, F. (2019) Original Experimental Campaign of Indentation Instrumented on Aggregates of Non-Hazardous Waste Incineration Bottom Ash to Study the Heterogeneity of their Rigidity. *Key Engineering Materials*, **805**, 177-182.
<https://doi.org/10.4028/www.scientific.net/KEM.805.177>
- [17] Robinet, A. (2008) The Treated form Layers in Railway Bedding Structures. Thesis for an Engineering Degree from CNAM, France.
- [18] Sow, L. (2020) Study of the Behaviour of Senegalese Ballast Materials during Compaction with the C-Mould: Case of Bandia Limestone and Diack Basalt. *Key Engineering Materials*, **831**, 81-86.
<https://doi.org/10.4028/www.scientific.net/KEM.831.81>
- [19] Elysée, K.N., Portance, K.M., Sow, L., Bilez, N.B., Corneille, K.M. and Obed, T.K. (2020) Coupling Discriminating Statistical Analysis and Artificial Intelligence for Geotechnical Characterization of the Kampemba's Municipality Soils (Lubumbashi, DR Congo). *Geomaterials*, **10**, 35-55. <https://doi.org/10.4236/gm.2020.103003>
- [20] Trinh, V.N. (2011) Comportement hydromécanique des matériaux constitutifs de plateformes ferroviaires anciennes. PhD Thesis, Université Paris-Est, France.
- [21] Kouroussis, G. (2009) Modelling of the Vibration Effects of Rail Traffic on the Environment. PhD Thesis, Polytechnic Faculty of Mons, France.
- [22] Athanassiadis, A. G., Miskin, M. Z., Kaplan, P., Rodenberg, N., Lee, S.H., Merritt, J.,

- Brown, E., Amend, J., Lipson, H. and Jaeger, H.M. (2017) Particle Shape Effects on the Stress Response of Granular Packings. *Soft Matter*, **10**, 48-59.
<https://doi.org/10.1039/C3SM52047A>
- [23] Börzsönyi, T., Somfai, E., Szabó, B., Wegner, S., Ashour, A. and Stannarius, R. (2017) Elongated Grains in a Hopper. *EPJ Web of Conferences*, **140**, Article No. 06017. <https://doi.org/10.1051/epjconf/201714006017>
- [24] Aissoun, B.M. (2011) Etude de l'influence des caractéristiques des granulats sur la performance des bétons fluides à rhéologie adaptée. Sherbrooke (Québec), Canada. <https://savoirs.usherbrooke.ca/bitstream/handle/11143/1590/MR83651.pdf?sequence=1&isAllowed=y>
- [25] Hafid, H. (2011) Influence des paramètres morphologiques des granulats sur le comportement rhéologique des bétons frais: Etude sur systèmes modèles. PhD Thesis, Université Paris-Est, France, 160. <https://tel.archives-ouvertes.fr/tel-00695922/document>
- [26] Ouhbi, N. (2017) Une description morphologique précise des grains pour l'étude numérique des propriétés mécaniques du ballast ferroviaire. PhD Thesis, Université Paris-Est, France. <https://pastel.archives-ouvertes.fr/tel-01730240>
- [27] AFNOR (2003) Granulats pour ballasts de voies ferrées. Standard, France.