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Preventive Maintenance of Railway Tracks: Ballast Performance Anticipation in the Cameroon Railway

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Abstract: The aim of the present research study is to produce a methodology that provides an understanding of the mechanical behaviour of ballast and its degradation in order to reflect field performance of different ballast materials used by CAMRAIL in their railway network, and to better anticipate an efficient planning of the railway track maintenance. Based on existed literature, on collected data of different railway sections, and on the finite element analysis of the vehicle-track mechanical interaction, a preventive ballast cleaning and renewal strategy, formulated through ballast deterioration indexes is proposed. Comparing to the ongoing day-to-day maintenance strategy the proposed functionality-based preventive maintenance offers the following advantages: security and comfort of users; forecasting of ballast corrective measures; planned maintenance actions; higher functional and exploitation level of the track and availability of needed materials and mechanisms. The administration of CAMRAIL has promised to extend further the findings of this work in other to fully optimized the track maintenance cost in each railway section.

Key words: Ballast deterioration, ballast renewal, critical state, rail-vehicle interaction, threshold index, wear rate

INTRODUCTION

The high traffic demand from CAMRAIL (Cameroon National Railway), due to economic constraints in the Central Africa Region, has led to an ever-increasing per-axle loading, and to an annual budget allocation of more than 800 million USD for track rehabilitation and renewal (CAMRAIL, 2008). A very large portion of the annual budget to sustain the railway track system goes into track maintenance (Fig. 1). The deterioration of the track geometry is mainly caused by the settlement of the substructure and ballast, being its main component because by its function, is important for providing the fastest and most economical method of restoring track geometry, especially at a subgrade failure situation. However when it is not well conditioned and entertained, ballast is also one of the main sources of track geometry deterioration (Selig and Waters,1994) and observed derailments in many countries (Mforgham, 2009; Kouby *et al*., 2010). Under traffic loading, the stresses in the ballast are sufficient to cause significant strain in the ballast, ballast particle breakage, and thereafter track settlement and acute need of multi-cycle track restoration in the form of ballast cleaning or renewal (Fig. 1b, c and d). Researchers (Selig and Boucher, 1990; McDowell and Amon, 2000; Evesque, 2002) have shown that conventional ballast abrasion tests give conflicting results and often fail to represent actual field performance. For particle mechanical testing Aggregate Crushing Value (ACV) gives information about the average strength of 10-14 mm particles, but does not give information about the average strength of larger ballast particles used in the trackbed. There is therefore a need for field oriented and a more consistent ballast testing method that provides results reflecting the mechanical behaviour of different ballast materials.

The aim of this study is to produce a methodology that provides an understanding of the mechanical behaviour of ballast and its degradation in order to reflect field performance of different ballast materials used by CAMRAIL and to better anticipate an efficient planning of the railway track maintenance process. Based on specific literature (Wright, 1983; Selig and Boucher, 1990; McDowell and Amon, 2000) and on collected data on the exploitation of different sections of the railway network of Cameroon, the Finite Element Method (FEM) is used in the discretization of the vehicle-track system and of its effects. The ballast behavioural response to railway traffic and its corresponding deterioration model correlated to the vehicle loading cycle is found thereafter. As a result of the present research work a proposed preventive ballast cleaning and renewal was presented

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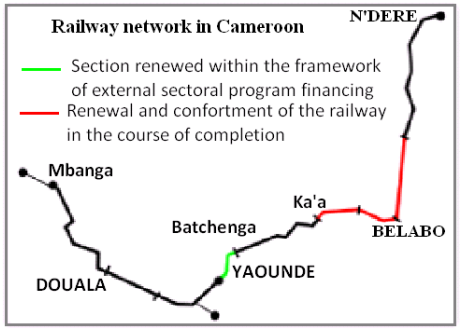


(a) The railway network

(b) Heavy mechanical stuffing

(c) Semi-mechanized raking of the way

(d) Pose of the rails with carriage platelayers

Fig. 1: Cameroonian railway network and maintenance works

on various network sections through the formulated ballast deterioration index as the wear rate. Comparing to the ongoing maintenance strategy the proposed functionality-based preventive maintenance offers the following advantages: security and comfort of users; forecasting of ballast corrective measures; planned maintenance actions; higher functional and exploitation level of the track and availability of needed materials and mechanisms. With the proposed test-based numerical tool to predict ballast deterioration, the administration of CAMRAIL promised to further the findings of this work in other to fully minimize the track maintenance cost of their railway network (Fig. 1a).

MATERIALS AND METHODS

Track components are divided into the superstructure and the substructure. The superstructure refers to the rails, the fastening system and the sleepers, while the substructure refers to the ballast, the subballast and the subgrade. Ballast is the crushed granular material found at the top layer of the substructure, in the cribs between the sleepers, and in the shoulders beyond the sleeper ends down to the bottom of the ballast layer. One of the main functions of ballast is to retain track position by resisting vertical, lateral and longitudinal forces applied to the

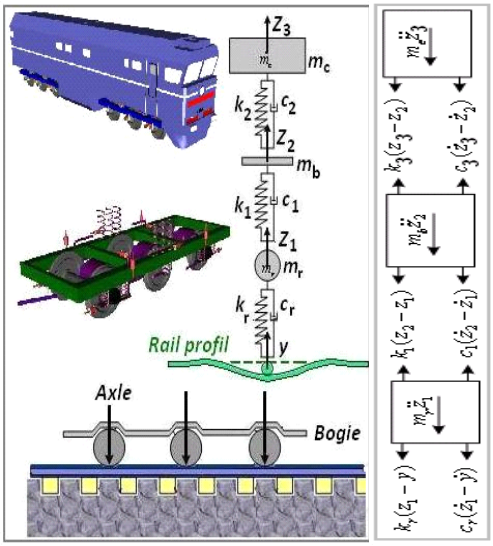


Fig. 2: Vehicle-track interaction model and the corresponding FB diagram

sleepers. The vertical force of the moving train and the squeezing force of maintenance tamping are two main forces which act on ballast. The vertical wheel force is distributed through a number of sleepers according to the sleeper spacing and the rail moment of inertia.

Vehicle-track coupled model: A railway car (for example Diesel Locomotives series CC 2600 or 3300) is modelized as a system with masses, springs and dampers as shown in Fig. 2. The rail is considered as an Euler-Bernoulli beam resting on simple supports or sleepers. Under a moving wheel load a rail behaves as a damped oscillator of an infinite length but with a finite deformed shape around the load application point. In this work we study the deformed shape only on eight continuous spans representing distances between sleepers, four from each side of the railway wheel. Using the superposition method and the FEM we can know the load distribution on each sleeper from each wheel of the trail. Each span has two nodes *i* and *j* with corresponding angular and vertical displacement θ_i, υ_i, θ_j and υ_j. Taking into account static and dynamic effects of the vehicle-rail interaction we consider the n^{-th} wheel of a railway vehicle having six axles acting on the given model. The equilibrium of the Free-Body (FB) diagram in Fig. 2 allows us to write the dynamic differential of motion as:

$$[M]\{\ddot{z}\}+[C]\{\dot{z}\}+[K]\{z\}=\{F_r(t)\} \qquad (1)$$

where, $\{F_r\ (t)\} = [k_r y + C_r \dot{y}\ 0\ 0]^T$ is the interaction applied force vector on the rail; k_r and C_r is the spring and the damping constants of the rail on the applied point; [K], [C] and [M] are the system stiffness, damping and mass matrices respectively; z_3 is the carbody (with rigidity k_2, damping c_2 and mass m_c) displacement as function of the human frequency limit (Alias, 1984); z_2 is the bogie (with rigidity k_1, damping c_1,and mass m_b) displacement; z_1 is the axle (with rigidity k_r, damping c_r and mass m_r) vertical displacement relative to the rail.

To describe the behavior of each node at each time with the given discretization of motion at different wheels positions, we adopt without description the following algorithm: generation of the rail static deflection; dynamic response calculation; and the calculation of the k^{-th} interaction force on the rail which becomes $\{F_{ri}(t)\} = [k_{ir} z_{1i} + C_{ri} y\ \dot{z}_{1i}\ 0\ 0]^T$ in the present case. At the end we use the superposition principle to integrate the effect of each axle *k* on the i-th and j-th sleeper with the help of shape functions and nodal displacements described above to find displacement at any point and reaction at every sleeper:

$$z(\lambda)=\sum(N_{1k}(\lambda)u_{ik}+N_{2k}(\lambda)\theta_{jk} + N_{3k}(\lambda)u_{jk}+N_{4k}(\lambda)_{jk})) \qquad (2)$$

where, $\lambda = x/L$ is the transformed local coordinate; L is the span distance between two sleepers; *x* is the distance from the left sleepers to the k-th axle point load; N_{ik} are well known shape function for the i-th degree of freedom of the element.

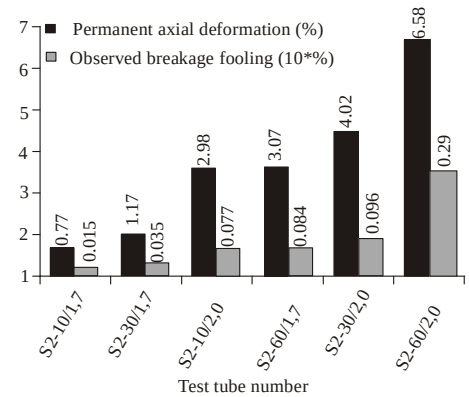


Fig. 3: Deformation and breakage for various ballast samples after 100 000 loading cycles (adapted form SHI (2009))

The rail is thus subjected to an interaction ΣF_{ri} in addition to the applied wheel load P. Nodal angular deflections θ_{ik} (or simply θ_i) are computed taking into account wheel loads and interaction forces F_{ri} so that we are able to find support reactions from each sleeper R_i, of element of the eight-element model, through the following expression:

$$R_j = R_{j,a} + R_{j,b}$$

$$\begin{Bmatrix} R_{j,a} \\ R_{j,b} \end{Bmatrix} = [K_j]\begin{Bmatrix} \theta j \\ \theta_{j+1} \end{Bmatrix} - \{F_j\}$$

$$F_j = \begin{Bmatrix} -\dfrac{(P+F_{ri})\lambda(L-\lambda)^2}{L^2} \\ \dfrac{(P+F_{ri})\lambda^2(L-\lambda)^2}{L^2} \end{Bmatrix} \qquad (3)$$

Ballast deterioration model: The vertical downward forces at the rail-wheel contact points tend to lift up the rail and sleeper some distance away from the contact point (Selig and Waters, 1994). As the wheel advances, the lifted sleeper is forced downward causing an impact load, which increases with increasing train speed. This movement causes a pumping action in the ballast, which increases the ballast settlement by exerting a higher force on the ballast and causing "pumping up" of fouling materials from the underlying materials in the presence of water. The increase of impact load leads to an increase in ballast settlement and to a larger gap underneath the sleeper. According to Selig and Waters (1994) ballast breakage constitutes 76% of the source of ballast fouling material, while the minor sources of fouling materials are infiltration from underlying granular layer and surface, subgrade infiltration or sleeper wear. Festag and Katzenbach (2001) defined particle breakage as the dissection of grains into parts (Fig. 3) with nearly the

same dimension and the probability of particle breakage in an aggregate increase with an increase in applied macroscopic stress and particle size, and reduction in coordination number (i.e., number of contacts with neighboring particles).

Various researchers have empirically modelled the permanent deformation of ballast under cyclic loading. Alva-Hurtado and Selig (1981) related the permanent stress (ε_N) after a number of cycles (N) to the permanent strain after one cycle (ε_1) through the following expression:

$$\varepsilon_N = \varepsilon_1(1 + C\log N) \tag{4}$$

where, C is a dimensionless constant controlling the rate of the deformation growth.

Since CAMRAIL does not have appropriate laboratory equipments to carry on needed cyclic experiments on ballast materials, the ballast model is chosen after the work done by SHI (2009) in the University of Nottingham. Seven triaxial tests were carried on different ballast samples, each submitted to 100000 cycles of axial loading-unloading with a growing-in-time frequency of load application. Obtained diagrams of permanent deformations, versus the number of cycle N, revealed that when N is less than 10000 permanent deformations are important, and for N above 100 0000, the accumulation of permanent deformations is very slow and a linear relationship between these variables is observed. Furthermore, ballast particle breakage is linearly related to permanent axial strain in cyclic triaxial tests after 100,000 cycles and before failure. The influence of stress level on permanent accumulated strain after a certain number of repeated loads is directly related to the ratio of deviatoric stress q to confining stress p. Increasing the stress ratio q/p increases the permanent strain and, for the same stress ratio, increasing the stress path-length increases the ratio $(q/p)_{max}$ and the amount of permanent strain accumulated (Lekarp *et al*., 2000; SHI, 2009) up to sample failure. In order to calculate the equivalent number of cycles, the available triaxial test results were plotted in a figure with a coordinate system of permanent axial strain rate accumulation ($d\varepsilon_{a.}/dN$) against the permanent axial strain $\varepsilon_{a.}$ The ideal settlement equation was able to predict the permanent deformation as a function of stress level and number of load cycles, and is therefore easy to use for railway track design. From analysis of the triaxial test results, it was also found that when the ballast permanent deformation is plotted in a coordinate system of $de_{a.}/dN$ against number of load cycles (N) on logarithmic scales, the plotted curves are approximately straight lines verifying the following expression:

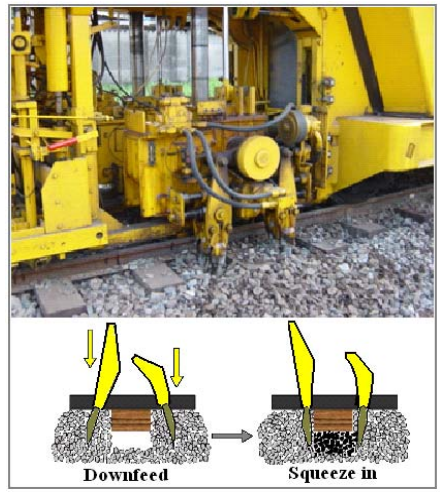


Fig. 4: Ballast tamping unit of CAMRAIL

$$\log\frac{d\varepsilon_a}{dN} = A - B\log N \tag{5}$$

where, A is a coefficient controlling the intercepts of these lines and B is the gradient.

By integrating this last equation and by simplifying it after Hettler (1984), the following exprssion of the permanent axial strain after a certain number of load cycles was given as:

$$\varepsilon_a = (5\times 10^{-6}\times(5\times\sigma_3' + 400)^{(q/p')\max} + 0.008\times 1.08^{\sigma_3'} + 0.48)\times N_m \tag{6}$$

where, Nm-N $^{10^{-9}\times(2\times107)\wedge((q/pt)max/(q/pt)p)\div 0.05}$ is the monotonic cycle number; $(q/p')_p = (2.6\text{-}0.41\times \text{In}\sigma'_3)\times C_r$ is the peak stress ratio from triaxial tests results; $(q/p')_{max}$ is maximum calculated stress ratio; σ'_3 is the sample cell pressure in kPa; C_r is a compaction ratio.

Track maintenance model: In a clean ballast sample, almost all aggregates are supposed to establish contact with each other at the aggregate surface to carry the load while dirty ballast will have the voids in between contacting aggregates filled with fine particles, maintaining aggregate to aggregate contact. A situation that decreases the railway track performance including higher permanent deformation and poor drainage and increased geometry deterioration. In order to reduce ballast fouling, ballast cleaning and replacement with fresh ballast should be carried out. Maintenance tamping, the most effective way of restoring track geometry as shown in Fig. 4, involves lifting the sleeper to a desired level and inserting tamping tines into the ballast with the lifted sleeper between each pair of tines. The tamping

tines then squeeze ballast to fill the void underneath the lifted sleeper. The impact from the insertion of the tamping tines into the ballast and the high squeezing force are sometimes the cause particle breakage. This position has been contradicted by the works of Wee (2004), who found from results of ballast ACV tests that the effect of rearrangement of ballast caused by temping does not affect the total particle breakage underneath the sleeper, a situation that might be explained by additional reaction of a resulted denser ballast packing.

Different ballast indexes have been introduced to display the state, the maintenance and the exploitation level of ballast layers. It has been shown by Hardin (1985) that there is a linear correlation between the total breakage factor and some factors as the weighted tensile strength, the relative strength index, the relative voids ratio and the permanent axial strain for ballast underneath the sleeper in box tests. The Hardin's total breakage factor B_t, obtained through the ACV tests and the breakage potential B_p, is defined as:

$$B_\tau = \int_0^1 (b_{po} - b_{pi}) df \tag{7}$$

where, $B_p = \int_0^1 b_p df$; b_p is the potential for breakage of a particle of a given size; df is a differential of percentage passing by mass divided by 100; b_{po} is the original value of b_p; b_{pi} is the value of b_p after loading.

Preventive maintenance, from the European Pré-norm 'NF EN 13306 X 60-319' viewpoint, is a set of activities performed according well approximated analytical behavioral indicators of degradation while the structure (ballast layer) is still in a good or fair condition to inhibit progressive failure. It is based on the crossing of a predefined threshold indicating the degradation level of ballast materials before its critical deterioration. In our case, we set two indicators to assess the performance of the ballast, in particular its deformation and wear rate. We thus define the wear rate (R_ε = ballast debris mass/ballast total mass) of a ballast sample as the ratio of debris mass from grain on the total mass of the ballast at a given time. This rate can be represented by cumulative weight passing in percentages through a 25 mm square mesh sieve, sieve initial grain sizes are considered to be between 25 and 50 mm. In a general manner taking into account all factors (chemical, mechanical, contamination) influencing the ballast degradation this rate can be substituted with the Fouling Index FI described as the level of fouling in track and calculated as the summation of the percentage of material passing the #4 sieve plus the percentage of material passing the #200 sieve (Selig and Waters, 1994). Parameters that must be established, as seen in Fig. 5, are:

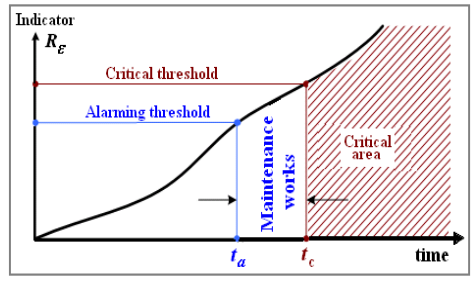
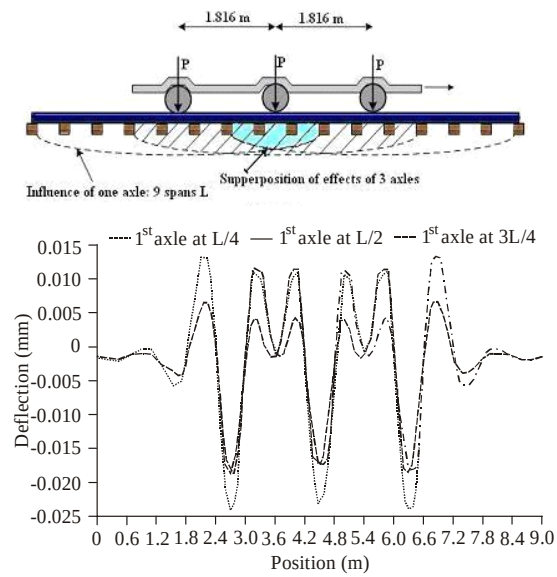
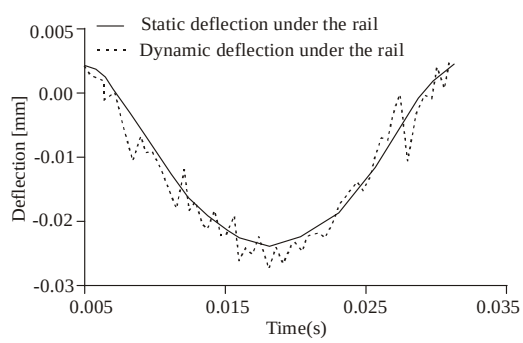


Fig. 5: Preventive maintenance applied to ballast



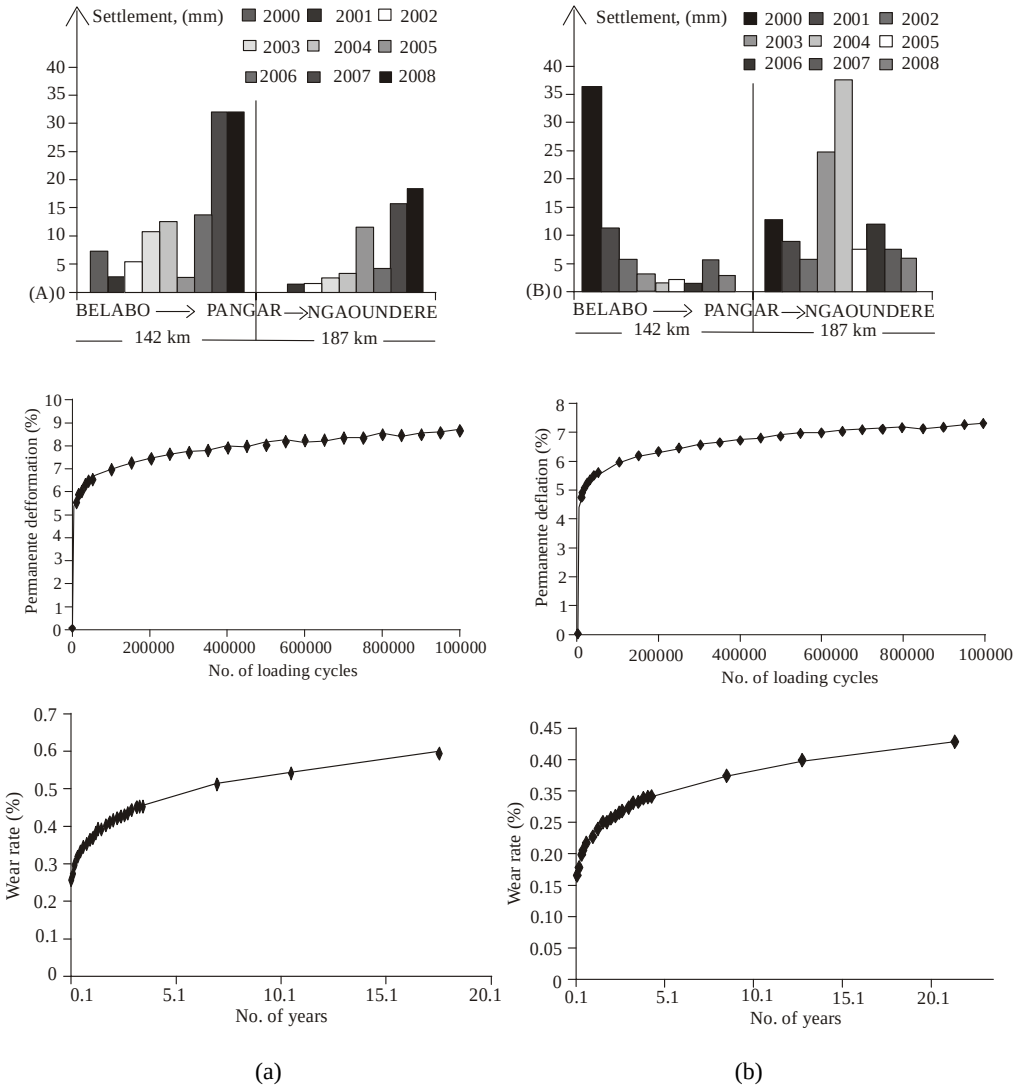
(a)



(b)

Fig. 6: Rail-Vehicle response, (a) deflection, (b) Rail-Vehicle dynamic interaction

the diagram of the degradation indicator as function of time; the alarming degradation threshold from which maintenance works must be planed and executed with minimum functionality of the railway track; and the critical deterioration threshold from which we observe



(a) (b)

Fig. 7 : Track response to traffic: recorded settlement for two different railway sections, (a) Belabo-Ngaoundere and, (b) Yaounde-Tabene); ($_1$) estimated ballast permanent deformation, and ($_2$) estimated ballast wear rate

excessive permanent deformations that can lead to derailments or traffic disclosure. Since there is a correlation between ballast deformation ε and the wear rate R_ε we can give an approximation of the ballast wear rate (fragmentation rate of ballast grains), according to results of triaxial tests on ballast sample done by SHI (2009), non-linearly related to the resulted permanent deformation of the track as:

$$R_s = 0.005\varepsilon^2 + 0.09\varepsilon \quad (8)$$

RESULTS AND DISCUSSION

Rail response to axle loads: Numerical analysis is carried out with a CC 2600 vehicle running at 70 km/h and having a 18.85-ton axle load of a 3-axle bogie with dimensions given in Fig. 6a. Rails are of Vignole type weighing 54 kg/m with the following characteristics: Cross sectional area, A = 69.34 cm^2; Inertia moment, I = 2127 cm^4; Rigidity modulus, EI = 4.47 MN.m^2; the distance between sleepers is L = 60 cm; primary and secondary characteristics of suspensions are:

k_1 = 86×10^4 N/m
c_1 = 3000 Ns/m
m_b = 3000 kg
k_2 = 12×10^6 N/m
c_2 = 15000 Ns/m
m_c = 5500 kg
k_r = 192×υ×EI/L^3

where υ is the stiffness factor; c_r = 1 % of the critical; m_r = 5500 kg. Some of these data are not available in CAMRAIL for various reasons and are taken from technical documents. The first wheel being on the fifth span as shown in Fig. 6a, while the other two wheels of the bogie are on the eighth and on the eleventh span, we can see the deflection history when the first wheel is on the quarter, the half and the thee-quarter span respectively. It is easy to see that the maximal deflection occurs when the first wheel is at the midspan L, and that these diagrams correspond to a set of periodic functions having a half-period of 0.0309 sec, the time needed for the axle to travel from sleeper i to sleepers i+1. As the vehicle travels along the rail it induces deflections and dynamic rail-vehicle interaction that are taken into consideration in the calculation of loads transmitted to sleepers and to ballast through the dynamic Eq. (1) as depicted in Fig. 6b. The rail response is shown under the first axle only for the considered span with a dynamic magnification factor that can reach 20%.

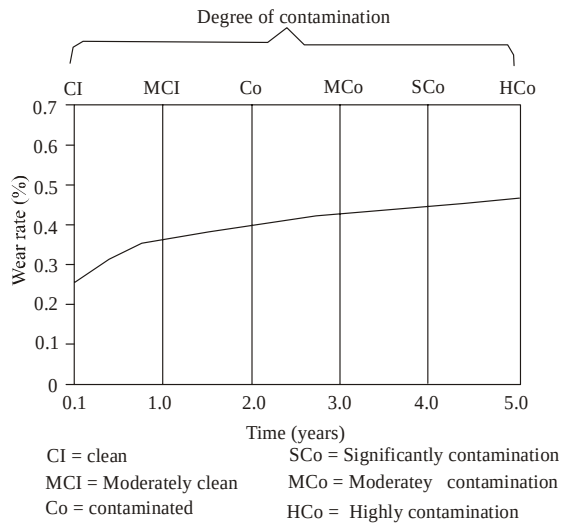


Fig. 8: Influence of wear rate on critical states of ballast

Ballast response to railway traffic: The heaviest good traffic of the Cameroonian railway network appears to be the Douala-Belabo section that is subjected to traffic loading towards Thad, Central African Republic and the Far North of Cameroon. The average daily traffic recorded in January 2010 in the Douala-Belabo section shows that we had an average of five trains per day each having 32 four-axle cars carrying 10.9 tons/axle, traveling on wooden or metallic sleepers distributed at 1500 or 1714 units/km, and moving at a velocity between 20 and 80 km/h depending on the track practicability condition. Knowing, for a railway section the average daily traffic, the average load per axle and the track characteristics, we evaluate according to Eq. (6) and (8) the ballast permanent deformation and the corresponding wear rate. Estimated ballast permanent deformations and wear rate are plotted in Fig. 7. From these curves we observe that ballast settlement under a railway track is due to the vibratory process that causes granular rearrangement, and to a lesser extent to the grain wear. The most significant deformations of the ballast are observed during its first month of exploitation and then, after grain rearrangement when the ballast layer is sufficiently dense, grain wear and breakage occur on a relatively lower rate. Furthermore field records shows that track distortion is observed more on a section with lower stiffness of the rail (30 kg/m rails instead of 50 kg/m) as it is accentuated on the segment Belabo-Pangar in Fig. 7a, and not on the segment Yaounde-Tabene in Fig. 7b.

The performance of railway ballast depends largely on maintenance and renewal decisions taken during its life cycle. In order to maintain the quality of railway track at an accepted level, two aspects of the ballast quality need to be considered: measurement of the ballast quality on a continuous basis, and means to achieve the required infrastructure quality when the quality falls below the accepted level. With an increase in railway track demands in terms of axle load, gross tonnage, speed, etc., the ballast and then the track experiences more failures, which require more maintenance. At the same time, the availability of financial means to perform the necessary maintenance decreases, due to the increased traffic poor management and lack of adequate local technical knowledge. To optimize maintenance activities in terms of cost-effectiveness, serviceability and safety with respect to technical advancements, a ballast deterioration and replacement approach is proposed.

Proposition of ballast deterioration indexes: The maintenance strategy employed by the CAMRAIL track department is based on discovering signs of track (or some of its parts) failure in order to take appropriate restoration measures. Since communication and administrative decisions are not always in phase with the gravity of the failure rate, it's possible to encounter worst traffic events (Mforgham, 2009) in the network. We propose that this form of action-oriented maintenance be replaced by a strategy that reduces the frequency of failure by performing planned inspections and diagnostics to compare the actual state of the ballast with a prescribed functional state of a normal ballast. Based on ballast samples from the track under exploitation we define the actual wear rate of ballast R^* that is compared with the proposed normative wear rate scale R_L that takes into account the total degradation effects from all sources. The present scale explained in Fig. 5 and presented in Fig. 8 shows different functional levels of ballast in its operational state from clean ballast to highly contaminated ballast.

Since CAMRAIL does not have ballast management historical records to display previous behavior of local ballast materials on its railways we recommend to study the mechanical behavior of these materials and establish appropriate behavioral functional indicators (permanent deformation and wear rate). If the a ballast material i, under experimental cyclic test, has a permanent deformation $\varepsilon^i(N)$ and a wear rate $R_i(N)$, then it is possible to define the contribution of chemical and contamination factors on the general degradation of any ballast material under exploitation by the expression R^*- $R_i(N)$. From a statistical analysis of long-term historical data of used ballast and from provisional traffic data of a particular railway section, it is possible to establish for each ballast material a predictive maintenance relationship between the experimental ballast wear rate R_e and a predictive wear rate $R_L(N)$ and thereafter design a wear rate scale to establish the degree of contamination depending on the experimental wear rate as shown in Fig. 8. With the given methodology it is possible to determine the number of loading cycles N, or the time needed for a given railway traffic, required to achieve an established critical degree of contamination, and plan in time for adequate restoration measures before the occurrence of a failure event. This possibility gives freedom to the railway administrator to establish its own ballast degradation critical indicators with specific values given to represent the state of clean, moderately clean, contaminated, moderately contaminated, significantly contaminated and highly contaminated ballast layers.

Over the present ballast action-oriented maintenance the proposed methodology offers the following advantages:

- Security and comfort of passengers since the track behavior is constantly monitored and corrective measures are taken before any eventual breakdown.
- Forecasting of ballast corrective measures is done by developing a probability distribution of past ballast functional data.
- Programmed maintenance actions are taken in advance whenever an observed track operational indicators reaches an alarming threshold.
- The functionality and the exploitation level of the track are higher since any eventual failure risk is minimized with predictive planned monitoring and subsequent corrective measures.
- The availability of needed materials and mechanisms before monitoring and the occurrence of predicted critical threshold.

CONCLUSION

Under the increasing pressures to quickly improve the performance with limited financial means, local railway managers are forced to focus on supplying short-term cost and performance improvements only, and uncertainty on long-term behavior of the track result in its functionality not being sufficiently appreciated. The proposed functionality-based preventive maintenance of ballast layers, in the present study, offers degradation indicators of ballast with appropriate methodology using FEM of the vehicle-track interaction and experimental results conducted on ballast in the laboratory or in the field. Remedial or corrective decisions determine when the ballast needs to be maintained, what maintenance action is to be carried out and how the maintenance action will meet the ballast objective to secure the safety of the system track-vehicle-user. Comparing to the ongoing maintenance strategy the methodology presented in this study displays the following advantages: security and comfort of users; forecasting of ballast corrective measures; planned maintenance actions; higher functional and exploitation level of the track and availability of needed materials and mechanisms. With the proposed test-based numerical tool to predict ballast deterioration, administration of CAMRAIL promised to further the findings of this work so that they can be applied in recording historical ballast cleaning and renewal data, in forecasting ballast monitoring, cleaning and renewal, and in planning for availability of materials and mechanisms in other to fully optimized the track maintenance cost in each railway section.

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