NAU Journal of Civil Engineering (NAUJCVE) November/December 2025
Nnamdi Azikiwe University Journal of Civil Engineering (NAUJCVE)

Volume-4, Issue-3,113-121
www.naujcve.com
Research Paper Open Access

An evaluation of the effect of compaction on the durability of road pavements

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ABSTRACT :*This paper explores the fundamental role of compaction in ensuring pavement durability and longevity by integrating insights from established civil engineering literature. The background highlights compaction as a critical process that improves soil density, reduces permeability, and enhances the structural integrity of pavement layers. The study addresses the growing concern of early pavement failure linked to poor compaction practices. Drawing from multiple peer-reviewed sources, it outlines the mechanisms of compaction and contrasts them with consolidation, a slower, time- dependent soil behaviour. Methods discussed include traditional Proctor tests, field density measurements, and the application of intelligent compaction (IC) technologies. Key findings from reviewed studies emphasize that achieving optimal compaction, typically 95–100% of maximum dry density, directly improves pavement performance by minimizing deformation, cracking, and water ingress. The paper concludes that integrating innovative technologies, such as GPS-based monitoring and machine- learning-guided rolling patterns can significantly enhance outcomes. The study recommends broader adoption of these techniques and consistent quality control to ensure uniform compaction.*

KEYWORDS:*Soil compaction; Pavement durability; Intelligent compaction; Subgrade stability; construction.*

Date of Submission: 24-12-2025 Date of acceptance: 30-12-2025

1. INTRODUCTION

In civil engineering, achieving soil stability is a fundamental prerequisite for the longevity of any built structure. Compaction is the mechanical process of increasing soil density by reducing air voids, typically through the application of static or vibratory loads (Das & Sobhan, 2017). This immediate densification forces soil particles into closer proximity, thereby increasing inter-particle friction and shear strength. Optimal results are traditionally achieved when the soil is at its optimum moisture content (OMC), a state where water acts as a lubricant to facilitate particle rearrangement without occupying excessive void space (AASHTO, 2010).

By contrast, consolidation represents a natural, time-dependent reduction in soil volume. While compaction addresses air voids, consolidation involves the gradual expulsion of pore water from saturated, fine-grained soils, such as clays, under sustained loading (Terzaghi et al., 1996). Understanding this distinction is vital for pavement engineering; whereas compaction is a deliberate construction activity intended to provide immediate stability, consolidation is a long-term hydraulic process that can lead to post-construction settlement and structural distortion (Lambe & Whitman, 1969).

The structural integrity of a pavement system relies heavily on the quality of the subgrade and base layer compaction. Inadequate mechanical densification remains a primary catalyst for premature pavement failure. Well-compacted layers create a robust foundation capable of distributing traffic loads effectively, thereby mitigating the risk of rutting, cracking, and surface wear (Huang, 2004). Furthermore, high-density soil exhibits significantly lower permeability. By restricting moisture infiltration, proper compaction protects the pavement from the deleterious effects of freeze-thaw cycles and subgrade softening (Mehedi et al., 2020).

On the other hand, failure to reach target density levels often results in uneven settlement. As noted by Bowles & Guo (1996), such instability manifests as surface ruts and potholes, which escalate maintenance costs and diminish the service life of the infrastructure. Since the subgrade serves as the ultimate support for all superimposed layers, its compaction is particularly sensitive; any structural deficiency at this level propagates upwards, leading to catastrophic failure of the bituminous or concrete surface (Conduct e al., 2019).

Recent advancements have sought to move beyond traditional, static compaction methods to improve precision. Intelligent Compaction (IC) technology, which integrates Global Positioning Systems (GPS) with real-time vibratory monitoring, allows operators to achieve uniform density across large areas (Yuan et al., 2022). Such innovations, alongside the integration of sustainable materials like Recycled Asphalt Pavement (RAP), offer a path toward more resilient infrastructure (Ebrahim & Karim, 2019).

Despite these benefits, a significant disparity exists in the global adoption of modern techniques. In many regions, particularly within Sub-Saharan Africa, rural road projects continue to rely on outdated, non-automated methods. This lack of technological penetration often results in infrastructure that cannot withstand modern traffic volumes or volatile climatic conditions (Ngezahayo et al., 2019). This gap highlights a pressing need for a systematic re-evaluation of current compaction practices and the standardisation of advanced quality control procedures.

This paper provides a comprehensive synthesis of existing research regarding the role of compaction in pavement performance. By evaluating the mechanisms of mechanical densification, the equipment employed, and the challenges inherent in modern construction, this study identifies the critical factors that contribute to sustainable pavement design. The following sections explore quality control procedures and innovative technologies that may assist engineers in bridging the gap between traditional practices and modern requirements for resilient infrastructure.

2. METHODOLOGY

This study employs a qualitative research approach, which is well-suited for synthesizing existing knowledge on soil compaction in pavement construction. Qualitative approach enables undertaking a detailed review and analysis of available literature, case studies, technical standards, and engineering reports. As Saunders *et al. (2019)* found out, qualitative research is commonly applied to study complicated problems revolving around reviewing the available data and making links between the numerous sources. This is the method to use especially where a comprehensive picture of a topic is required without employing new empirical data.

The literature review to this study is based on the basic texts on the field of geotechnical engineering such as Das and of Sobhan (2017) and Bowles& Guo(1996) which has commanding authority in the industry representing the most crucial information on soil compaction mechanism. These sources allow to develop a good theoretical framework of the research. Furthermore, developed parameters, which are accepted in other renowned organizations such as AASHTO (2010), are implemented into the research, whose specifications are used in the construction of pavements in order to guarantee them quality compaction and efficient functioning. AASHTO (2010) has classified the role of proper compaction when enhancing structural integrity of the pavements as being very crucial to the focus of the study. Furthermore, the work references the major theories of consolidation by Terzaghi *et al.* (1996) and Lambe and Whitman (1969), which provide a historical context for understanding compaction in relation to soil behavior under load. These theories form the cornerstone in the differentiation between the process of compaction which is a controlled mechanical process on one hand and consolidation on the other hand which is a natural time-eternal process which influences the long-term stability of pavements (Terzaghi *et al.,*1996; Lambe & Whitman,1969).

Moreover, several case studies are used to give practical examples of the application of compaction methods, which are undertaken in different parts of the world, such as China (Yuan et al., 2022) and Sub-Saharan Africa (Ngezahayo et al., 2019). These case studies indicate an impact of local environmental and economic circumstances on compaction processes and pavement performance as it is observed by Yuan *et al.* (2022) and Ngezahayo *et al.* (2019).

The sources used in this study were chosen in consideration of their academic authenticity, significance to the existing forms of pavement construction and implication relating to infrastructure enhancement. The analysis encompasses empirical results, technical drawings as well as recent innovations in the field of compaction methods and materials. Such synthesis is consistent with the technique promoted by Creswell (2014), who stresses the necessity of ambiguity combination of empirical data and new solutions during the review of the existing literature. The primary goal of this methodology is to offer a well-rounded and practical examination of the impact of compaction on pavement design, performance, and long-term sustainability.

3. DISCUSSION

3.1 Compaction and Consolidation

While both compaction and consolidation affect the stability and strength of pavement structures, they operate differently and are important at different stages of the construction process. Compaction is a mechanical technique used in the onset of constructing pavements in order to enhance the density and stability of soil. Consolidation does, however, take place slowly with time especially in the fine-grained soils and it does not cease even after the pavement is done.

The most significant distinction between the compaction process and the consolidation process is in their time scale and process of action. Compaction takes place instantaneously and usually takes place in a matter of few hours or days after the construction work, whereas consolidation is a very slow process that happens gradually over months or even years by expelling the water in the soil by pressure (Lambe & Whitman, 1969). Compaction is commonly applied in shallow pavements, but consolidation is more applicable to the deep paves and soft soil that needs long-term controlling of the settlements (Coduto et al., 2011).

In practical terms, compaction becomes very important at the stage of construction to verify the pavement capable of supporting the early loads and offering a foundation upon which additional developments can be made. Consolidation, however, must be recognized to play a role in the long- term structural stability where foundations must be of long-term loading. To have a good performance of the pavement, both the processes have to be well controlled so that the good compacting provides immediate strength and the one that ensures that the pavement is firm in the long-term aspect is good consolidation.

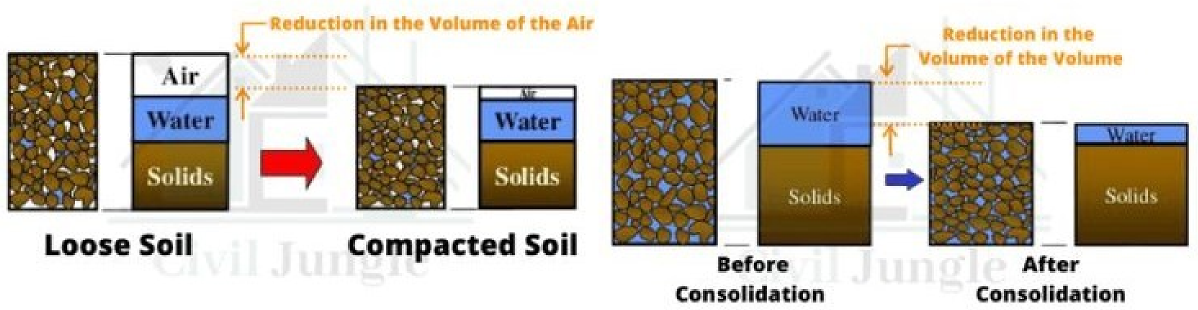

Fig. 1. Compaction vs. Consolidation (Source: Coduto et al., 2011).

3.2 Components of Pavement Structure

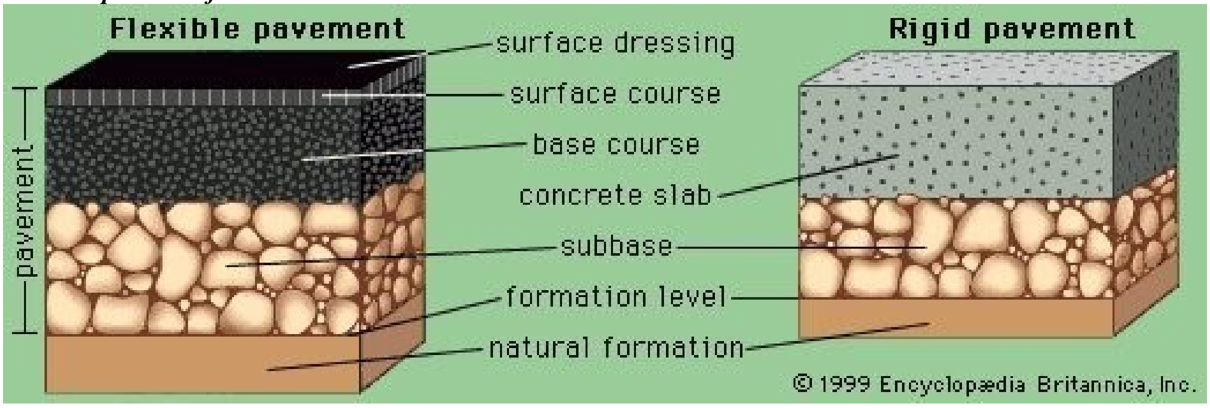

Fig. 2. Flexible and Rigid Pavement Structures (Source: Encyclopaedia Britannica, 1996)

Pavement structures are broadly categorized into flexible and rigid types based on their composition, load distribution behaviour, and structural performance. Long-term serviceability of both systems is entirely dependent on the adequacy of the sub Layers which have been well compacted. Common materials used for pavements include asphalt and concrete. However, other materials, like the artificial stone, flagstone, cobblestone, bricks, tiles, and even the timber may be utilized as the road surface material as well, according to the design specifications and aesthetic needs.

3.2.1 Flexible pavement structure

Flexible pavements are made up of a series of layers, the purpose of those layers is to distribute the traffic loads imposed on them progressively gradating the traffic. The major factors consist of:

a) Natural Formation/Subgrade: This native soil layer must be well compacted and stabilized to support all subsequent layers.
b) Subbase: It serves as an added support layer and it provides drainage.
c) Formation Leveling: Ensures a stable, even surface before base construction
d) Base course: This is constructed of compact aggregates, it serves to distribute loads in an efficient manner.
e) Surface Course: Composed of high-quality asphalt, it withstands traffic and environmental stress.

f) Surface Dressing: Provides a smooth, skid-resistant finish for vehicular use. Each of these layers requires adequate compaction to avoid structural issues such as rutting, settlement, or moisture ingress (AASHTO, 2010; Huang, 2004).

3.2.2 *Rigid pavement structure*

Rigid pavements are usually regarded as a single structural layer and reinforced concrete or plain concrete is used. They consist of:

a) Natural Formation (Subgrade): This is the soil, which supports the weight of the pavement.
b) Formation Level: Ready to make the concrete slabs uniformly held.
c) Subbase: Ameliorates load distribution as well as provides frost protection.
d) Concrete Slab: It is the main structural component, which transfers loads into a wide area because it is stiff (Bowles & Guo, 1996). Under the rigid pavements, less dependence of distribution on underlying layers is maintained, nonetheless, the soundness of uniformity of compaction remains important in avoiding any occurrences of differential settlement or crack formations (Coduto et al., 2019).

3.3 Compaction in the Different Layers of a Pavement

a) Subgrade: Through good compaction, soil gets its strength and the future settlement is avoided.
b) Base and Subbase Levels: The compaction gives effective distribution of load and can minimize the chances of structural failure.
c) Surface Layer (Flexible Pavements): The more compact there is, the more resistant to moisture and the less wear and crack it will have (Huang, 2004).
d) Overall Impact: Uniform compaction across all layers improves pavement performance and extends its lifespan (Das & Sobhan, 2017).

3.4 Key Mechanisms Behind Soil Compaction

The compaction process involves several key mechanisms that improve the pavement's structural stability. One mechanism is the reduction of air voids, where mechanical energy expels air from soil pores, thereby increasing the soil's density (Das & Sobhan, 2017). Another is particle rearrangement, whereby soil particles rearrange themselves in a more compact manner, increasing shear strength and load resistance capabilities (Xu et al., 2022). Additionally, frictional resistance is overcome during compaction, allowing soil particles to surpass internal interlocking forces, forming a more cohesive structure (Leshchinsky & Boedeker, 1989). Finally, there is elastic and plastic deformation: granular soils are likely to recover since they experience elastic deformation, whereas cohesive ones are likely to experience plastic deformation, which leads to stiffening and densification of the material (Holtz et al., 1981; Bowles & Guo, 1996).

3.5 Factors Affecting Compaction

Efficiency and effectiveness of the soil compaction is determined by a number of inter-related factors each playing a different role towards the resulting pavement performances. One of these is soil type which forms a base determinant. Non-cohesive soils such as sand and gravel soils are well treated with vibratory technique since they are easy to work with relative to more cohesive soils such as clay and silt soil which require kneading and impact techniques to attain optimum density (Leshchinsky & Boedeker, 1989). The reason behind this is attributed to the fact that cohesive soils have properties to hold moisture and oppose rearrangement of particles under mechanical efforts, and this trait requires application of mechanical force to counter the natural plasticity exhibited by such soils.

The moisture content is also another significant factor that may affect the results on compaction since excess and too little moisture compromises the results of compaction. An increase in moisture content decreases shear strength and rises pore water pressure, whereas lack of moisture results in the inability to sufficiently bind particles (Das & Sobhan, 2017). Namely, to get the best results in compaction, it is important to ensure the optimum moisture content.

Compaction energy, which refers to the force applied as well as the kind of equipment used, directly influence the densification of the soil. AASHTO (2010) determined that the type of equipment passes made and the amount of force applied identify the fact that the soil has attained desired density. Closely linked to this is the number of passes, which give better dispersion of energy and increased compaction, particularly in the more extensive layers of the soil. A weak pavement may develop weak areas when an insufficient extent of compaction is used. This may cause long time problems in the performance of the pavement.

3.6 Compaction Equipment

Compaction equipment is selected based on soil type, compaction objectives, and project specifications. All the types of equipment produce force in a different way, either on the basis of the static pressure, vibration, kneading or a combination of the three.

a) Smooth Wheel Rollers: These are mainly used on finishing the surfaces and densifying granular soils. They use static pressure.
b) Pneumatic Rollers: These are fitted with series of rubber tires where the tire works

in kneading mode and sealing as they can be used on various soils and asphalt areas.

c) Sheepsfoot Rollers: The Sheepsfoot rollers have projecting lugs or feet, which are very efficient in cohesive soils such as clay as they offer substantial penetration and kneading action.

d) Vibratory Rollers: These sorts of rollers are fitted with vibrating drums and are best suited to granular soils (i.e., sand, gravel) in that the vibration of the drum assists the particles to re- group in a denser formation.

e) Grid Rollers: The soils that are coarse-grained are compacted initially and large clods broken up and a little of the soil is compacted.

The choice and usage of the appropriate equipment is essential when it comes to achieving the equal compaction and examining the pavement durability.

Plate 1. Types of Compaction Equipment (Source: Ebid, 2018).

3.7 *Methods of Compaction*

Various techniques of compaction are adapted to soil properties and requirements of projects.

a) Soil Compression (Static Compaction): This is characterized by weight adding force whereby weight is placed on the soil using rollers thus compressing the soil particles. This approach is normally applied on the early phases of the construction of pavements and has to maintain the stability of soil but does not produce vibrations that may cause destabilization of sensitive soils (Sobhan, 2017; Budhu, 2010).

b) Vibration Compaction: in contrast, dynamic forces apply in this technique to destabilize and reorient particles of the soil. It is especially good on granular materials because it removes air out of the gaps and increases particle interlock (AASHTO, 2010, Craig, 2004).

c) Kneading and Impact Compaction: this method induces a combination of shear and tamping movements. This two-step practice works well with cohesive soils where it forms a denser and interlocked structure that will not result in settlement requirement (Das &Sobhan, 2017; Coduto et al., 2011). The choice of the suitable method depending on soil and environmental conditions greatly influences the end quality of pavement.

3.8 *Quality Control in Compaction*

Adequate quality control during compaction is crucial in making sure that the pavements are capable of both structural and durability standards. The effectiveness of soil compaction is checked with the help of laboratory and field-testing practices.

3.8.1 *Testing methods*

Assessment of the soil density and moisture content relies on a number of standardized tests. Both the Standard and Modified Proctor Tests occur in the laboratories and are used to identify the amount of moisture content that gives the maximum dry density. The modified one uses more compaction energy and more closely represents the real environment during the construction of the heavy-duty pavement (AASHTO, 2010; Das & Sobhan, 2017).

Field density tests play significant roles in ensuring that the compaction is within the engineering requirements. The Sand Cone Method is one of the most widely used field techniques; one analyzes the measurements of the in-place density by removal of a tiny cavity of compacted soil and replacing it with measured amounts of sand. The Nuclear Gauge Method is the technique which makes the possible non-destructive and fast detection of the soil density and its moisture content. Core Sampling will as well enable the engineers to extract cylindrical samples of compacted layers and have the samples tested in the laboratory in order to confirm the quality and uniformity of compaction (Huang, 2004; Bowles & Guo, 1996).

3.8.2 *Key performance metrics*

The performance statistics also underline that compacted soils must reach 90% - 100% of the maximum dry density when they are on the field with the air void being less than 5%. Low permeability and high shear strength are essential objectives in the fine-grained nature of soils. In addition to that the compaction should be uniform throughout the pavement structure to prevent uneven settlement, cracking and water ingress (Holtz et al., 1981).

3.9 *Compaction Challenges and Solutions*

Despite its importance, compaction presents multiple field challenges.

3.9.1 *Common issues*

The over-compacting issue is one barrier to be directed to, as the soil aggregates may be ruptured due to the increased compacting activities and, therefore, the material strength and the ability of the soil to be permeated is decreased (Budhu, 2010). The other problem which is likely to occur is under-compaction that causes weak areas through creation of voids through the uneven settlement of the structure (Coduto et al., 2019). There is also a possibility to damage the pavement performance and the results of the compaction due to changes of moisture levels, especially seasons (Das & Sobhan, 2017; Holtz et al., 1981).

3.9.2 Solutions

To tackle these problems, thorough analysis of sites is essential. These entail soil stratification/classification and moisture study to come up with specific soil compaction plans by site specific conditions (Bowles & Guo, 1996). Real time monitoring tools/technologies, like the Intelligent Compaction (IC) technology, would allow contractors to know about the status of compaction immediately so that maximum and consistent density is obtained, meeting the acceptance criteria of the AASHTO (2010) organization. Moreover, soil stabilization methods, e.g. lime- or cement incorporation, have a strong potential to enhance the soil parameters and compaction effectiveness, also promoting a high pavement level of performance and stability (Xu et al., 2022; Craig, 2004).

3.10 Case Studies and Applications

Plate 2. Schematic Diagram of Unmanned Rolling (Source: Yuan *et al.,* 2012).

The research presented highlights the effectiveness of intelligent compaction (IC) technology in improving pavement durability.

3.10.1 Improved pavement lifespan through optimized compaction in urban highways

Yuan *et al.* (2012) carried out a research study that investigated the utilisation of intelligent compaction (IC) technology implemented by Sany heavy industry and Shanghai Beidou Platform Company in the setting of Shanghai Zhujian Road construction project in compacting subgrade density and reducing asphalt layer and subgrade variability. The presence of real-time monitoring systems allowed the evaluation of the efficiency of compaction that served as one of the significant sources of improvement. Engineers detected soft areas and fixed inconsistencies through the use of GPS- based compaction mapping technology on vibratory rollers before finishing the construction. This resulted in a 1% reduction in maintenance costs (Yuan *et al.,*2012).

3.10.2 Impact of inadequate compaction on rural roads' premature failure

Rural road projects have shown early signs of failure because of poor soil preparation and inadequate quality control procedures which led to insufficient compaction. This was indicated in the outcome of a study conducted by Ngezahayo *et al. (2019)* which stated that due to shoddy sub-Saharan Africa rural road compaction, pavements were damaged in the first three years of operation. The paper provided special attention to the significance of quality control and adequate compaction in rural territories where no additional resources are available to cover maintenance needs. It also revealed how poor compaction of the surface caused rutting and breaking of the surface and this is a typical indicator of premature pavement failure that can be experienced in such pavements (Ngezahayo *et al., 2019)*.

3.11 Innovations in Compaction Technology

The technology of compaction is also emerging with new-fangled progression, modifying the conventional construction procedures.

3.11.1 Intelligent compaction (IC)

Intelligent Compaction (IC) represents a modern revolution in pavement construction because it advances current compaction technologies. IC is exceptional as it has a system that can analyze site conditions on the go and this enables operators to adjust compaction parameters as they gauge (Chang et al., 2014). IC establishes stiffness using accelerometers, combined with automated feedback controls to aid in the process of decision-making that reduces chances of under-compaction and over-compaction (Liu et al., 2016).

The mapping tool powered by GPS is another critical aspect of IC that offers complete coverage of the roads and identifies regions that may suffer structural weaknesses on the pavement. Engineers through GPS tracking systems have been able to get accurate measurements of patterns of movements of the grasses that establish equal distribution of density through the pavements (Wang et al., 2014). IC systems based on GPS have significant benefits of enhancing pavement density leading to reduced costs spent in maintenance and extended service life of pavement (Lee et al., 2022).

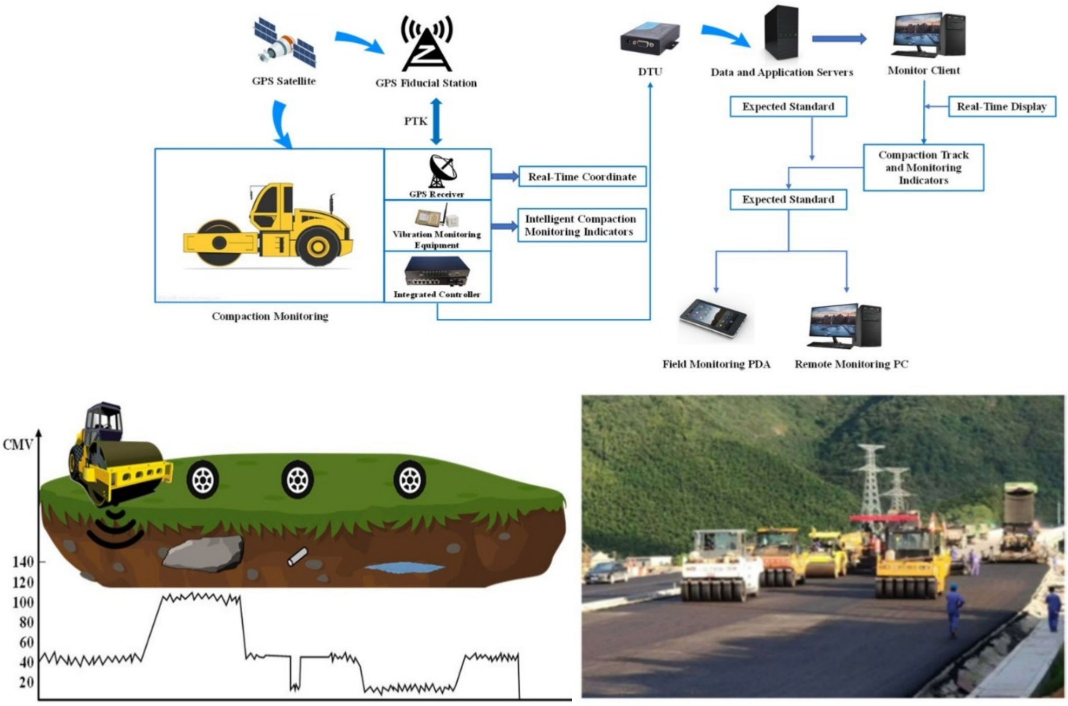

Figure 3. Intelligent Compaction System Overview (Source: Wang et al., 2024)

The emerging feature of IC includes machine-learning algorithms that assess compaction data to forecast the best rolling patterns and necessary energy usage. The use of IC systems in predictive modeling reduces the amount of energy consumed as well as the waste of materials used to build structures that facilitate sustainable functioning in the construction industry (Zhan et al, 2023).

Plate 3. Crushing Plant Used to Produce RCA for Concrete Pavement (Source: Cavalline et al., 2022)

4 CONCLUSION

The study has determined that effective compaction is the basis of the structural integrity and viable service life of the pavement structures. Pavement systems now constitute of subgrade, sub- base, base, and surface and people effectively depend on compactness to get the anticipated strength, stiffness, and moisture resistance. Due to better compaction, which prevents pavement deformation, water penetration, and thermal effects, as emphasized by Huang (2024), well-compacted pavements become resistant to deformations.

The use of intelligent compaction, GPS-guided rollers, and sustainable materials such as fly ash and RAP has proven to enhance compaction outcomes and reduce construction errors (Yuan et al., 2022;Mahedi et al., 2020). Also, the high compliance with the quality control indicators, such as attainment of 95%-100% of the highest dry density and the low level of air voids, will guarantee pavement strength against like pressure and climatic fluctuation (AASHTO, 2010; Das & Sobhan, 2017).

Ultimately, a combined use of technological advances with real-life experiences of engineering solutions will be a leap to sustainable, long-term, and affordably constructed pavement systems. Application of these recommendations into practice by the industry will increase the infrastructure and infrastructure investment by reducing premature pavement failures greatly.

5 RECOMMENDATIONS

To improve pavement durability and achieve better compaction results, implementing both recent construction approaches and environmentally friendly practices is essential

5.1 Adoption of Advanced Compaction Technologies

Modern compaction technologies should be implemented and therefore, a modern technology like Intelligent Compaction (IC) should be embraced. Real-time feedback about stiffness and density of the soil is seen on the IC systems and it allows engineering firms to adjust compaction parameters in real-time and correctly. The case study of the Shanghai port showed that the combination of GPS-operated systems and IC lowered 15% the variability in compaction and several hundreds of thousands of maintenance costs (Yuan et al. 2022). The introduction of such instruments as accelerometer-installed rollers and machine-learning-enhanced systems further streamlines the process of compaction, making it smooth in all layers of pavement (Chang et al., 2014; Wang et al., 2024).

5.2 Utilization of Sustainable Stabilizing Materials

Materials that are eco-friendly like fly ash, lime, cement-treated base (CTB), and recycled asphalt pavement (RAP) have the potential of increasing subgrade strength and reducing environmental degradation to a considerable level. Taha and Al-Khafaji (2010) reported that these materials minimize the shrinkages and swellings, especially in clayey soils. They enhance long-term stability and bonding of soil and reduce the amount of greenhouse gases emitted by the conventional construction technology.

5.3 Consistent Quality Control Practices

To facilitate maximum pavements life, it is imperative to ensure that the quality of compaction remains consistent among the project locations. Field testing methods like the Sand Cone Method, Nuclear Gauge Method, and Core Sampling, alongside laboratory procedures such as the Standardand Modified Proctor Tests, help verify compliance with compaction specifications (Das & Sobhan, 2017; AASHTO, 2010). The compacted soils must occupy 95-100% of the maximum dry density and less than 5% air voids and must be of low permeability with high shear strength.

5.4 Addressing Field Challenges Proactively

Construction projects must anticipate and mitigate factors such as seasonal moisture variations and under-compaction risks. Compaction plans should be site specific by taking into account soil tests, particularly including moisture content and type. Budhu (2010) and Coduto *et al. (2011)* highlighted that either over-compaction or under-compaction may result into material breakdown or instability, which needs to be addressed using the customized remedy of soil stabilization with either lime or cement.

5.5 Training and Capacity Building for Site Teams

In order to apply improved compaction technologies, engineers and contractors should be well experienced in new technologies and the functioning of the equipment. The training should include GPS and IC, roller settings, test procedures and field monitoring protocols. This will enable teams to achieve the best results in terms of compaction that can be in accordance with the design intention and updated standards (Lee et al., 2022).

5.6 Policy Support and Industry Adoption

Government agencies and construction regulatory bodies should promote the adoption of intelligent compaction and sustainable materials through incentives, updated specifications, and demonstration projects. By bringing the local practices to the international level of best practices that are comparable to the AASHTO standards and other globally accepted set of quality practices, calibration of local practice standard with international benchmarks will lead to more institutionalization of the quality-oriented culture of construction and lower cost of infrastructures on a long-term basis.

Acknowledgement

This research was not funded by any grant.

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