Jestr

Journal of Engineering Science and Technology Review 17 (5) (2024) 110-116

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Optimizing Soil Compaction Under Real-World Conditions and the Impact of Soil Moisture on Rammer Performance

Yuri Villa[1,*], Carlos Bravo[2], Mariella Carbajal[2,3,4], Sonia Caballero[5] and Lucio Villa[6]

[1]*Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC, United States of America.*
[2]*Departamento de Ingeniería Agrícola, Universidad Nacional Agraria La Molina, Lima, Perú.*
[3]*Electrical and Computer Engineering, North Carolina State University, Raleigh, NC, United States of America.*
[4]*NC Plant Sciences Initiative, North Carolina State University, Raleigh, NC, United States of America.*
[5]*Department of Postgraduate and Continuing Education, National Technical University (UTN-FRRo), Rosario, Argentina.*
[6]*Departamento de Ingeniería Ambiental, Universidad Nacional Agraria La Molina, Lima, Perú.*

Received 23 June 2022; Accepted 14 July 2024

Abstract

Compaction is a critical activity in construction projects, especially for facilities and underground utility projects, where commonly rammers are configured with appropriate tamping widths. Achieving an effective compaction rate according to project specifications sometimes requires a significant amount of energy and resources, and for that reason, it is necessary to optimize the soil moisture and minimize the number of passes. One effective strategy is to follow the Modified Proctor Test (MPT) guidelines, which determine the optimal moisture content (OMC) and maximum dry density (MDD). This study proposed a compaction method to optimize soil compaction under real-world conditions using various rammer models—Masalta MR68H, Wacker Neuson BS60-2i, Weber SRV660, and Atlas Copco LT6005— and each of them can be tailored to specific project requirements. The optimal soil moisture content determined by the MPT was used as a reference, and it was managed during compaction. Each rammer was operated for seven passes in a trench, with soil moisture of the refill material measured before and after the compaction, also the dry density was measured with the use of a density gauge. Other variables were also measured, such as the time spent per pass and total fuel consumption. Afterward, based on the actual soil moisture levels encountered during field operations, loyalty curves (LC) were developed to evaluate the rammers efficiency. Each rammer performed good results, for example, the Atlas Copco LT6005 achieved high compaction levels across varying moisture conditions in diverse soil conditions. The Masalta rammer MR68H had a faster operational speed, and Weber SRV660 achieved a positive compaction curve. As for the Wacker Neuson BS60-2i machine, it coped with high moisture levels, which is why the performance decreased. All rammers accomplished at least 85% compaction on the second pass, and one Atlas Copco LT6005 and Weber SRV660 reached 90% after the fifth pass, and the other Atlas Copco LT6005 up to 95%. The rammers demonstrated their potential to accomplish compaction tasks. These survey data present the basic information necessary to select suitable compaction equipment and adopt the compaction procedures customized to the specific requirements of the project in order to bring about the most efficient compaction outcomes. The test confirmed the complexity of managing ideal OMC in the soil in real operations; however, the strategy effectively oriented the compaction technique optimizing the process.

Keywords: Tamper; Construction efficiency; dry density; Proctor curve.

1. Introduction

The installation of pipelines in facilities such as gas, electricity, and communication networks needs the compaction of soil layers in trenches. These tasks often require rammers with petrol engines, configured with tamping widths ranging from 9 to 12 in. Such as other construction activities, the efficiency and resource utilization can be significantly enhanced by adopting advanced methods and technologies [1]. To optimize the compaction, it is crucial to manage soil moisture and tailor rammer specifications to meet the project's compaction level requirements [2].

Additionally, it is necessary to care about the quality of refill materials and the application of appropriate compaction methods to ensure the durability and longevity of the constructed structures [3]. The fundamental components to determine the compaction quality process are the MPT, the OMC, and MDD for soil compaction. The MPT is used to ensure the soil compaction levels, to support loads and to maintain structure stability under various conditions [4]. Also, the compaction standard accomplishment is essential for pavement stability, safety, and cost efficiency. Adequate compaction ensures structural integrity and reduces maintenance costs [5]. Otherwise, poor compaction can produce sinkholes, and mechanical damage of soil foundations, increasing the repair cost, and reducing longevity of structures like pavements [6].

Lastly, soil integrity and stability can be monitored through various approaches, including a Ground Penetrating Radar (GPR) to assess pavement conditions, detect internal damages, and facilitate preventive maintenance of concrete and asphalt roads [6].

The required compaction level for a project is determined by the type of construction and the local regulatory standards detailed by project owners. For example, for structures in cities, a minimum compaction level of 100% of the MPT density is required for high-traffic roads. In contrast, structures in parks and low-traffic areas typically need about

*E-mail address: yvilla.jd@gmail.com

doi:10.25103/jestr.175.15

90% compaction, which is sufficient to maintain stability and compaction levels over the required will produce additional costs and efforts associated, because a higher compaction rate represents higher investment and resources.

These projects usually have short-term deadlines, requiring a large fleet of rammers operating simultaneously with teams working for about five effective hours daily. Sometimes, these operations have low-quality control over the refill material, underestimating the environmental conditions and the strict moisture control in all stages [7]. Those failures will reduce the compaction efficiency and increase project costs. The MPT plays an important role in these contexts by providing a standard against which the compaction process can be measured, ensuring that soil moisture levels are optimized for maximum density and structural stability [8]. Also, innovative approaches using neural networks can help to predict the OMC and MDD through parameters like granulometry, plastic limit and liquid limit [9].

Despite its importance, in general there is minimal development of compaction techniques or optimization focused on soil moisture management and the real performance of compactors, as well as the establishment of compaction protocols for rammers that target the compaction ratio required by project specifications.

Additionally, companies usually consider mainly the acquisition cost, with insufficient evaluation of the availability and reliability related to aftermarket services, and the technical training on optimal equipment usage and compaction techniques. As a result, many operations suffer from prolonged work times, soil saturation, and over compaction, leading to degraded soil structure, accelerated wear and tear on equipment, potential health risks for operators, and increased project costs.

The primary goal of this study was to propose a compaction strategy using rammers which can also be implemented on all compaction machines. This strategy was based on the technical equipment specifications and the physical properties of refill soil, aiming to increase productivity and minimize losses before intensive phases of construction projects. The specific objectives were: i) to evaluate the impact of soil moisture content on compaction efficiency; ii) to develop loyalty curves (LC) specific to a soil type and different rammers, working with seven passes; iii) to determine the parameters that maximize compaction rate with the minimum number of passes; and iv) to compare the performance of four rammer brands under real work conditions. Equivalent rammers (in terms of power and weight) from brands Masalta, Weber, Wacker, and Atlas Copco were evaluated and compared. The Modified Proctor curve for the soil (ASTM D-1557) was obtained to determine the optimal dry density and moisture content. Compaction levels were then measured using a nuclear density gauge in parallel trenches. Based on the actual soil moisture levels encountered during field operations, LC were developed to assess the performance of the rammers.

2. Materials and Methods

2.1 Modified Proctor Test

The civil engineer Ralph Roscoe Proctor was the inventor of the 'Proctor test' and the associated theory of compaction published in 1933, and his research focused on the relation between soil moisture, the specific dry weight, and the energy applied for the compaction mechanism (equipment). It was standardized to obtain the Proctor curve, employing specific energy applied to a soil sample. Afterward, the US Army Corps of Engineers proposed the MPT, which applies approximately four and a half times the energy of the standard Proctor method. The energy consumption was 0.75 kWh/m^3 and 0.16 kWh/m^3, respectively, during the compaction [10].

Proctor identified four variables that affect the compaction of cohesive soil: dry unit weight, moisture content, soil type, and compaction energy. Equation 1 can be applied to both the Standard Proctor and MPTs, with the compaction energy expressed as follows [11]:

$$E_c(kg/m^3) = ((N * n * W * h))/V \quad (1)$$

Where E_c is the compaction energy in kg/m^3, N is the number of blows per layer, n is the number of soil layers, W is the rammer weight, h is the rammer impact height, and V is the volume of compacted soil.

The Proctor curve is built for the dry unit weight (or density) as a function of the water content, these data are collected in the laboratory. The Proctor curve represents the maximum compaction rates achievable across a range of soil moisture contents, being the focus on the maximum OMC.

2.2 Nuclear Density Gauge

The nuclear density gauge, or nuclear densitometry, is a fast and accurate *in-situ* radiation-based sensor widely used in civil construction to determine soil density and moisture [12]. This device determines soil density by emitting gamma rays into the soil and calculating the rate of returning particles to the sensor. Thus, the number of reflected rays is inversely proportional to soil porosity [12], with dense soils absorbing more radiation than non-compacted soils.

2.3 Proposed Compaction Protocol Using Loyalty Curve

Each soil type with specific moisture has a unique behavior, differing in MDD. Consequently, it is reasonable to consider that each soil requires its own control curve, representing the relationship between moisture content and MDD as determined by the MPT. Therefore, a compaction testing phase is fully justified, using the OMC obtained from the Proctor test to optimize the compaction or density, in addition to establishing the most suitable compaction strategy according to ASTM D-1557 [13].

The proposed compaction protocol (Table 1) shows the construction of a LC specific to each rammer working with a particular soil type and moisture. The LC shows the MDD as the number of passes increases, tailored to each rammer's energy output. The MDD is achieved at the optimal moisture content, as determined by both the Standard and MPT [14], enhancing stability and performance. Thus, this curve serves as a decision-making tool to improve compaction efficiency for various project requirements [15] and allows the development of a compaction strategy.

2.4 Rammers and Operators

The rammers selected for the compaction test –Atlas Copco model LT6005, Wacker Neuson model BS60-2i, Masalta MR68H, and Weber model SRV660 – were chosen based on their similar technical specifications: similar petrol engine sizes, weight, handheld operation, and with 11-inch shoes (Table 1, Fig. 2A) [16]. Five rammers were used, one model from each brand, and an additional Atlas Copco rammer was included to deal with the effect of soil inhomogeneity and soil density variations due to moisture changes under real work conditions [17]. These brands have ergonomic features and adhere to noise standards, with similar performance and emissions using petrol as fuel. The rammers had preventive maintenance (oil changes, filter replacements, and calibration adjustments [18]), and surface testing to ensure optimal performance during the compaction test.

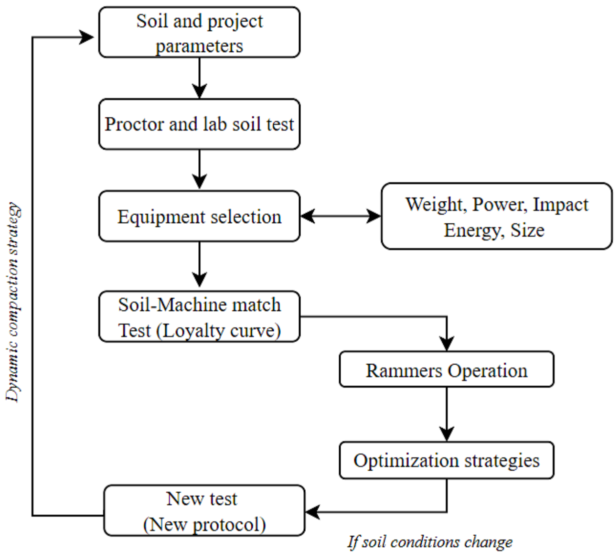

Fig. 1. Schematic of the proposed protocol for performing compaction tests to construct a loyalty curve specific to each rammer.

Table 1. Rammers specifications

Rammer	Displacement(cm^3)	Tank(l)	Weight(kg)	Noise(dB)
Atlas Copco LT6005	121	3	69	103-106
Wacker BS 60 2i	80	3	67	106-108
Masalta MR68H	98	2.8	70	105-107
Webert SRV660	121	3	77	106

Three trained operators, each with over four years of experience working with rammers on various projects in Peru, were hired to perform the test, and to reduce variability and minimize bias; the operators were rotated after completing passes in each layer on each trench.

2.5 Work Site

The compaction tests were conducted at the National Agrarian University, Lima - Peru. Four trenches were excavated with 0.5 m width, 0.6 m depth, and 4 m length. Afterward, 30 cm layers were added to each compaction lane for the test, following the AASHTO compaction standards (Fig. 2B). The work site was selected for its similarity to Lima districts and ease of manual excavation, and trenches were built using handheld tools to avoid pre-compaction bias from the skid steer. Then, random trenches were assigned to each rammer and operator.

2.6 Soil Laboratory Tests

The field soil tests and full laboratory analyses of refill soil were conducted by Labyconst EIRL. The MPT, conducted in the soil mechanics lab, focused on the critical parameters of optimal soil moisture and maximum density and dry density. For this goal, a soil sample was used for a granulometry test and group index calculation to categorize the material according to the AASHTO classification.

2.7 Compaction test

The compaction test began at 7:30 a.m. and continued for 5.8 hours throughout the day during spring, with temperatures ranging from 16°C to 21°C and corresponding changes in relative humidity. Equipment specifications were compared under similar work parameters, also its performance including compaction speed, fuel consumption, and compaction levels, was analyzed to develop a strategy for maximum performance. The methodology aimed to achieve the highest compaction level in the shortest time and most cost-effective manner by approximating the soil moisture to within ±1.5% of the optimal level [19].

The compaction test began by homogenizing the refill material (the same as the excavated soil) by mixing it with the skid steer bucket 12 times. The soil moisture content was measured and compared to the OMC determined by the MPT (Fig. 2C). As moisture compensation, water was then added to achieve the OMC level as a repetitive routine for each soil layer, and the soil was mixed again with the skid steer bucket. The trench was backfilled with a 30 cm lift of soil, which was then compacted using a rammer. Soil density and moisture content were measured using a nuclear density gauge (Fig. 2D), in accordance with ASTM D6938. This procedure was performed seven times (passes) consecutively for each rammer, and they were tested in a random order, to ensure consistency. All tests were conducted with seven passes based on prior evidence indicating that for Clay-Gravel-Sand soils, exceeding 7-10 passes can result in over compaction [5], which compromises soil structure integrity. This compaction is identified by an inflection point on the compaction curve, where the trend shifts, indicating a transition from effective compaction to detrimental consolidation. The soil moisture content and density measurements were also conducted by Labyconst EIRL, using a nuclear densometer.

Fig. 2. Work site compaction activities: A) Rammer's set-up, B) Trench excavation process, C) Initial test with nuclear densometer, and D) Measuring soil density and moisture with the nuclear densometer.

The total time, the time per pass, and cumulative time were evaluated and compared across the machines. Also, for the evaluation of fuel consumption, each machine was filled to maximum capacity with petrol according to specifications, and the results were recorded for each rammer, with a single measurement set of data. Specifically, after seven passes, fuel consumption was measured by fully draining the fuel tanks and calculating the residual petrol volume; the difference indicated the total fuel consumption for the test.

Complementary, the salient points of each rammer's geometry were measured to determine how closely they could operate to the trench wall during compaction. This assessment was usable for evaluating their maneuverability in confined and narrow trenches, and the design as trenching rammers.

3. Results and Discussion

3.1 Soil Laboratory tests

The soil texture analysis of the refill material identified it as clay gravel with sand, with a plasticity index of 10, classified as A-2-4 (0) according to the AASHTO classification system. For this soil, the MPT curve was constructed using four moisture-dry density measurements: [3.7%, 2.169 g/cc], [5.7%, 2.207 g/cc], [7.8%, 2.246 g/cc], and [9.6%, 2.158 g/cc], and the Equation 2.

$$Y = -0.0029X^3 + 0.05X^2 - 0.2551X + 2.5759, \quad R^2 = 1 \qquad (2)$$

Where X is the moisture content, and Y is the dry density. This fitted curve determined a MDD of 2.246 g/cc at an OMC of 7.61%.

3.2 Compaction Test

The loyalty curves, constructed using the MPT results as a reference, illustrate the maximum compaction rates with their averaged soil moisture over seven passes per rammer (Fig. 3). The results show that the Atlas Copco "B" rammer achieved the highest dry density of 2.167 kg/cc, corresponding to 96% of compaction, among the other rammers and across the seven passes; however, the water content level effect cannot be ignored according to the soil type [20].

The Masalta rammer worked under moistures between 4.4 and 5.9%, the Wacker rammer between 12.2 and 13.9%, the Weber rammer between 6.9 and 9.7%, the Atlas Copco "A" between 10.2 and 11%, and the Atlas Copco "B" between 2.8 and 4.6%, obtaining maximum dry densities of 2.071, 2.026, 2.089, 2.105, 2.167 kg/cc, and compactions of 91, 90, 93, 93, and 96%, respectively (Fig. 3).

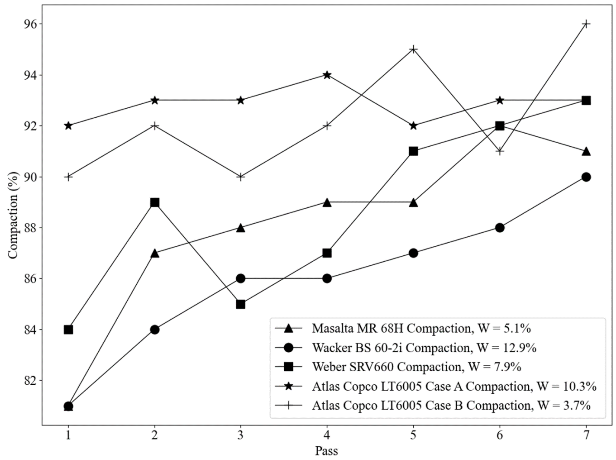

Fig. 3. Loyalty curves depicting the compaction percentages achieved over seven passes for different rammers, W is the average moisture in %

All rammers – with different compaction energy – showed a positive compaction trend as the number of passes increased with different slopes, consistent with their respective soil moisture levels and the OMC, because there is a correlation between the MDD and OMC [4]. The Masalta rammer achieved relatively low overall compaction due to the fact that it was working in a drier region, also demonstrating the most rapid increase in dry density with each pass. This performance is likely due to its lower-powered GX100 engine, and lower weight, combined with its higher operational speed which could be inferred that it was due to lower impact energy. The Wacker rammer achieved a lower compaction rate and exhibited the slowest loyalty curve evolution, likely due to operating at a moisture level outside the Proctor test range in the saturated region, which can be considered the less accurate results. The Weber rammer achieved one of the highest dry densities, but it fell short of expectations despite operating near the optimal soil moisture content of 7.6%. The behavior of their curves suggests that additional passes may further enhance the compaction rate for the Masalta, Wacker, and Weber rammers. In contrast, the Atlas Copco rammers "A" and "B", which operated under contrasting moisture conditions, performed higher compaction in seven passes, demonstrating strong performance from the first pass. Interestingly, the Atlas Copco rammer operating under lower moisture conditions performed better. The amplitude, spring's impact force capacity, and total weight given by each rammer had a direct influence on the compaction level [21].

Despite efforts to maintain soil moisture near the optimal level during the compaction test, the recorded moisture levels varied. This variability may be attributed to changes in air temperature throughout the day, spatial variability of soil moisture, and operational variability, which can be controlled in a laboratory test condition with the consequent homogeneity in results [22]. However, the contribution of the current study was due to the realistic work replication during compaction activity in any project to develop a compaction strategy according to the kind of soil and the kind of compactor.

Fig. 4 illustrates the compaction-moisture relationship for various rammers, with compaction percentage and dry density on the y-axis, and moisture content percentage on the x-axis. Different symbols represent the rammers, showing their performance relative to the Proctor Curve, which indicates the OMC for MDD [5]. The data points cluster around the Proctor Curve, indicating significant compaction within this moisture range. Results of the drier region (left side of the Proctor curve) show higher compaction percentages compared to the wetter region (right side of the Proctor curve), where compaction efficiency decreases due to excess moisture. Notably, the Atlas Copco "B" rammer achieved higher compaction than "A", demonstrating superior performance at lower moisture contents. However, the compaction evolution curves for the Atlas Copco rammers "A" and "B" exhibited a lower positive slope compared to other rammers from passes 1 to 7 (Fig. 3). This limitation was attributed to the out-of-range moisture levels required to achieve maximum compaction. This correlation was demonstrated by Gurtun [23], who explained the constrained compaction efficiency under certain moisture conditions. Furthermore, [24] Roknuzzaman's findings indicate that increased impact energy leads to a higher compaction rate.

Only two rammers operated within the optimal moisture range: the Weber SRV660 functioned near the OMC, while the Masalta MR68H worked in a drier region. In contrast, the Atlas Copco LT6005 "A" worked in soil with high moisture, and the Wacker BS60-2i operated in a saturated region (Fig. 4), dealing with the poor progress of compaction as a result of the reduced void spaces which became filled with water. A similar phenomenon, the effect of excess soil moisture on the undrained shear strength of compacted clayey soil was found by Ghosh [25].

Moreover, when the first and second soil layers were in the compaction process, it was noted that the presence of superficial water in the first layers adversely affected the performance and compaction level of subsequent soil layers. The result was impacted due to various factors such as environmental conditions, moisture content, operator skills, and mechanical performance. Among these, the moisture content is the most critical parameter in the refill material, as even a one percent deviation will affect compaction performance especially when excess moisture.

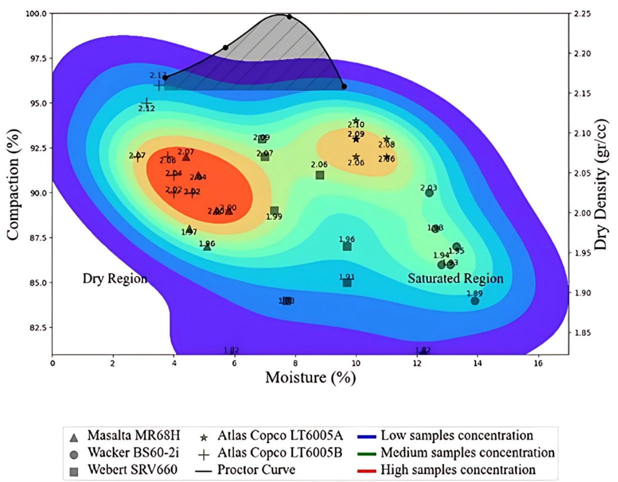

Fig. 4. Compaction rates and dry density for different rammers plotted against moisture content. The Proctor curve indicates the OMC for MDD, and the colors plot shows the sample concentrations in the test and the moisture compensation efficacy.

The loss of control of the soil moisture undoubtedly impacts negatively the machine's durability, the operator's exposure to higher noise and vibration levels, and the project's profitability. In addition to the other variables such as the compaction method, the number and thickness of soil layers, the number of passes, dry unit weight, soil type, and compaction energy play crucial roles in the compaction process.

For that reason, these factors should be carefully managed to avoid over compaction, which can negatively impact the workers' health and cause damage to both the soil structure and the compactor itself [26]. Furthermore, improper compaction can compromise the integrity of pipelines, for example in the deformation of buried large-diameter steel pipes during staged construction and compaction [27].

Another finding was related to compaction time, rammers with higher weights, such as the Weber, recorded longer total times, probably because of the reduced energy recovery due to the soil's high-impact energy absorption (loose soil). The total time was significantly affected by its performance on the initial lane pass, introducing a potential bias. In comparison, the Masalta rammer with the lightest weight due to its smaller engine, reported the shortest total compaction time decreasing steadily from 23.36 seconds on the first pass to 16.16 seconds on the last pass. The Atlas Copco LT6005 maintained consistent compaction times, ranging from 30.0 seconds on the first pass to 12.6 seconds on the last pass, despite the initial pass being the longest recorded. The Wacker rammer showed a gradual decrease in time, from 33.43 seconds on the first pass to 17.46 seconds on the last one, demonstrating good uniformity. In summary, the Masalta rammer operated for a total of 103.2 seconds, the Atlas Copco for 116.9 seconds, the Wacker for 147.2 seconds, and the Weber for 173.4 seconds (Fig. 5).

Typically, all brands encountered high soil resistance during the initial lane passes due to the uncompacted material, resulting in slower compaction speeds. As compaction progressed, speeds increased, indicating that the material initially absorbed more impact energy, leading to lower idle energy and delaying compaction progress [27]. Furthermore, when working with very soft, uncompacted material, the machines had to be stopped and manually repositioned to continue compaction in the trenches.

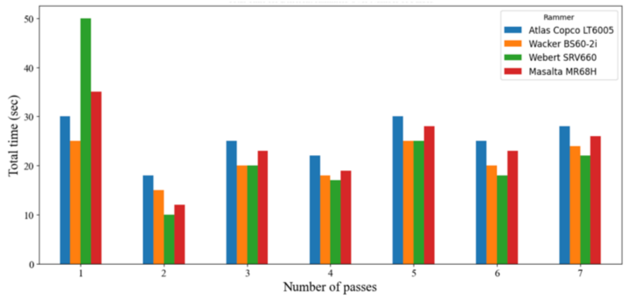

Fig. 5. Time result for each pass, per rammer

The Masalta rammer reported lower fuel consumption, attributable to its smaller displacement engine, the Honda GX100, which has a displacement of 98.5 cm³ [28]. This lower fuel consumption contrasts with other brands using engines equivalent to the Honda GX120 (Table 2). All rammers were 70 kg category, the Wacker model BS60-2i reported the lowest fuel consumption, likely due to its use of a petrol-oil mixture which enhances efficiency. In contrast, the Weber model SRV660, equipped with a Honda GXR120 engine and a displacement of 121 cm³ [29], showed higher fuel consumption. During compaction it was observed that the presence of superficial water created intermittencies by moisture excess, and additional energy demands during initial compaction lane passes could increase the fuel consumption. The Atlas Copco rammer, with a similar engine model, reported lower fuel consumption than the Weber rammer, likely due to lower energy requirements for initial compaction, as indicated by the recorded total operation time (Table 2).

Table 2. Rammers fuel consumption

Rammer	Fuel Consumption Brochure	Tank (l)	Measurement (l)	Fuel Consumption (l)
Atlas Copco LT6005	0.8 Lt/h	3	1.85	1.15
Wacker BS 60 2i	1.2 Lt/h	3	2.075	0.93
Masalta MR68H	0.88 Lt/h	2.8	2.5	0.8
Weber SRV660	No data	3	1.7	1.3

The compactor's behavior in trenches was evaluated by measuring the rammers lateral profile salient points and their proximity to the trench wall during compaction confirming the design as trenching rammers. The rammers Atlas Copco and Wacker achieved a minimal clearance of 3 cm and 4 cm respectively from the trench wall, followed by the Wacker rammer.

In field operation, the shorter distances allow for an effective compaction near the trench wall, enhancing soil consolidation and increasing the durability of the compacted structure. In contrast, rammers like Weber and Masalta, which had greater distances from the trench wall, showed less efficacy of the compaction in these areas.

Larger rammer profile salients can impact negatively soil consolidation in trenches and potentially compromise structural integrity over time (Fig. 6). For confined applications, such as facility projects, the Atlas Copco and Wacker rammers with minimal clearance not only improve compaction uniformity but also contribute to better soil stability and project longevity.

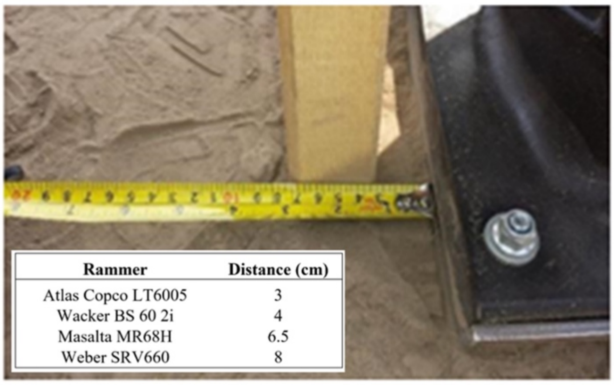

Fig. 6. Measurement of lateral distance per rammer

4. Conclusions

This study proposed a compaction protocol to achieve the MDD with the minimum number of passes while ensuring maximum uniformity. It underscored the critical importance of monitoring soil moisture and compaction progress, tailored to the technical specifications of various rammer brands – particularly their impact energy – and the physical properties of the soil as determined by the MPT.

However, in this test, in seven passes the MDD was not achieved due to various environmental factors and real-work conditions. Despite these challenges, the protocol optimizes compaction efficiency, reduces operational costs, and serves as a valuable reference for future projects, to achieve the desired dry densities based on project requirements.

The current study does not offer definitive conclusions about the differences in compaction rates among brands, nor does identify a single brand or product as the superior performer. Each rammer can meet the compaction level, under certain circumstances and technical compaction requirements at different soil moisture levels, and the test provides valuable insights into their potential benefits for diverse project scenarios.

Under the conditions of this study, the Atlas Copco LT6005 demonstrated high compaction performance, consistently achieving high compaction levels regardless of soil moisture content, and the Masalta MR68H reported faster compaction speed with a lower compaction rate, making it suitable for time-sensitive tasks, and the Weber SRV660 performed progressive soil compaction due to its proximity to OMC.

The Wacker BS 60-2i demonstrated robust potential compaction capacity; however, it operated in saturated soil conditions, which affected its performance. Compacting is the reduction of void spaces in the soil, and in this case, during the compaction process of this saturated soil, the void spaces were reduced and gradually filled with water, forming a mass that could no longer be compacted unless the moisture content was reduced. Consequently, the MDD could not be achieved under these saturated soil conditions. Furthermore, more passes would only cause damage to the operator, machines, and soil, leading to economic losses.

In summary, in this test all rammers achieved at least 85% compaction by the second pass, with the Atlas Copco LT6005 and Weber SRV660 exceeding 90% compaction by the second pass, and only the Atlas Copco LT6005 reached 95% compaction after the fifth pass.

The development of loyalty curves facilitates informed decision-making tailored to project-specific technical requirements, optimizing costs, time, fuel consumption, and compaction efficiency. This approach enhances operational effectiveness, minimizes the risk of over compaction, subsidence, sinkholes, soil consolidation, and fracturing, and significantly improves project outcomes under real-world field conditions. Nevertheless, further research is necessary, including new rammers, a larger sample size for each brand, and multiple repetitions of compaction tests to effectively address moisture variability and improve data consistency.

References

[1] Y. Yao and E. Song, "Intelligent compaction methods and quality control," *Smart Constr. Sustain. Cities*, vol. 1, no. 2, pp. 1–12, Aug. 2023, doi: 10.1007/s44268-023-00004-4.

[2] Y. Ma, W. Lu, Y.-C. Luan, T. Ma, and C.-L. Wang, "Research on global optimization mechanism of intelligent compaction parameters of soil subgrade based on difference method," *J. Build. Engin.*, vol. 82, pp. 2352–7102, Apr. 2024, doi: 10.1016/j.jobe.2023.108381.

[3] L. Zhao, L. Cheng, C. Zhou, L. Ding, and F. Wang, "3D conditional random fields simulation for rockfill compaction quality assessment with sparse EVD measurement," *J. Rock Mechan. Engin.*, pp. 1–10, Mar. 2023, doi: 10.1016/j.rineng.2023.101710.

[4] G. Spagnoli and S. Shimobe, "An overview on the compaction characteristics of soils by laboratory tests," *Engineering Geology*, vol. 278, p. 105830, Dec. 2020, doi: 10.1016/j.enggeo.2020.105830.

[5] F. Tatsuoka and A. Gomes Correia, "Importance of controlling the degree of saturation in soil compaction linked to soil structure design," *Transport. Geotechn.*, vol. 17, pp. 3–23, Dec. 2018, doi: 10.1016/j.trgeo.2018.06.004.

[6] M. Rasol *et al.*, "GPR monitoring for road transport infrastructure: A systematic review and machine learning insights," *Construct. Build. Mater.*, vol. 324, Art. no. 126686, Mar. 2022, doi: 10.1016/j.conbuildmat.2022.126686.

[7] T. Allsop, "Early compaction history of marine siliciclastic sediments.," Thesis (Doctoral), Durham University, Durham, 1994. [Online]. Available: http://etheses.dur.ac.uk/5675/

[8] J. Liu, J. Yuan, H. Xiong, and W. Chen, "Dynamic compaction treatment technology research of red clay soil embankment in southern mountains," *J. Cent. South Univ. Technol.*, vol. 15, no. S2, pp. 50–57, Dec. 2008, doi: 10.1007/s11771-008-0435-7.

[9] K. Othman and H. Abdelwahab, "Prediction of the soil compaction parameters using deep neural networks," *Transport. Infrastruct. Geotechnol.*, vol. 10, pp. 147–164, Nov. 2023, doi: 10.1007/s40515-021-00213-3.

[10] A. G. Mahardika, E. S. Mulya, A. W. Biantoro, D. Setiawan, Ariostar, and and G. D. R. B. Nuryono, "Analysis of soil compaction using Proctor standards in highway construction design," *J Phys Conf Ser*, vol. 1933, no. 1, Aug. 2020, doi: 10.1088/1742-6596/1933/1/012084.

[11] J. Connelly *et al.*, "Nebraska Department of Transportation research reports," *Nebraska Department of Transportation*, p. 31, 2008, Accessed: May 20, 2024. [Online]. Available: http://digitalcommons.unl.edu/ndor/31

[12] L. M. P. Blanco, "Compaction quality control on site of earthworks - A comparative study," Master's Thesis, Universidade Nova de

Lisboa, Lisboa, 2015. [Online]. Available: https://run.unl.pt/bitstream/10362/16025/1/Blanco_2015.pdf

[13] E. Karakan and S. Demir, "Effect of fines content and plasticity on undrained shear strength of quartz-clay mixtures," *Arabian J. Geosci.*, vol. 11, no. 23, pp. 1–12, Dec. 2018, doi: 10.1007/s12517-018-4114-1.

[14] H. S. Shaivan and A. Sridharan, "Comparison of reduced modified Proctor vs modified Proctor," *Geotechn. Geolog. Eng.,* vol. 38, Nov. 2020, doi: 10.1007/s10706-020-01405-3.

[15] G. E. P. Paez, "Comparison Study Between Field Compaction Control Devices of Unbound Materials," 2018, *Unpublished*. doi: 10.13140/RG.2.2.12699.98084.

[16] Construction Tools GmbH, "Pisón LT para pequeños trabajos de compactación," *Atlas Copco*, 2014, Accessed: May 19, 2024. [Online]. Available: https://munercompresores.com.mx/wp-content/uploads/2016/11/apisnador-atlas-copco-ficha-t%C3%A9cnica.pdf

[17] K. Zhang and C. N. Frederick, "Experimental investigation on compaction and Atterberg limits characteristics of soils: Aspects of clay content using artificial mixtures," *KSCE J. Civ. Eng.*, vol. 21, no. 2, pp. 546–553, Feb. 2017, doi: 10.1007/s12205-017-1580-z.

[18] W. Neuson, "Wacker Neuson BS60-2i compactor rammer - repair manual," 2011, Accessed: May 20, 2024. [Online]. Available: www.wackerneuson.com.

[19] G. McNally, *Soil and Rock Construction Materials*, 1rst ed. CRC Press, 2017. doi: 10.4324/9780203476574.

[20] W. Hu, X. Jia, X. Zhu, A. Su, Y. Du, and B. Huang, "Influence of moisture content on intelligent soil compaction," *Autom Constr*, vol. 113, May 2020, doi: 10.1016/j.autcon.2020.103141.

[21] T. Xu *et al.*, "Real-time monitoring method for layered compaction quality of loess subgrade based on hydraulic compactor reinforcement," *Sensors*, vol. 20, no. 15, Art. no. 4288, Jul. 2020, doi: 10.3390/S20154288.

[22] A. Lekea, "Evaluation of the electrical density gauge for in-situ moisture and density determination," Master's Thesis, University of Cape Town, Cape Town, 2015. [Online]. Available: https://open.uct.ac.za/items/947babc6-ff6d-464f-a770-b3bd807d6aa9

[23] Y. Gurtug, A. Sridharan, and S. B. İkizler, "Simplified method to predict compaction curves and characteristics of soils," *Iranian J. Sci. Techn. – Transact. Civ. Engin.*, vol. 42, no. 3, pp. 207–216, Sep. 2018, doi: 10.1007/s40996-018-0098-z.

[24] M. Roknuzzaman, M. I. Mostazid, M. A. Asef, and A. R. Rakin, "Performance of locally made compaction rammer for compacting granular backfill soil," *J. Sci. Techn.*, vol. 21, no. 1, pp. 41–50, Jul. 2023, doi: 10.59125/JST.21105.

[25] R. Ghosh, "Effect of soil moisture in the analysis of undrained shear strength of compacted clayey soil," *J. Civ. Eng. Constr. Techn.*, vol. 4, no. 1, pp. 23–31, Jan. 2013, doi: 10.5897/JCECT12.070.

[26] R. V. Rinehart and M. A. Mooney, "Instrumentation of a roller compactor to monitor vibration behavior during earthwork compaction," *Autom Constr*, vol. 17, no. 2, pp. 144–150, Jan. 2008, doi: 10.1016/j.autcon.2006.12.006.

[27] A. Emami Saleh, H. Hojat Jalali, A. Pokharel, and A. Abolmaali, "Deformation of buried large diameter steel pipes during staged construction and compaction: case study and finite element analysis," *Transport. Geotech.*, vol. 31, Nov. 2021, doi: 10.1016/j.trgeo.2021.100649.

[28] Honda Motor Co, "Safety information," 2015, *Honda*. Accessed: May 19, 2024. [Online]. Available: https://www.honda-engines-eu.com/files/files/shop-manual-gxr120-en.pdf

[29] Honda, "Horizontal shaft gasoline (petrol) engine," 2020, *Honda*. Accessed: May 19, 2024. [Online]. Available: https://www.honda-engines-eu.com/files/files/owners-manual-gx120-160-200-ut1-english-32z4f605.pdf