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Comparative Analysis of Laboratory Soil Testing Productivity across Five Locations: Insights into Bottlenecks and Optimization Strategies

Osuorah, Arthur C,[1]. J. C. Agunwamba[2]M. Onyia[3], Udechukwu John Abaraogu[4]

[1,2,3]Department of Civil Engineering, University of Nigeria, Nsukka

[4]Department of Civil Engineering, University of Uyo, Nigeria.

ABSTRACT

Timely geotechnical laboratory testing is essential for infrastructure planning and construction. Delays in reporting soil properties often result in extended project timelines, increased costs, and disputes. Understanding the relative efficiency of different soil tests can help laboratories and project managers allocate resources more effectively.This study evaluated the duration and productivity of six common geotechnical tests—Particle Size Distribution (PSD), Atterberg Limits, Specific Gravity, Natural Moisture Content, Compaction Moisture–Density Relationship (M–D), and California Bearing Ratio (CBR)—conducted at five sites: four in the United States (New Orleans, Miami, Maryland, and New York) and one in Southeastern Nigeria.. Geological variations—such as lateritic soils in Southeastern Nigeria, soft organic clays in New Orleans, and glacial deposits in New York—were found to influence laboratory performance and test durations.Laboratory throughput is dictated by the slowest tests rather than the average pace across all tests. To improve efficiency, laboratories should prioritize resource allocation to bottleneck tests, adopt parallelization and batching strategies, and implement staggered scheduling. Site-specific planning and predictive correlations can further reduce turnaround times, thereby enhancing the reliability and timeliness of geotechnical data for infrastructure development.

***KEYWARDS**: Geotechnical Timeline, Time Reduction, Soil Testing.*

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I. Introduction

Soil characterization through laboratory testing forms the cornerstone of geotechnical engineering practice. Accurate determination of soil properties such as grain size distribution, consistency limits, strength, and compaction behavior is essential for the safe and economical design of foundations, pavements, embankments, and other civil engineering structures. Geotechnical engineers rely on a suite of laboratory tests—most notably Particle Size Distribution (PSD), Atterberg Limits, Specific Gravity, Natural Moisture Content, Compaction Moisture–Density Relationship (M–D), and California Bearing Ratio (CBR)—to evaluate the engineering suitability of soils for construction purposes (Li et al., 2020). The timeliness of these tests is critical because results directly influence decision-making in project design and execution phases.

Despite the centrality of these tests, many laboratories worldwide face challenges related to efficiency, turnaround time, and resource allocation. This is particularly true for large-scale infrastructure projects, where numerous soil samples must be tested under strict project deadlines. When testing times are prolonged or uneven across different procedures, delays in the availability of geotechnical reports can ripple into project planning, material procurement, and construction schedules (Daramola & Adeyemi, 2021). In such contexts, identifying and addressing bottlenecks in laboratory processes becomes not only a matter of technical efficiency but also of economic and logistical importance.

Previous research has shown that certain soil tests, especially those involving multiple stages of preparation and precision measurements, tend to consume more time compared to relatively straightforward procedures (Adeleke et al., 2021). For example, compaction tests and Atterberg Limit tests often require repeat trials to ensure accuracy, whereas moisture content and specific gravity tests are simpler and more easily parallelized with other laboratory activities. The uneven distribution of time demands among different tests suggests that laboratory throughput is typically governed by the slowest procedures rather than by the average pace of all tests (Cao & Jang, 2022).

Furthermore, variations in geomorphological and geological settings across different locations can affect soil composition, which in turn may influence the complexity and duration of certain tests. For instance, lateritic soils common in tropical regions often require more elaborate preparation than sandy soils in coastal areas (Onyelowe et al., 2020). This implies that site-specific soil characteristics, coupled with laboratory practices, play a role in determining test productivity.

Against this backdrop, this study presents a comparative analysis of soil test durations across five locations—four in the United States and one in Nigeria. By systematically evaluating test times and productivity, the research identifies critical bottlenecks, highlights site-level variations, and proposes strategies for improving laboratory efficiency in geotechnical engineering practice.

1.1 Problem Statement

While geotechnical standards define testing methodologies, little emphasis is placed on comparative productivity across test types and laboratory contexts. Prolonged laboratory turnaround times can delay project execution, particularly when bottleneck tests consume disproportionate time (Li et al., 2020). This gap necessitates a structured evaluation of soil test durations across locations.

1.2 Study Objectives

The objectives of this study are to:

1. Quantify and compare the time required for standard soil tests across five laboratory sites.
2. Identify productivity bottlenecks that affect throughput.
3. Recommend strategies to optimize laboratory efficiency.

1.3 Location Description, Geomorphological, and Geological Features

This study draws on data from five testing sites distributed across two continents: one in **Southeastern Nigeria** and four in the **United States (New Orleans, Miami–Florida, Maryland, and New York)**. These sites represent varied climatic, geomorphological, and geological contexts, allowing for a comparative analysis of how soil properties may influence laboratory testing behavior.

1.3.1 Southeastern Nigeria

The Nigerian site lies within the **humid tropical belt** of West Africa. The region is characterized by a **bimodal climate**—a long rainy season (April to October) and a dry season (November to March). Annual rainfall averages between 2,000–2,500 mm, which significantly influences soil formation. Geomorphologically, the area consists of **low-lying plains with gentle slopes** drained by networks of seasonal rivers and streams.

Geologically, this region is dominated by **sedimentary formations of the Benue Trough and Niger Delta basin**, with extensive development of **lateritic soils**. Laterites are residual soils rich in **iron and aluminum oxides**, formed through intense weathering. They are typically reddish-brown, clay-rich, and exhibit **high plasticity** and moisture sensitivity. In the laboratory, lateritic soils often complicate **Atterberg Limit** and **compaction tests**, as repeated trials are required to capture consistent values due to heterogeneity and water retention properties (Onyelowe et al., 2020).

1.3.2 New Orleans, Louisiana

New Orleans is situated within the **Mississippi River Delta**, one of the largest fluvial-deltaic systems in the world. The city is largely **low-lying, with significant portions below sea level**, necessitating extensive flood protection systems. Geomorphologically, the area reflects **deltaic deposition processes**, producing **alluvial plains, backswamps, and natural levees**.

The geological profile consists predominantly of **soft, highly compressible clays, silts, and peat layers**, deposited during the Holocene epoch. These soils have high organic matter content and elevated groundwater tables. Such conditions complicate laboratory handling, particularly in **CBR** and **compaction tests**, where specimen stability during preparation is difficult to achieve (Yu et al., 2021).

1.3.3 Miami, Florida

Miami lies on a **coastal limestone platform**, underlain by the **Miami Oolite and Biscayne Aquifer**. The region's geomorphology is dominated by **flat coastal plains**, low-lying **karstic depressions**, and barrier islands. With a subtropical climate and high groundwater table, soil drainage conditions are critical.

The soils are mainly **sands, silty sands, and carbonate-rich sediments**. These are typically cohesionless, free-draining soils, which facilitate **moisture content** and **PSD tests**, as drying and sieving are straightforward. However, their drainage characteristics present challenges in **compaction tests**, since achieving optimum moisture content requires careful water addition and control (Chen et al., 2019).

1.3.4 Maryland

Maryland occupies a transitional zone between the **Piedmont Plateau** and the **Atlantic Coastal Plain**. The Piedmont is characterized by **rolling uplands with residual soils** derived from weathered metamorphic and igneous rocks. In contrast, the Coastal Plain features **unconsolidated sediments**, including sands, silts, and clays deposited by rivers and coastal processes.

The geological variability produces soils ranging from **plastic clays to silty sands**, often within short distances. Such diversity requires multiple laboratory tests for accurate classification. In particular, **Atterberg Limits** can vary significantly between samples, and compaction behavior may be inconsistent, complicating predictive correlations (Wen et al., 2020).

1.3.5 New York

New York's geology and geomorphology are strongly shaped by **Pleistocene glaciation**. The landscape includes **glacial moraines, drumlins, eskers, and outwash plains**, leading to highly variable soil deposits.

Glacial tills dominate upland areas; these are dense, well-graded soils containing a mixture of clays, silts, sands, and gravels. In contrast, low-lying valleys contain **lacustrine silts and clays**, which are compressible and moisture-sensitive. This heterogeneity introduces challenges in **laboratory scheduling**, as sandy tills are quick to test, while cohesive lacustrine clays require repeated trials for Atterberg Limits and extended soaking for CBR tests (Cao & Jang, 2022).

1.3.6 Comparative Implications

A comparative analysis highlights how **regional geomorphology and geology influence soil testing productivity**:

- **Nigeria's lateritic soils** extend compaction and plasticity testing times due to water sensitivity and variability.
- **New Orleans' deltaic clays** increase preparation and curing times, especially in CBR and compaction tests.
- **Miami's sandy-carbonate soils** facilitate quick PSD and moisture tests but complicate achieving consistent compaction curves.
- **Maryland's diverse soils** necessitate broad test coverage, prolonging overall lab schedules.
- **New York's glacial soils** present stark contrasts between rapid sandy till tests and slow cohesive clay tests.

Thus, laboratory managers must recognize that **testing efficiency is site-specific**, shaped not only by laboratory resources but also by underlying soil-forming processes.

II. Materials And Method

2.1 Data Source and Scope

The study utilized data from five laboratory sites, four located in the United States (New Orleans, Miami–Florida, Maryland, and New York) and one in Southeastern Nigeria. At each site, a suite of six standard geotechnical laboratory tests was conducted on representative soil samples. These included:

1. **Particle Size Distribution (PSD)**
2. **Atterberg Limits** (liquid limit, plastic limit, plasticity index)
3. **Specific Gravity of Soil Solids**
4. **Natural Moisture Content**
5. **Compaction Moisture–Density Relationship (M–D)**
6. **California Bearing Ratio (CBR)**

The tests followed the **American Society for Testing and Materials (ASTM)** standards (e.g., ASTM D422 for PSD, ASTM D4318 for Atterberg limits, ASTM D698/D1557 for compaction, ASTM D1883 for CBR) and comparable standards in Nigeria (BS 1377 methods, where ASTM apparatus was unavailable). The principal variable recorded was **time (minutes)** required to complete each test per sample, serving as a proxy for laboratory throughput.

2.2 Time Measurement Procedure

For each test, the **total practical testing time** was measured, excluding sample collection and transportation but including all preparation, conditioning, drying, soaking, and measurement stages. Where tests involved extended waiting periods (e.g., oven-drying for moisture content, 4-day soaking for CBR), these were incorporated into the total time because they affect overall laboratory turnaround. Data were collated into a structured table, giving site-wise durations for each of the six tests.

2.3 Data Analysis Framework

The dataset was analyzed in three stages:

1. **Total Time and Averages:**

The sum of testing durations was calculated per site, followed by average test durations across all five sites.

2. **Productivity Calculation:**

Productivity was defined as the number of samples processed per hour, using the formula:

Ps,t=60Ts,tP_{s,t} = \frac{60}{T_{s,t}}Ps,t=Ts,t60

where Ps,tP_{s,t}Ps,t = productivity (samples/hour), and Ts,tT_{s,t}Ts,t = testing time in minutes for test t at site s.

This metric normalizes performance, enabling comparisons across different test types and sites.

3. **Comparative Evaluation:**

Results were benchmarked across sites and tests to identify **bottleneck procedures** and **efficiency variations**. Graphical analysis (bar charts and tables) was employed to visualize differences in total times and productivity.

2.4 Quality Control Measures

Consistency of test procedures was verified through adherence to laboratory standards at each site. In cases where local variations in apparatus existed (e.g., Nigerian laboratories using BS test methods), equivalent international standards were cross-referenced to ensure comparability. Productivity values were rounded to three decimal places, and averages were computed to highlight central trends.

2.5 Limitations of Method

- The study assumes that reported times represent **single-sample durations**. Actual throughput may differ when batching is employed.
- Extended conditioning steps (e.g., soaking in CBR) were included, though in practice, laboratories may run these concurrently with other tests.
- Personnel skill levels and equipment conditions may also have influenced test duration, but these were not directly measurable.

2.6 Ethical and Practical Considerations

All data were drawn from routine geotechnical testing associated with civil engineering projects. No additional soil disturbance was required beyond standard sampling, and data confidentiality was maintained where project-specific identifiers existed.

III. Results And Discussion

3.1 Total Testing Times

Table 3.1: Time spent for each test on the different construction locations

Laboratory Tests / Location	Particle Size distribution. (min)	Atterberg Limit of soil Mat. (min)	Specific Gravity table of value. (min)	Natural Moisture Content (min)	Compaction Moisture-Density Relationship (min)	California Bearing Ratio. (CBR) (min)	TOTAL PRACTICAL TI (MIN)	AVG. SOIL MATERIAL LAB. TESTING
Site Location in South East Nigeria	673	1356	450	607	1866	870	5822	5822
Site Location in New Orlean	700	1400	435	678	1690	870	5162	
Site Location in Miami Florida	765	1546	500	589	1600	900	5900	(5749)
Site Location in Maryland	673	1350	503	675	1700	950	5851	
Site Location in New York	670	1546	600	675	1690	900	6081	

The table above shows the time taken to obtain Laboratory Analysis results for different Laboratory tests from different Locations (5 Locations: 4 in the USA and 1 in Nigeria).

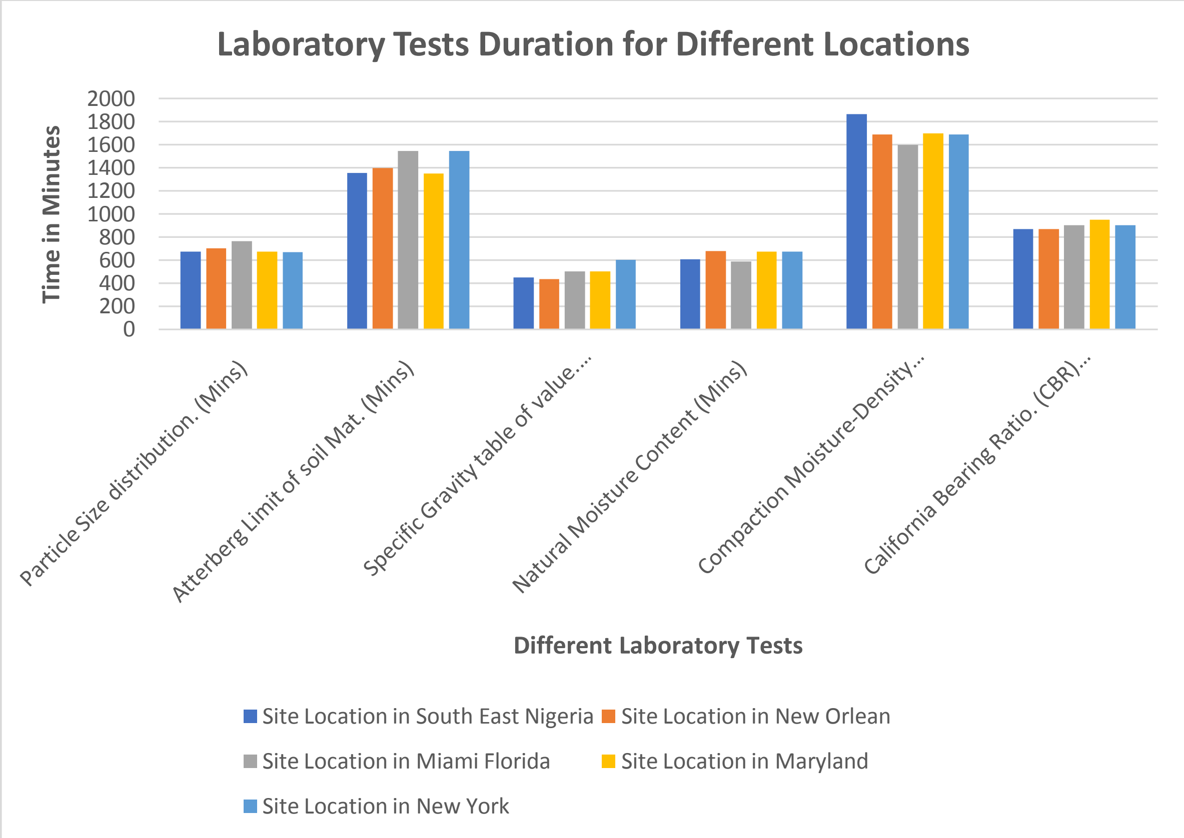

Fig 3.1:Chart showingTime spent for each test on the different construction locations

Across the five sites, average test durations (minutes) were: Particle Size (696), Atterberg (1440), Specific Gravity (498), Natural Moisture (645), Compaction M–D (1709), and CBR (898). The Compaction M–D and Atterberg tests consumed the most time, validating their bottleneck nature.

3.2 DATA ANALYSIS OF RESULT

Time duration formulas used

Let $T_{s,t}$be the time (minute for test t at sit Indexes: Sites S = 1.5, tests t = {Particle, Atterberg, Specific Gravity, Natural Moisture, Compaction, CBR}.

i. **Productivity of test t at site** s (samples per hour), assuming the listed tie is for one **sample**:

$\overline{P}_{s,t} = \frac{60 \text{ minutes}}{T_{s,t}}$ (samples per hour) (1)

ii. **Average productivity** for **test**t across all sites (minutes):

$_{s,t} = \frac{1}{5}\sum_{s=1}^{5} P_{s,t}$ (2)

iii. **Total time for test**t across all sites (minutes):

$T_t = \sum_{s=1}^{5} T_{s,t}$ (3)

iv. Average time per test t across sites (minutes):

$\overline{T}_t = \frac{T_t}{5}$ (4)

3.2.1 Productivity results — samples per hour (rounded)

A. Productivity per test at each site (samples/hour)

(Each value = $60/T_{s,t}$)

Table 3.2: The productivity of each Site on the different laboratory tests

Site → Test ↓	Particle	Atterberg	Specific Gravity	Natural Moisture	Compaction	CBR
Site 1	0.0892	0.0442	0.1333	0.0988	0.0322	0.0690
Site 2	0.0857	0.0429	0.1379	0.0885	0.0355	0.0690
Site 3	0.0784	0.0388	0.1200	0.1019	0.0375	0.0667
Site 4	0.0892	0.0444	0.1193	0.0889	0.0353	0.0632
Site 5	0.0896	0.0388	0.1000	0.0889	0.0355	0.0667

Interpretation: e.g. at Site 1 the Particle Size test productivity ≈ **0.089 samples/hr** (i.e., one particle-size sample every ≈11.2 hours).

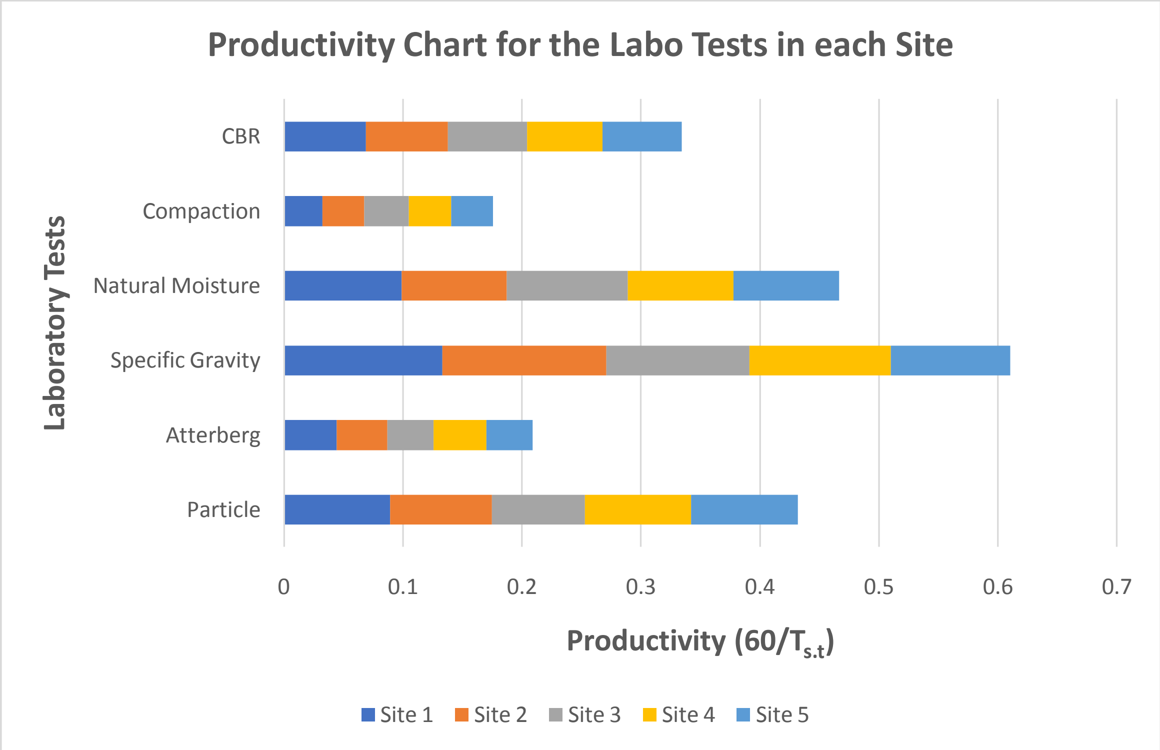

Fig 3.2: Chart showing The productivity of each Site on the different laboratory tests

3.2.2. Average productivity per test across the 5 sites

Table 3.3: Average productivity of each of the Laboratory tests

Test	**Avg productivity (samples/hr)**
Particle Size	**0.0864**
Atterberg Limit	**0.0418**
Specific Gravity	**0.1221**
Natural Moisture	**0.0934**
Compaction M–D	**0.0352**
CBR	**0.0669**

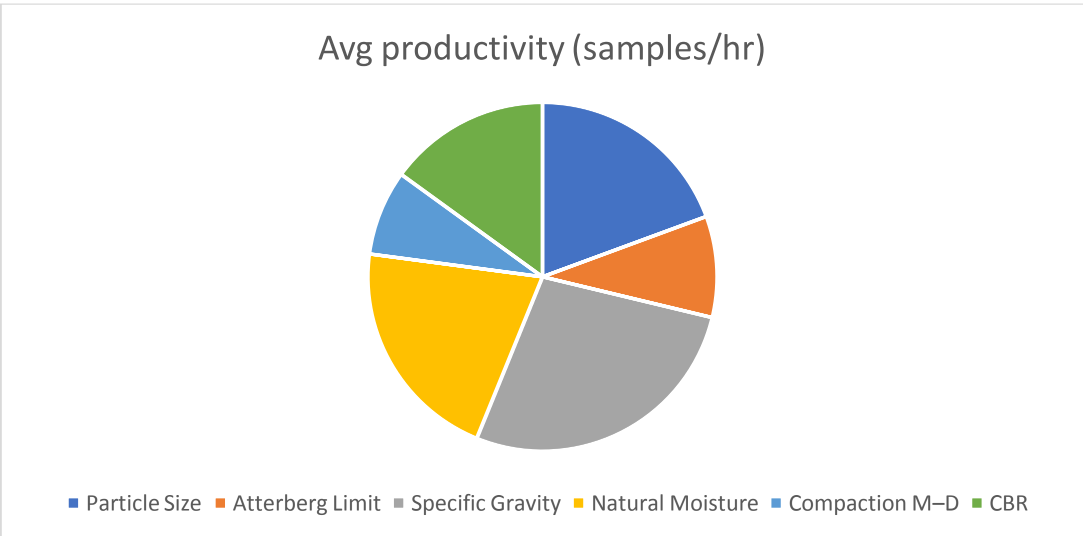

Fig 3.3: Chart showing the Average productivity per test across the 5 sites

Interpretation: On average, a single lab can complete:

- ~0.086 particle-size samples/hour ⇒**~2.07 particle-size samples per day** (24-hr day) or **~0.693** per 8-hr shift (use your working-shift hours to convert).
- Compaction M–D is slowest: **~0.035 samples/hr⇒~0.84 samples/day (24-hr)** or **~0.28 per 8-hr shift**.

3.2.3. Total and average times per test (minutes) — for reference

Test	Total time across all sites (min)	Average per site (min)
Particle Size	3,481	**696.2**
Atterberg Limit	7,198	**1,439.6**
Specific Gravity	2,488	**497.6**
Natural Moisture	3,224	**644.8**
Compaction M–D	8,546	**1,709.2**
CBR	4,490	**898.0**

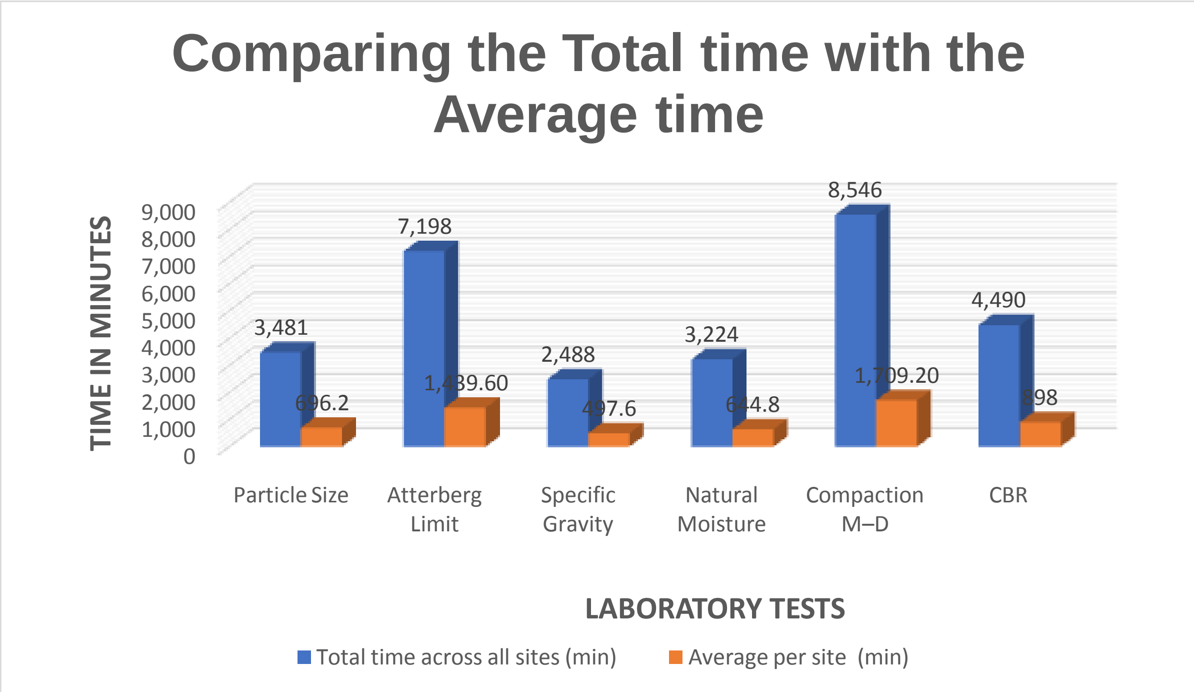

Fig 3.4: Chart showing the comparison between the total time and the average time

3.2.4 Discussion of Interpretation & Practical Notes

1. Compaction M–D and Atterberg Limit as Bottlenecks

The results show that **Compaction Moisture–Density (M–D)** and **Atterberg Limit** tests have the **lowest productivity rates** among the six laboratory tests:

- Compaction M–D: ~**0.035 samples/hour** → less than **1 sample per 24-hr day** (≈0.28 per 8-hr shift).
- Atterberg Limit: ~**0.042 samples/hour** → ≈1 sample per 24-hr day (≈0.34 per 8-hr shift).

These two tests alone consume over **50% of total lab time** across the five sites.

Why so slow?

- **Compaction M–D:** Each compaction curve involves preparing multiple soil specimens at different moisture contents, compacting them at standard effort, drying, and measuring density. This is highly labor- and time-intensive, especially if repeat trials are needed to refine the optimum moisture content.
- **Atterberg Limit:** Requires careful preparation (sieving, rolling threads for plastic limit, multiple trials with liquid limit devices). The repeatability requirement (within a small margin of error) often means additional test runs.

Implication: These two tests are the **critical bottlenecks** in laboratory throughput. Unless multiple setups are available, they will dictate how many soil samples can be processed in a given timeframe.

2. Specific Gravity and Natural Moisture as Faster Tests

By contrast, **Specific Gravity** (~0.122 samples/hour) and **Natural Moisture Content** (~0.093 samples/hour) are significantly more productive.

- Specific gravity typically requires fewer steps: oven-drying, weighing, pycnometer/volumetric flask method.
- Moisture content tests involve weighing wet soil, oven-drying, and re-weighing — relatively straightforward once samples are in the oven.

These tests can often be run **in parallel** with other tasks (since oven-drying is a waiting process). As a result, technicians can multitask, and productivity here is higher.

Implication: These tests do not constrain overall throughput. Their scheduling should be coordinated to "fill gaps" while longer tests (like compaction) are running.

3. Particle Size Distribution and CBR — Mid-Range Productivity

- **Particle Size Distribution (PSD):** ~0.086 samples/hour. This test is moderate in duration, requiring sieving and sometimes hydrometer analysis for fine fractions. It is equipment-intensive but can be batched (several samples sieved simultaneously if multiple sieve sets are available).
- **California Bearing Ratio (CBR):** ~0.067 samples/hour. This is slower than PSD because it involves specimen preparation, soaking (up to 4 days in some standards), and penetration testing. Even though the active testing time per sample is less, the **soaking time delays throughput** unless multiple moulds are used concurrently.

Implication: While not as slow as compaction or Atterberg tests, these two tests still take significant time. Their productivity can be improved with **parallel apparatus** (multiple CBR moulds, multiple sieve stacks).

4. Implications for Lab Scheduling

Given the productivity rates:

- **Compaction M–D and Atterberg Limit tests** should be treated as the **schedule-defining activities** in the laboratory workflow.
- Labs should plan their **daily schedules around these bottleneck tests**, ensuring technicians are not idle during waiting periods (e.g., oven drying, soaking, or curing).
- A **staggered workflow** is advisable: start new Atterberg or compaction tests while earlier ones are in drying/soaking phases. This way, testing capacity is maximized.

5. Strategies for Improving Productivity

a. **Parallelization of equipment:**
 i. Use multiple compaction moulds and CBR moulds to allow simultaneous sample preparation.
 ii. Have duplicate Atterberg test devices (liquid limit apparatus) to reduce waiting.

b. **Shift optimization:**
 i. If a lab runs single 8-hour shifts, output is very limited (e.g., less than 1 compaction test/shift). Running **extended shifts or 24-hour rotation** can double or triple capacity without changing equipment.

c. **Batching samples:**
 i. For PSD tests, batching sieving of multiple samples can significantly reduce per-sample time.
 ii. Moisture content tests can also be batched, with many tins sharing oven capacity.

d. **Pre-screening soils:**
 I. If soils are clearly unsuitable (e.g., organic clays), reduce the number of samples undergoing full suites of tests.
 II. Focus compaction and CBR tests on the most representative soils to reduce unnecessary repetition.

6. Planning for Large Projects

For large infrastructure projects (highways, airports, urban foundations), dozens of soil samples may need to be tested within tight timelines. Using the productivity results here, planners can estimate **required lab capacity**:

- Example: If 20 compaction M–D tests are required, and one apparatus produces only 0.28 samples/shift, then:

Shifts required=200.28≈71 shifts\text{Shifts required} = \frac{20}{0.28} \approx 71 \text{ shifts}Shifts required=0.2820≈71 shifts

At one shift/day, that is 71 working days with a single setup.

- To reduce this to 10 working days, **at least 7 parallel setups or rigs** would be required.

This type of calculation is critical in contract planning and in setting up temporary site laboratories.

7. Cost and Resource Implications

- Because compaction and Atterberg tests dominate lab time, they also dominate **labor costs and equipment usage**.
- Investing in additional setups for these tests offers the **greatest return** in terms of reducing project delays.
- Faster tests (moisture content, specific gravity) require fewer resources and can be easily scaled without major cost implications.

The productivity analysis highlights a **classic bottleneck structure**: two tests (Compaction M–D and Atterberg Limit) dominate time and thus control lab throughput. The other tests are important but secondary in scheduling impact.

For effective laboratory planning:

- Prioritize resources (equipment, technicians, shifts) on bottleneck tests.
- Use batching and parallelization for mid-range tests (PSD, CBR).
- Treat moisture and specific gravity as quick, supportive tests that can fill downtime.

Ultimately, the lesson is that **lab capacity is not determined by the average test, but by the slowest one**. Managing these slow tests effectively is the key to delivering results on time in soil improvement and geotechnical projects.

IV. Conclusion And Recommendations

4.1 Conclusion

This study has provided a comparative evaluation of the time required to complete six fundamental geotechnical laboratory tests—Particle Size Distribution (PSD), Atterberg Limits, Specific Gravity, Natural Moisture Content, Compaction Moisture–Density Relationship (M–D), and California Bearing Ratio (CBR)—across five distinct locations: Southeastern Nigeria, New Orleans, Miami, Maryland, and New York.

The findings confirm that **testing productivity is unevenly distributed across test types**. Compaction M–D and Atterberg Limit tests emerged as the **principal bottlenecks**, consuming over half of the total laboratory time across all sites. In contrast, Specific Gravity and Natural Moisture Content were the most time-efficient, while Particle Size Distribution and CBR occupied an intermediate position.

These results highlight that **laboratory throughput is not defined by the average test but by the slowest one**, a principle consistent with the “bottleneck theory” in production and operations management. This insight is especially relevant for geotechnical laboratories that handle large volumes of samples for infrastructure projects, where delays in delivering soil data can lead to costly project hold-ups, design revisions, and contract disputes.

Furthermore, location-specific conditions influenced soil characteristics and indirectly affected test durations. Lateritic soils in Southeastern Nigeria, organic silty clays in New Orleans, carbonate-rich sands in Miami, and glacial deposits in New York each presented unique challenges. These differences underscore the importance of **regional soil conditions** in shaping laboratory workload and efficiency.

4.2 Recommendations

Based on the findings, the following recommendations are proposed for improving laboratory efficiency and reliability in geotechnical testing:

1. **Resource Allocation to Bottleneck Tests**
   - Laboratories should prioritize investments in equipment and manpower for Compaction M–D and Atterberg Limit tests, as these largely determine overall throughput.
   - Procuring multiple compaction moulds, rammer sets, and Atterberg devices can significantly reduce idle time and testing delays.
   -
2. **Parallelization and Batch Processing**
   - PSD and moisture content tests can be batched, with several samples processed simultaneously using multiple sieve stacks or large-capacity ovens.
   - Laboratories should schedule quick tests (e.g., moisture, specific gravity) during waiting times for longer tests (e.g., CBR soaking, compaction drying).

3. **Workflow Optimization**
   - Staggered scheduling is advised to ensure continuous use of laboratory capacity. For example, while one sample undergoes soaking for CBR, another can be prepared for Atterberg or compaction.
   - Laboratories operating under tight timelines should consider extended shifts or 24-hour rotations.
4. **Use of Predictive and Correlation Models**
   - Where permissible by standards, preliminary correlations (e.g., estimating CBR from compaction data or Atterberg indices) should be used to reduce the frequency of full-duration tests, particularly for screening purposes**Site-Specific Test Prioritization**
   - Recognizing the influence of soil type, laboratories should adjust test schedules to reflect regional soil behaviors. For example, high-plasticity soils may require multiple Atterberg trials, while sandy soils may justify more compaction-based testing.
5. **Capacity Planning for Large Projects**
   - Before project commencement, laboratories should estimate required testing capacity using productivity values, thereby determining whether additional apparatus or temporary site laboratories are necessary.

4.3 Final Remark

Improving geotechnical laboratory efficiency demands a balance of technical rigor and operational management. By focusing on the slowest tests, employing batching strategies, and aligning resources with project needs, laboratories can substantially reduce turnaround times. These measures not only enhance the reliability of geotechnical data but also contribute to the timely delivery and cost efficiency of civil engineering projects.

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