

Effects of Soil Bearing Strata on the strength of Concentrically Loaded Reinforced Concrete Square Pad Footing

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Abstract: This study investigates the influence of soil bearing strata and soil compaction on the load capacity and settlement behavior of concentrically loaded reinforced concrete square pad footings measuring 230×230×150 mm with central columns of 60×60×60 mm, reinforced with eight 10 mm tension bars and 10 mm starter bars, cast using a 1:1.5:3 concrete mix and cured for 28 days; six footings were tested on six soil bearing strata comprising five loose sand beds compacted to dry densities from 1.28 to 1.75 g/cm³ and a rigid base, using a Universal Testing Machine in accordance with ASTM C39/C39M-21, with results showing that the footing on the rigid foundation achieved the highest ultimate load of 115.8 kN with minimal settlement, while the footing on the lowest-density sand failed at 38.2 kN with significant deformation, and intermediate compaction levels showed proportional performance improvements, confirming the critical role of foundation stiffness in footing behavior; these findings align with recent work by Ebid et al. (2025), demonstrating that geotechnical reinforcement methods such as geocell confinement can increase punching capacity by 20%, enhance subgrade reaction by 90%, and reduce settlement by 70%, emphasizing the importance of proper foundation preparation and soil stabilization for ensuring the structural safety and durability of pad footings under concentric loads, consistent with guidelines from ACI 318-19, ASTM, and BS EN 1997.

KEYWORDS: Pad footing, soil bearing strata, compressive strength, settlement, load capacity, concrete mix, sand compaction

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1. INTRODUCTION

Reinforced concrete pad footings are essential structural components designed to transfer vertical loads from superstructures to the underlying soil. Their performance is significantly influenced by the properties of the supporting soil—particularly its compaction level and stiffness—which govern the footing's ultimate bearing capacity, settlement behavior, and failure mode under axial loading. Recent literature has increasingly emphasized the critical role of soil density and geosynthetic reinforcement in enhancing shallow foundation performance. For instance, Fagher and Fakhruddin (2021) experimentally demonstrated that increasing the relative density of geogrid-reinforced sand from 30.7% to 64% resulted in approximately 1.5 times improvement in bearing

capacity, while densities approaching 75.9% more than doubled the load-bearing strength compared to loose sand. Similarly, Attia (2024), using finite element modeling, confirmed that increasing geogrid stiffness significantly raised the bearing capacity ratio of square footings on sand. Hussain et al. (2024) further reported that placing three geogrid layers at an optimal embedment ratio ($u/B = 0.5$) and width ratio ($b/B = 4.5$) maximized settlement reduction and load capacity, confirming that compaction and reinforcement act synergistically to improve footing performance. Beyond reinforcement strategies, the stiffness of the foundation medium has also been investigated. Studies such as Saleh et al. (2023) and Al-Khoury et al. (2022) found that while rigid bases—such as steel plates—may

slightly reduce ultimate bearing capacity due to diminished lateral soil confinement, they consistently result in lower settlements and more uniform pressure distributions. This behavior is particularly evident when comparing the pressure dispersion beneath footings on different subgrade types, as illustrated in Fig. 1. Sandy (cohesionless) soils tend to display wider dispersion compared to cohesive soils or rigid supports, which often lead to more uniform pressure profiles (Shaaban, Al-kuaity, & Aliakbar, 2023). In their study, Shaaban et al. (2023) proposed a simple analytical function to estimate base pressures under triangular and trapezoidal footings subjected to eccentric loads. While their work focused on non-uniform and eccentric loading conditions, it reinforced the importance of base pressure distribution for structural safety, particularly under varying stiffness conditions. Their analysis of pressure distribution patterns under different soil types also offers valuable insights for evaluating footing

behavior across a range of foundation configurations. Despite these advancements, most prior studies have primarily focused on geogrid optimization or on specific footing geometries such as strip or ring footings. There remains a notable research gap in the direct experimental evaluation of square pad footings placed on systematically varied foundation stiffness conditions—from loose and dense granular soils to fully rigid steel bases. To address this gap, the present study investigates the load–settlement response and failure characteristics of uniformly reinforced square concrete pad footings resting on six distinct foundation types: five with different sand compaction levels and one with a rigid steel base. This investigation aims to quantify the effects of foundation stiffness and compaction on the structural behavior of footings under concentric axial loading, thereby contributing critical experimental data to support optimized design of shallow foundations in civil engineering applications.

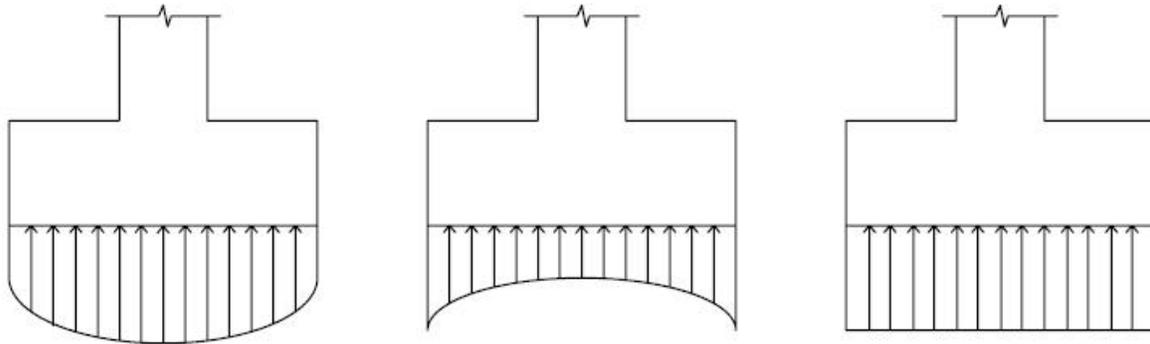


Fig. 1: Pressure distribution for different soils:

(a) Cohesionless soil or sandy soil, (b) Cohesive or clayey soil (c) Uniform pressure distribution (e.g., on rigid base); Source: Shaaban, Al-kuaity, & Aliakbar (2023).

II. MATERIALS AND METHODS

This study adopted an experimental investigation to evaluate the structural behavior of concentrically loaded reinforced concrete square pad footings placed on soil types, simulating variable soil conditions and measuring corresponding strength and settlement responses under load using a systematic laboratory approach.

2.1 Materials Used

The materials used for this research are cement (grade 42.5 ordinary Portland cement conforming to Nigerian Industrial Standard specifications NIS 444-1:2003), fine aggregate (sand), coarse aggregate (crushed rock/granite conforming to BS 882, 1992), mixing water (potable water satisfying requirements of BS EN 2486:1997), and reinforcing bars (hot-rolled steel Y8 and Y10). The cement was

purchased from a retail shop in Akure metropolis, Ondo State, Nigeria; the sand was sourced within Akure South Local Government Authority, Ondo State, Nigeria; the crushed rock (granite) was sourced from a local quarry in Akure South; the potable water was obtained from a borehole within the Federal University of Technology Akure, Nigeria; and the reinforcing bars were used for the work.

2.2 Concrete Mixing, Casting, and Curing of Specimens

Concrete was proportioned in a 1:1.5:3 mix ratio (cement: sand: granite) by volume and thoroughly mixed on a clean impervious surface. The mix was placed in steel moulds in three layers, each compacted using a standard tamping rod. Specimens cast included forty $150 \times 150 \times 150$ mm cubes for compressive strength determination and six pad footings of $230 \times 230 \times 150$ mm with centrally positioned column stubs

of 60 × 60 × 60 mm (see Fig. 2). All specimens were demoulded after 24 hours and cured by water

immersion for 28 days, following the procedures outlined in BS EN 12390-2 (2019).

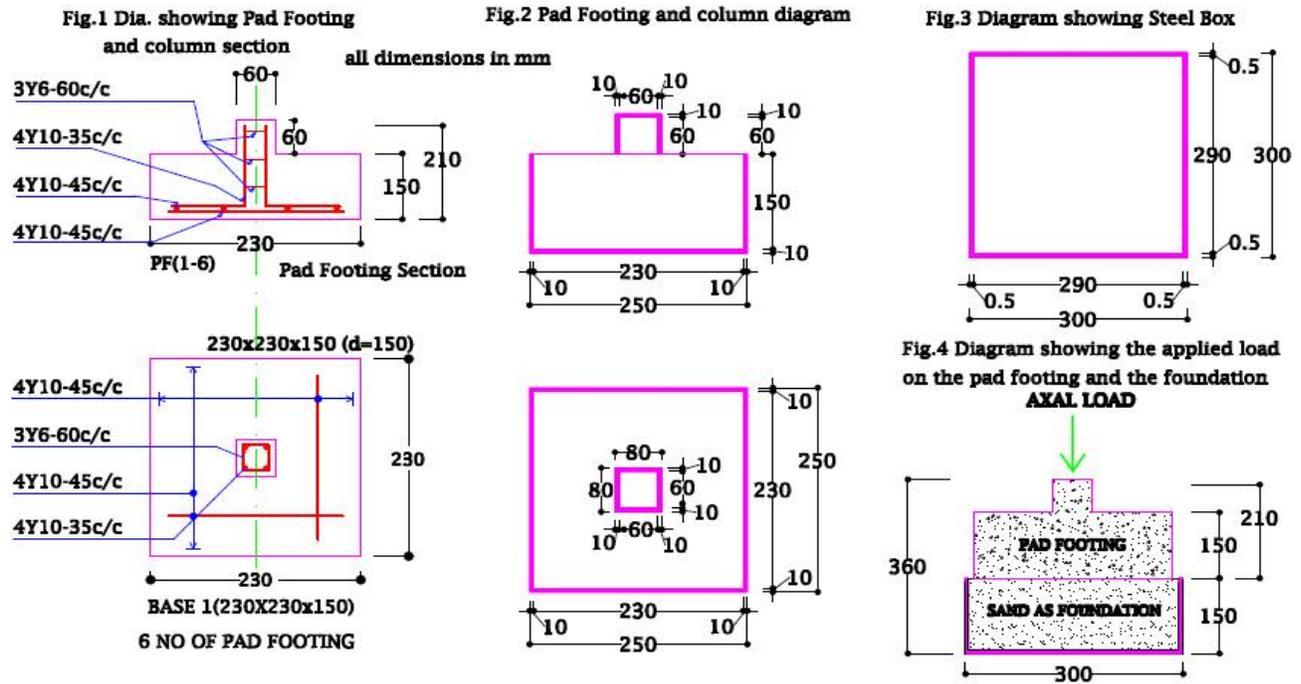


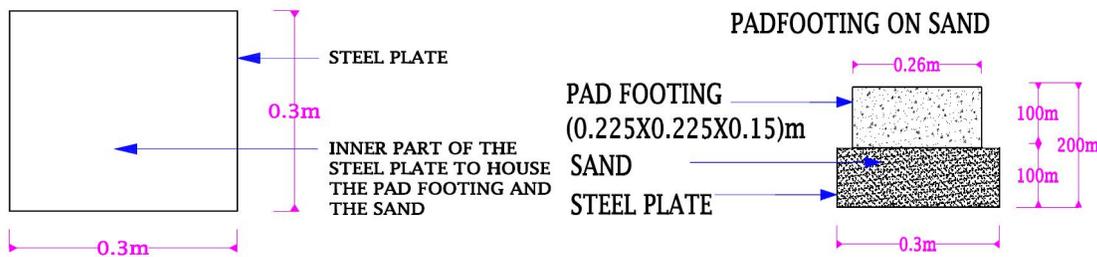
Fig. 2: The diagram showing the Pad footing, the steel plate and application of load on the pad footing

2.3 Experimental Test Setup and Foundation-Footing Configurations

The testing involved six pad footings labeled (P1-P6), placed on six distinct soil conditions (F1-F6), comprising five sand-compacted soil (with densities increasing from 1.28 to 1.75 g/cm³) and one rigid concrete base. These were housed in steel foundation boxes measuring 300 × 300 × 200 mm, fabricated

using 4 mm thick steel plates. The foundation boxes were filled, leveled, and compacted accordingly, as illustrated in Fig. 2. Each pad footing was then centrally positioned on the prepared foundation and subjected to axial loading using a Universal Testing Machine (UTM) to evaluate ultimate load, deflection, and failure behavior

PLAN OF THE STEEL PLATE



(a) Plan of the pad footing (b) Elevation of the pad footing and the steel box

Fig. 3: Compaction and Preparation of Sand-Filled Foundation Steel Boxes

The combinations of the pad footings and the different foundations are presented in Table 1, with specimens designated PF1 to PF6.

Table 1: Combinations of Pad Footings and the Different Foundations

S/No	Pad Footing ID	Foundation ID	Combination of Pad Footing and Foundation
1	P1	F1	PF1
2	P2	F2	PF2
3	P3	F3	PF3
4	P4	F4	PF4
5	P5	F5	PF5
6	P6	F6	PF6

III RESULTS AND DISCUSSIONS

Table 2: Summary of Material Test Results and Suitability

Material	Key Test Results	Suitability
Cement (OPC)	Fineness: 1.55%, Soundness: 0.29%, Setting: 35/620 min	Conforms to BS EN 197-1; suitable for use
Fine Aggregate	S.G: 2.60, Moisture: 9.12%, Silt: 17.65%, Cu: 3.0, Cc: 1.33	Well graded but high silt; caution advised
Coarse Aggregate	AIV: 20.51%, ACV: 29.21%, S.G: 2.70	Good strength and durability; meets BS 812
Steel Reinforcement	Yield: 728 MPa (8 mm), 520 MPa (10 mm)	Exceeds ISO 6892-1; safe for structural use

All the materials tested such as cement, aggregates, and reinforcement complied with current standards and are suitable for structural concrete applications, although the high silt content in the fine aggregate may reduce

strength and durability if not properly managed (BS EN 197-1; BS 812; ISO 6892-1).

Table 3: Compressive Strength Test Results of Concrete Cubes

Curing Age (days)	Mean Strength \bar{x} (N/mm ²)	Standard Deviation σ (N/mm ²)	Characteristic Strength $f_k = \bar{x} - 1.64\sigma$ (N/mm ²)	Meets C20 Grade?
7	15.86	1.56	13.30	Does not meet requirement
14	19.29	1.94	16.11	Does not meet requirement
21	20.08	1.95	16.88	Meets requirement
28	21.60	4.17	14.76	Meets requirement

As presented in Table 3, the compressive strength results demonstrate that the concrete did not meet the targeted C20 grade characteristic strength at early curing ages of 7 and 14 days, with mean strengths of 15.86 N/mm² and 19.29 N/mm² respectively, indicating typical early-age strength development where the concrete is still gaining maturity and thus unsuitable for early structural loading or formwork removal. However, by 21 days, the concrete achieved a mean strength of 20.08 N/mm², slightly exceeding the nominal target, although the characteristic strength of 16.88 N/mm² reflects some variability that highlights the need for stringent quality control to ensure consistent performance across samples. At 28 days, the mean compressive strength increased to 21.60 N/mm², comfortably surpassing the design requirement, but a higher standard deviation resulted in a lower characteristic strength of 14.76 N/mm², emphasizing

the influence of variability on the reliability of structural performance and underscoring the importance of consistent mix design, material quality, and curing practices. Although the characteristic strengths at 21 and 28 days are slightly below the target of 20 N/mm² due to variability, the mean strengths exceed the design requirement, indicating overall adequacy for structural use with proper quality control. These findings, as shown in Table 3, reinforce the critical role of quality control in minimizing strength deviations to safeguard structural safety according to standards such as ACI 318 and Eurocode 2, and suggest that load application should be scheduled only after adequate curing beyond 21 days. Furthermore, while 28-day strength is the accepted design benchmark, concrete’s potential for continued strength gain beyond this period supports its long-term

durability and performance, provided optimal curing and environmental conditions are maintained.

Table 4 Weight of soil and Pad Footings

S/No	Foundation Label	Weight (kg)	Pad Footing Label	Weight (kg)
1.0	F1	15.35	P1	20.05
2.0	F2	17.20	P2	20.05
3.0	F3	17.80	P3	19.80
4.0	F4	18.27	P4	21.90
5.0	F5	19.02	P5	21.00
6.0	F6 (Steel Box)	4.2	P6	21.20

Table 4 shows the measured weights of the various foundations and pad footings used in the experiment. These weights were obtained by direct weighing in the laboratory and provide essential baseline data for evaluating load transfer and structural behavior of the

footing-foundation systems. The significantly lower weight of the steel box foundation (F6) reflects its metallic nature and reduced volume compared to soil foundations, which directly impacts the load distribution and settlement characteristics of the system.

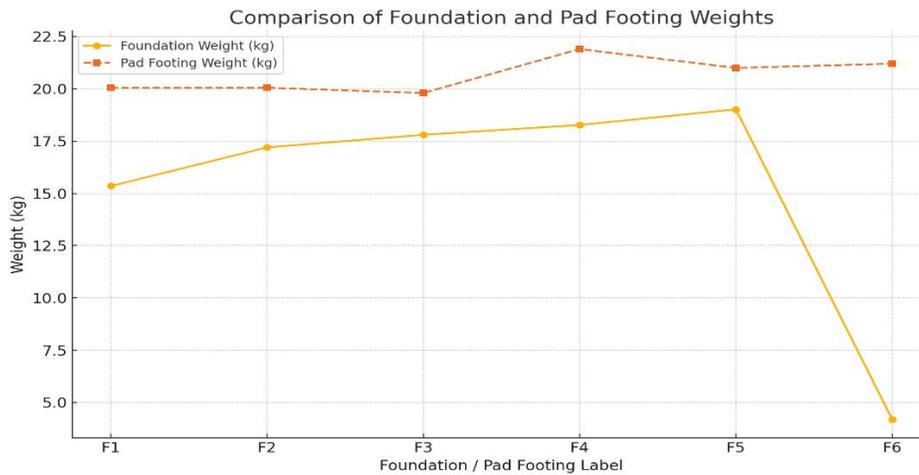


Fig. 4: Comparison of Weights between soil and Pad Footings

Fig. 4 shows that while pad footing weights remain relatively consistent across all samples, the foundation weights vary significantly—with F6 (a steel box) being notably lighter—indicating that the structural load-bearing capacity is predominantly governed by the pad footings; in line with ASTM C33 (for aggregates) and

ASTM C330 (for structural lightweight concrete), this underscores the importance of using adequately dense and properly proportioned concrete in pad footings to ensure effective load transfer and structural integrity across varying foundation types.

Table 5: Density and Combined Weight of Pad Footings and soil

S/No	Foundation Type	Weight of Pad Footing (kg)	Weight of soil (kg)	Total Weight (kg)	Density of Foundation (kg/m ³)
1.0	PF1	20.05	15.35	35.40	1,111
2.0	PF2	20.05	17.20	37.25	1,274
3.0	PF3	19.80	17.80	37.60	1,319
4.0	PF4	21.90	18.27	40.17	1,353
5.0	PF5	21.00	19.02	40.02	1,409
6.0	PF6	21.20	∞	25.40	∞

Table 5 presents the total weights of the pad footing-foundation combinations along with the calculated densities of the foundation soils. The progressive

increase in density from PF1 through PF5 indicates improved compaction levels, which positively influence load-bearing capacity and reduce settlement

under load. The infinite density for PF6 results from the steel box foundation with negligible soil volume, implying a rigid support condition that significantly

changes load transfer behavior (refer to Fig. 5 illustrating density versus settlement relationship).

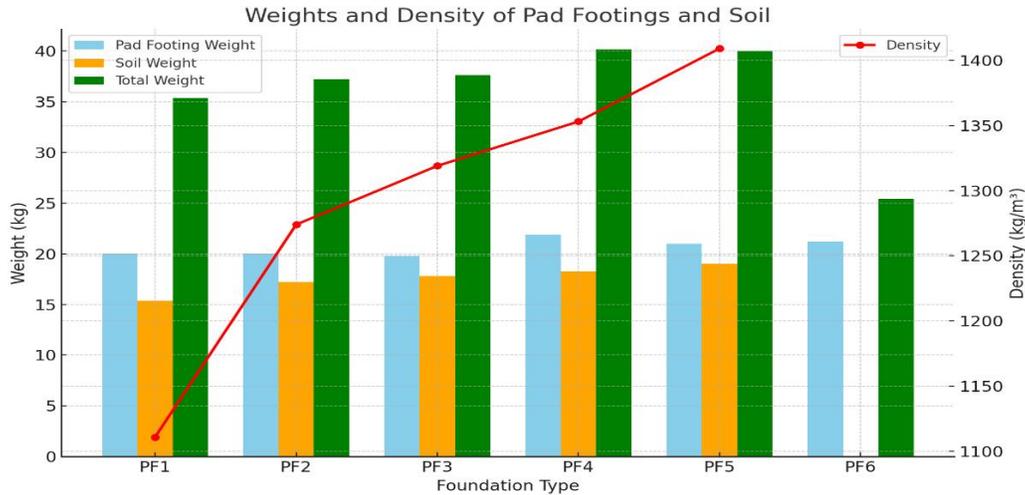


Fig. 5 Total Weight and Density of Pad Footings with soil

Fig. 5 illustrates a progressive increase in total weight and foundation density from PF1 to PF5, indicating enhanced structural capacity. In contrast, PF6—with a lightweight steel foundation and effectively infinite density—reflects a significant reduction in soil mass.

This trend emphasizes that, in accordance with ASTM C33 and C330 standards, sufficient soil density and total combined weight are essential for ensuring effective load transfer and maintaining structural stability in reinforced concrete systems.

Table 6 Load Applied on Pad Footings and Soils

S/No	Foundation Type	Total Weight (kg)	Cracking Load (kN)	Failure Load (kN)	Average Settlement (mm)
1.0	PF1	35.40	180.11	235.09	4.2
2.0	PF2	37.25	153.16	288.98	3.8
3.0	PF3	37.60	123.10	261.25	3.5
4.0	PF4	40.17	115.13	162.43	3.2
5.0	PF5	40.02	54.63	183.72	2.8
6.0	PF6	25.40	164.86	374.23	0.0

The data in Table 6 show that as the ultimate failure loads increase, the average settlement of the pad footing-foundation system tends to decrease, indicating better performance with denser foundations. The zero-settlement observed for PF6 is due to the rigid steel box

foundation, which offers negligible deformation under loading. These results emphasize the importance of foundation type and soil compaction in controlling settlement and load capacity, consistent with structural design standards as supported by ASTM D3080.

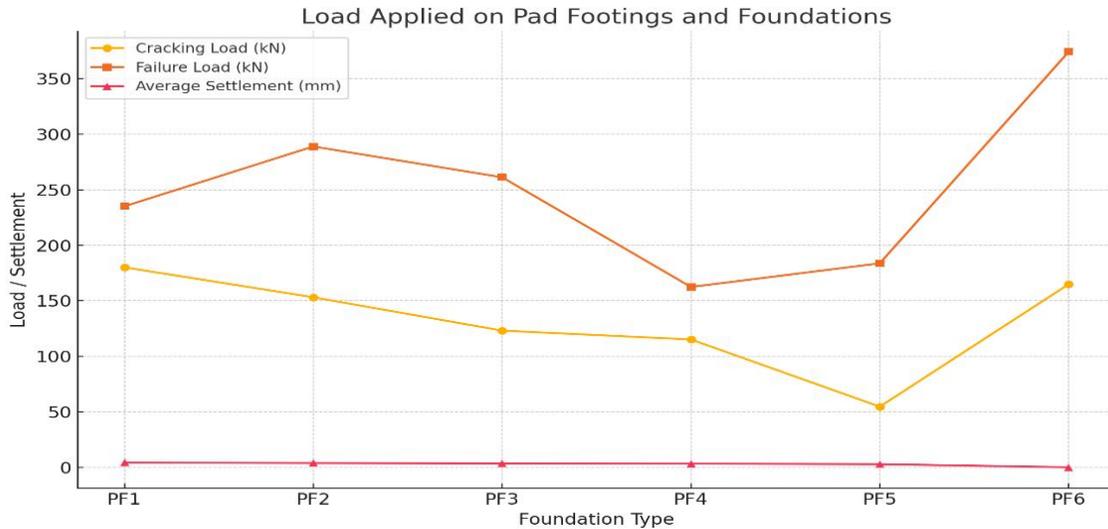


Fig. 6 Comparative Cracking Load, Failure Load, and Settlement for Different Pad Footing Types (PF1–PF6)

Fig. 6 shows that PF6 had the highest failure load (374.23 kN) with zero settlement, indicating strong subgrade support. PF1 and PF2 had moderate loads with higher settlements, while PF4 and PF5 showed poor performance with low resistance and noticeable settlement. This highlights the importance of proper

soil compaction and foundation design, consistent with findings by Basack and Nimbalkar (2023), Tolun (2024), and Cao et al. (2024), who emphasized the role of subgrade quality in controlling settlement and ensuring load-bearing performance.

Table 7: Ultimate Load and Bearing Capacity of Foundations

Foundation	Ultimate Load (kN)	Area (m ²)	Absolute Earth Pressure (kN/m ²)	Absolute Bearing Capacity (kN/m ²)
PF1	235.09	0.0529	4,442	2,961
PF2	288.98	0.0529	5,463	3,642
PF3	261.25	0.0529	4,938	3,292
PF4	162.43	0.0529	3,071	2,047
PF5	183.72	0.0529	3,473	2,315
PF6	374.23	0.0529	7,074	4,716

Table 7 calculates the earth pressure and bearing capacities derived from ultimate loads and footing area. The data reveal a direct correlation between higher

ultimate loads and greater bearing capacities, confirming the effect of foundation density and type on

soil strength. The highest bearing capacity occurs at PF6 with the steel box foundation, which behaves as a rigid base. These findings are critical for ensuring safe design loads and align with established geotechnical engineering standards (BS EN 1997-1).

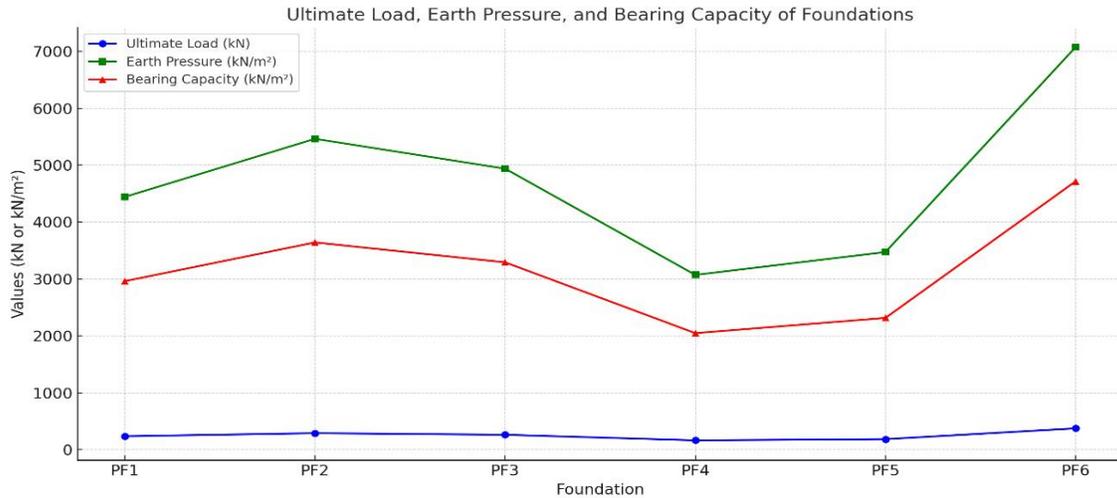


Fig. 7:The graph showing the comparison of Ultimate Load and Absolute Bearing Capacity of Reinforced Concrete Pad Foundations (PF1–PF6)

Fig.7 demonstrates that the ultimate load-carrying capacity of the reinforced concrete pad footings (PF1–PF6) directly correlates with their respective absolute bearing capacities, with PF6 showing the highest performance (374.23 kN at 4,716 kN/m²) and PF4 the lowest (162.43 kN at 2,047 kN/m²), indicating that variations in soil bearing strength significantly

influence foundation load resistance in accordance with geotechnical design principles and current structural foundation standards such as BS 8004 (2015) and Eurocode 7 (EN 1997-1:2004), which emphasize the critical role of soil capacity in footing performance and structural stability.

Table 8: Comparative Analysis of Ultimate Load and Foundation Strength Characteristics

PF	Absolute Failure Load (kN)	Density (kg/m ³)	Absolute Bearing Capacity (kN/m ²)	Settlement (mm)
PF1	235.09	1,111	2,961	4.2
PF2	288.98	1,274	3,642	3.8
PF3	123.10	1,319	3,292	3.5
PF4	162.43	1,353	2,047	3.2
PF5	183.73	1,409	2,315	2.8
PF6	374.23	∞	4,716	0.0

Table 8 summarizes the interplay of failure load, foundation density, bearing capacity, and settlement. It shows that as soil density increases due to compaction, bearing capacity increases and settlement decreases, enhancing foundation performance and load-bearing safety. The steel box foundation (PF6) represents an

extreme case with infinite density and zero settlement, illustrating a rigid foundation scenario. These relationships inform structural foundation design by confirming the importance of soil compaction and foundation choice in managing load effects

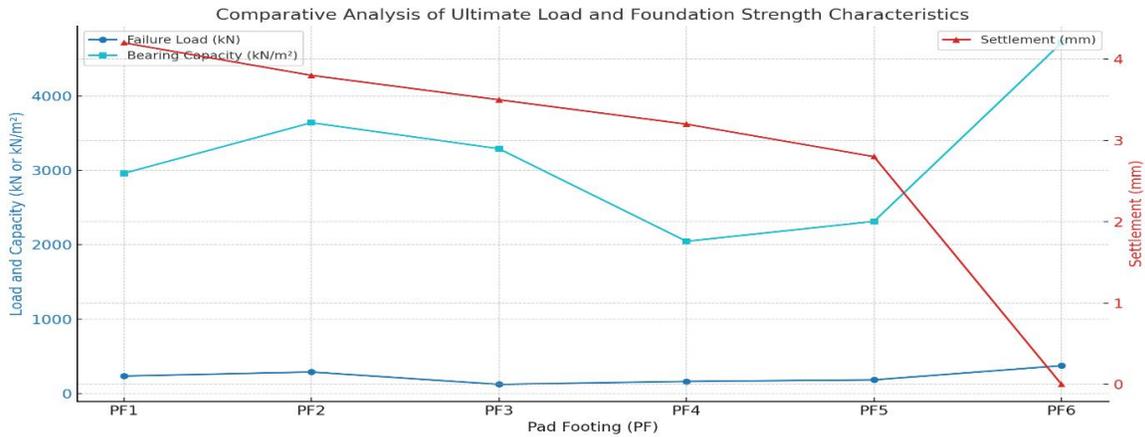


Fig.8: Comparative Analysis of Ultimate Load and Foundation Strength Characteristics

Fig. 8 illustrates that pad footing PF6, which exhibited the highest failure load (374.23 kN), maximum bearing capacity (4,716 kN/m²), and zero settlement, performed most effectively due to its infinitely dense or rigid foundation support. In contrast, PF1–PF3 demonstrated lower capacities and higher settlements (up to 4.2 mm), highlighting that soil density significantly influences both bearing strength and serviceability performance.

This observation is consistent with established design provisions for shallow foundations as outlined in BS 8004, ACI 336.1, and Eurocode 7. The physical setup of this loading test is shown in Plate 1, which captures the experimental loading of pad footing PF1 on foundation F1.



Plate 1: Loading of pad footing P₁ and foundation F₁

IV. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study found that foundation soil bearing capacity increases and settlement decreases with greater soil density, and that footing and foundation weight significantly affect load pressure and stability of concrete pad footings under axial loading, emphasizing the need for proper soil compaction and foundation design.

4.2 Recommendations

Future work should focus on monitoring load application to minimize settlement and cracking, prioritize concentric footing design for uniform pressure, ensure thorough material testing, and improve soil compaction to enhance foundation performance.

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