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Controlling Consolidation Settlement in Soil Using Foamed Material

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Abstract: Polyurethane (PU) foam is an alternative controlling consolidation method to resolve the problem of consolidation. In this study, a consolidation laboratory test was executed to determine the consolidation in soil improved with PU foam. This research aims to assess the effectiveness of PU foam in mitigating consolidation settlement. By conducting comprehensive laboratory testing and analysis, this study seeks to provide valuable insights into the practical applications and potential advantages of polyurethane spray in soil stabilization, with the ultimate goal of contributing to advancements in civil engineering and construction projects. The consolidation reduction is carried out by excavating the soil at a shallow depth and mix with PU foam. The performance of different percentages of PU foam as a consolidation controller is evaluated. The comparison is made by mixing PU foam with saturated clay and water to determine the reduction in consolidation by evaluating different parameters of soil like final deformation compression index etc. The percentage of mixing PU foam to soil varies from 3% to 5%. The different parameters like compressibility index, coefficient of volume compressibility, void ratio, and final deformation values for PU mixed with saturated soil are adopted in this study with the respective equations. The settlement reduces significantly up to a certain limit of PU foam and again increases beyond that limit of PU foam for the saturated soil.

Keywords: Polyurethane Foam, Consolidation, Laboratory, Assessment, Stabilization, compression, Settlement, Coefficient, Saturation, Deformation

I. INTRODUCTION

The high and non-uniform settlement causes numerous problems for geotechnical engineers while constructing buildings, dams, and embankments on cohesive soil. Clay has low permeability due to this reason the settlement takes a longer duration to occur. The settlement of the saturated clay layers under the application of external stresses generally depends upon the consolidation characteristics, like coefficient of compressibility, compression index, and coefficient of consolidation. The higher or non-uniform consolidation of soil may cause the failure of the structure (Ali, Kumar and Pathan 2019).

Therefore, it is important to make a stable structure against those failures by using different methods such as soil replacement and soil stabilization to reduce the settlement effects. Soil replacement and soil stabilization may modify the properties of soil by developing the basic characteristics of the soil. These are the most common chemical stabilizers that are used for modifying soil properties such as Bitumen, Lime, Fly Ash, Cement, and Silica Fume (Khalid and Siang 2021).

(Manzoor and Yousuf 2020) Conducted experiments to examine the effect of lime on soil compressibility according to his research compressibility decreased with lime content. (Cheng, Zhu et al. 2020) Conducted a comprehensive study investigating the influence of varying nano bentonite levels on key geotechnical parameters, including the compression coefficient, consolidation coefficient, secondary consolidation coefficient, and permeability coefficient. (Khalid and Siang 2021) Conducted a comprehensive study to identify the most efficient chemical additives for enhancing the strength of clay soil. Lime, cement, and fly ash were investigated as potential additives within a range of 8% to 10% in the soil mixture. A comparative analysis was conducted among lime, cement, and fly ash mixtures to determine the most effective chemical for enhancing soil strength. (Taytak, Pulat and Yukselen-Aksoy 2012) Conducted experiments on Xanthum Gum and Chitosan Biopolymers to improve soil properties. The maximum dry density of the bentonite-kaolin-sand mixtures was raised by the biopolymer's xanthan gum and chitosan. Chitosan exhibited a more pronounced effect compared to xanthan gum (Islam, Islam and Hoque 2022) conducted experiments to investigate the compressibility and hydraulic behavior of the clay soil in different ratios of construction and demolition waste (CDW). The Atterberg limit, consolidation settlement, coefficient of consolidation, compression index, permeability, and pre-consolidation pressure of the original soil, soil-CDW mixtures, and soil with circular CDW columns in triangular and square grid patterns were assessed, according to the research construction and demolition wastes can be used for soil improvement in various amounts depending on the needs.

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There are significant knowledge gaps in understanding how foamed materials interact with soil, degrade over time, and behave in various conditions. Specifically, the interactions between soil particles and foam, long-term foam degradation, and scalability of foamed mix soil consolidation techniques are not well understood. Furthermore, there is a lack of standardized testing protocols to evaluate the effectiveness of foamed mix soil consolidation. Addressing these gaps is crucial for predicting the long-term effectiveness and stability of foamed mix soil. (Hasan, Jarushi et al.) A laboratory testing program investigated the effect of lime and Portland cement additives on cohesive soil consolidation. The objective was to improve soil properties, reduce settlement and accelerate consolidation. Different additive materials were tested to achieve maximum consolidation control. Results show that, the lime-treated soil up to 10% offers the optimum in most characteristics compared to other additives. In contrast, the influence of cement is evident with the inclusion of cement content as 15 and 20%. The permeability and coefficient of consolidation are associated with the variation of additives percentage. That is to say, the most significant improvement of both is observed with the inclusion of 5% cement and 20% lime. (Jarushi and Talibullah 2023). The study found that incorporating granulate waste tires into clay soil decreases the liquid and plastic limits, maximum dry density, unconfined compressive strength, and Californian Bearing Ratios, while the optimum water content remains nearly unchanged. However, adding 20% granulate waste tires increases axial strain at failure and is recommended for reducing lateral stress on retaining walls or as lightweight fill material in embankments. Chemical and permeability tests are suggested to assess potential reactions and effects on hydraulic constructions. (Al-Saidi, Al-Juari and Fattah 2022) Upon conducting various experiments it was observed that by maximizing the number of grouting holes around the area of the footing, there was a reduction in settlement due to the increase in the L-SF-LH slurry and the optimum shape was D2 with a reduction of settlement 71.3% for hole depth equals to footings diameter and a reduction of settlement 90% for hole depth equals to 1.5 times the footings diameter (Alipour, Khazaei et al. 2017). The effects of adding 4-10% cement to clayey soil from Bandar Imam, Iran, were studied experimentally and numerically. Physical and mechanical properties were assessed at water contents of 30%, 48%, and 70%. The unconfined compressive strength (qu) and stiffness (E50) of treated soils increase with cement content but decrease with higher water content. For soft clayey soils in southwest Iran, E50 ≈ 115qu, significantly lower than the Federal Highway Administration's guideline of E50 = 300qu, which may result in unsafe designs. Rowe Cell laboratory test is executed to determine the consolidation settlement of marine clay soil improved with polyurethane foam. The ground improvement is carried out by excavating the soft soil at a shallow depth and replace with polyurethane foam. The performance of different thicknesses of PU foam as a ground improvement is evaluated. The comparison is made between the partial replacement of PU foam on saturated marine clay and water to determine the buoyancy and uplift behavior of the ground improved with lightweight PU foam. The percentage thickness of PU foam to soft clay layer and water varies from 20% to 80%.(Lat, Jais et al. 2019) . (Kalantari 2013) presented a method based on oedometer tests to determine the collapse potential upon wetting, where the simple oedometer tests involve soaking at a specific load. Samples of untreated and treated gypseous soil were tested to evaluate the effect of PF on the behavior of soil. A more comprehensive range of PF content (0, 0.75, 1, 3, and 5%) was used in performing oedometer tests to investigate how PF treatment affected the soil volumetric strain and collapse potential, which were considered an important aspect in this study.(Abdulrasool and Al-Wakel 2021). (Fattah, Al-Saidi and Jaber 2014) Have investigated the effect of lime on the consolidation properties of cohesive soil subjected to one-dimensional consolidation test. The cohesive soil was treated with 2%, 4% and 6% lime. (Zhafirah, Somantri and Permana 2019) Consolidation settlement in clay soils can be predicted by analyzing the consolidation parameters. Consolidation parameters were obtained from the results of a laboratory consolidation test using an oedometer and rowe cell. (Koley, Debnath and Pal 2023) conducted an experimental investigation was performed to estimate the consolidation characteristics of soil by oedometer apparatus and 3D consolidation apparatus by varying the drainage conditions; the condition having the highest co-efficient of consolidation as well as the rate of consolidation was determined. A comparison was also established between the consolidation characteristics of laboratory oedometer apparatus and 3D consolidation apparatus.

Research gap

The knowledge of knowing how Foamed materials interact with soil and how they degrade over time. It becomes difficult to predict the long term effectiveness of soil mixed with Foam.

Foam-Soil Interaction

It is not well understood that how soil particles interact with soil. So it becomes difficult to predict the behavior of foamed mix soil.

Long-term Foam Degradation

The Knowledge about long term foam degradation is very little.It raises the concerns about long term stability of foamed mix soil.

Scalability

Research is needed for scaling up foamed mix soil consolidation techniques for practical applications.

Lack of Standardized Testing Protocols

Standardized testing protocols are needed to identify the effectiveness of foamed mix soil consolidation.

This study aims to investigate the use of a suitable material to control consolidation issues beneath building foundations, while also assessing the cost implications of adopting this technique on the overall project.

II. STUDY AREA, AND DATA COLLECTION

A. Study Area

Bannu was chosen as the study area for this research. Bannu is a district in the Khyber Pakhtunkhwa province of Pakistan. It is located between 32°56′ and 33°16′north latitudes and 70° 22′ to 70° 57′ east longitude, as shown in Figure 1. The sample was collected from different regions of Bannu.

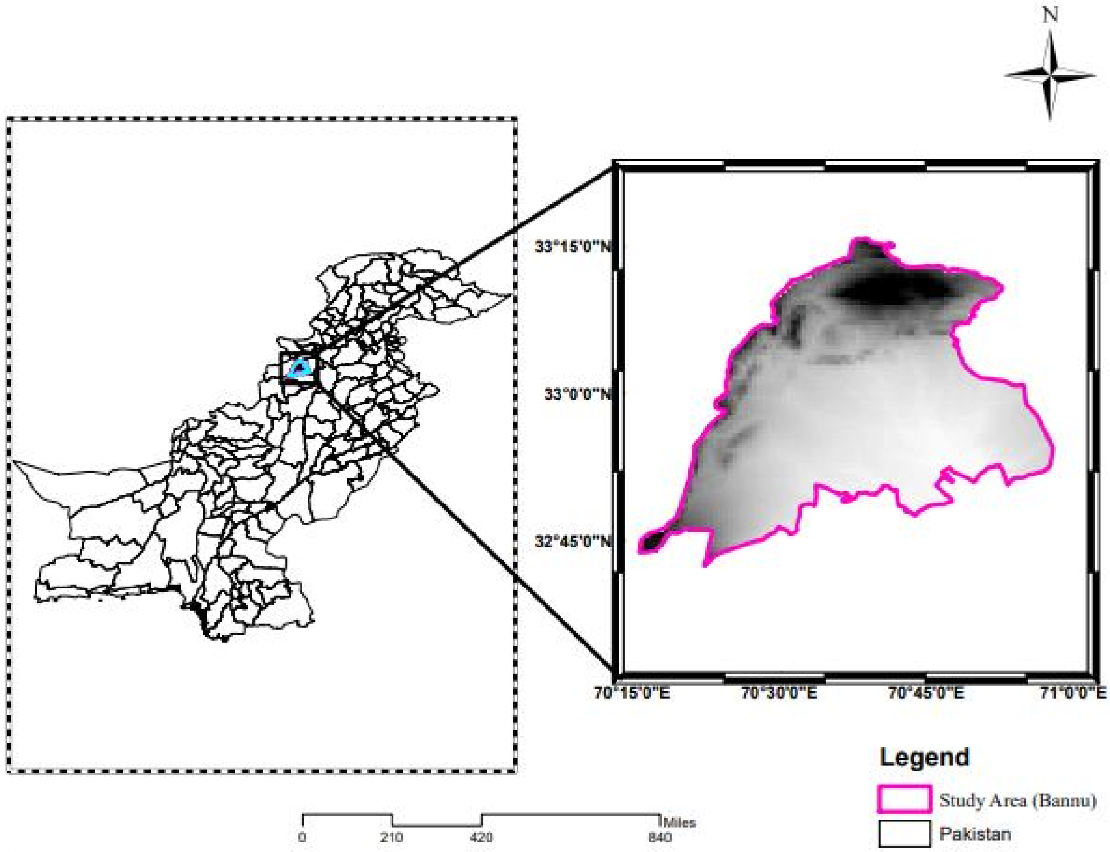

Figure 1 shows the study area map.

B. Data Collection Techniques

Sample Collection and Preparation

In this research, Soil samples were used. The samples were collected from different regions of Bannu, such as Mira Khel, Taji Kala, and Circular Road. The samples were brought to the lab, and testing commenced. The samples were divided into two groups: one for testing the pure soil sample in the oedometer and the other for the addition of foamed material.

III. RESEARCH METHODOLOGY

This research study employed an experimental methodology, utilizing a laboratory-based investigation to examine the effectiveness of foamed materials in controlling consolidation settlement in soil. Soil samples of varying types were collected and prepared according to standards, then mixed with selected foamed materials and compacted it. Consolidation tests were performed on treated and untreated soil samples using a consolidometer, and the resulting data were analyzed statistically to compare the consolidation settlement of soil with and without foamed materials as shown in Figure 2.

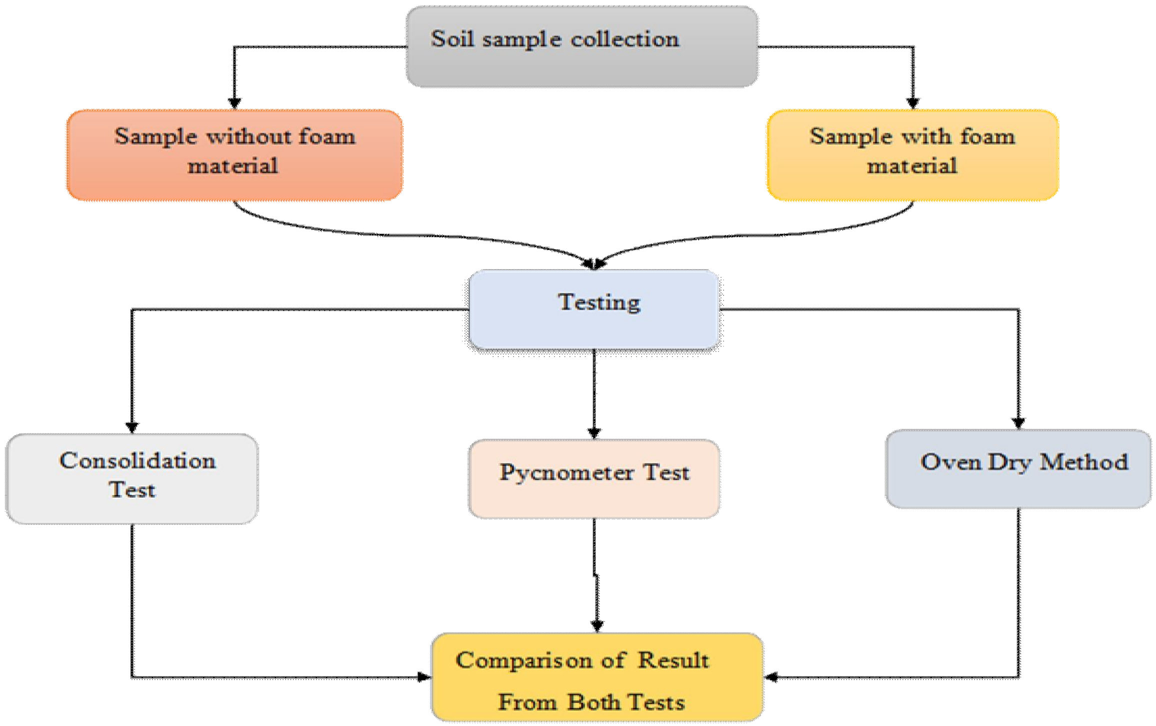

Figure 2 Flow chart depicting the detailed research methodology.

A. *Oedometer Test*

A laboratory test that measures the compression and consolidation properties of soils under various loads, simulating settlement and deformation behavior (Nelson, Chao et al. 2015).

1) *Preparation of Soil Specimen*

The preparation of the soil specimen generally involves assembling an undisturbed soil sample, placing it in an oedometer ring, measuring its initial height, and recording the changes in height due to the application of load. In this study, the undisturbed soil sample was precisely placed in the oedometer ring, the initial height was measured, and the deformation in height was accurately recorded under the applied loading conditions (Laloui and Rotta Loria 2020).

2) *Loading and Measurement*

A small initial load is applied to seat the soil sample and ensure good contact between the sample and the porous stone. Incremental loads are applied in a sequence, typically with each load being 2-4 times the previous load. Each load is maintained for a specified period, usually 24 hours, to allow the soil sample to consolidate. After the final load, the load is incrementally reduced to measure the rebound behavior of the soil sample. By applying incremental loads and measuring the resulting settlement, the consolidation test provides valuable information on the soil's compressibility, permeability, and consolidation behavior. In this study, the load was applied incrementally, and equilibrium was allowed to be reached after each increment. The vertical displacement of the soil sample was measured using a dial gauge at regular time intervals (Mohammed 2015).

3) *Drainage and Load Application*

In a consolidation test, drainage and load application are crucial steps that help to simulate the in-situ conditions of a soil deposit. During the consolidation test, drainage is allowed to occur from the top or bottom of the soil sample. This is achieved by using porous stones or filters that permit water to escape from the sample. The load is applied to the soil sample in increments, allowing for equilibrium to be reached after each increment. The load is typically applied using a loading frame or a hydraulic press. In this study, proper drainage of the soil sample was ensured by using porous stones and filter papers. The load was applied uniformly using a loading pad to obtain uniform deformations of the sample.

4) Compression Index

The coefficient of compression denoted as Cc, is a fundamental parameter used to characterize the compressibility of soils (Hsi, Gunasekara and Nguyen 2015). It describes the variation of the void ratio (e) as a function of the change in effective stress (σf) and is a measure of the soil's ability to undergo volume change in response to applied pressure. It can be calculated using the relationship (1).

$$Cc = \frac{e_2 - e_1}{\log \sigma f_2 - \log \sigma f_1} \quad \ldots\ldots\ldots\ldots.. (1)$$

Where e_1 and e_2 are the void ratios at the initial and final effective stresses, respectively σf1 and σf2 are the initial and final effective stresses. The Cc provides valuable insights into the compressibility characteristics of the soil, particularly in the context of settlement analyses and the prediction of soil behavior under different stress conditions. In this study compression index was calculated by using the above formula. The value of the Cc decreased with the use of PU foam.

5) Coefficient of Volume Compressibility

The coefficient of volume compressibility (mv) is the volume decrease of a unit volume of soil per unit increase of effective pressure during compression (Samuel, Kyakula and Mugume 2019). It represents the soil's ability to decrease in volume under an increase in effective stress. It is an important parameter in geotechnical engineering and is used to understand the behavior of soil under loading conditions. It is a key factor in analyzing soil settlement and consolidation. It can be calculated using equation (2).

$$m_v = \frac{a_v}{1 + E_{av}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Here, mv is the coefficient of volume compressibility, a_v is the ratio of change in void ratio and change in stress, and Eav is the average void ratio. In this study, the Mv value was calculated by using equation 2. It has been observed that the Value of the Mv is decreased after the addition of PU foam to the soil sample.

6) Relationship between Effective Stress and Void Ratio

It is crucial for understanding the compressibility and settlement behavior of soil. The relationship is typically represented by a consolidation curve, which shows the change in void ratio as a function of the applied effective stress (Nishimura, Hirabayashi et al. 2011). It is characterized by the compression index. The Cc defines sediment compressibility as the slope of the curve between void ratio and effective stress. It is a fundamental parameter used to quantify the compressibility of the soil. The relationship between effective stress and the void ratio is essential for predicting the settlement behavior of soils under different loading conditions. It allows for the estimation of the magnitude and rate of both primary and secondary consolidation settlement of a structure or an earth fill. It is also influenced by factors such as drainage conditions, stress history, and the permeability of the soil. These factors play a significant role in determining the rate and magnitude of consolidation settlement.

7) Deformation Vs Time Graph

A deformation vs time graph, also known as a consolidation curve, is a graphical representation of the deformation (settlement or compression) of a soil sample over time under a constant load (Nishimura, Hirabayashi et al. 2011). The graph shows a rapid increase in deformation initially, indicating primary consolidation. This stage represents the rapid expulsion of pore water from the soil. As time progresses, the rate of deformation slows down, marking the transition from primary to secondary consolidation. This stage represents the gradual rearrangement of soil particles and the continued expulsion of pore water. Eventually, the deformation curve flattens out, indicating that the soil has reached equilibrium. At this stage, the soil has fully consolidated, and the deformation has stabilized. This graph provides valuable information about the consolidation behavior of the soil, including the rate of consolidation, the amount of settlement, the time required for consolidation, and the soil's compressibility and permeability. By analyzing this graph, engineers can predict the settlement behavior of soils under various loading conditions, which is crucial for designing stable and safe structures.

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B. Water Content

Moisture content (mc) can be considered as the amount of water in a substance. In general, water content is difficult to measure due to the complex intermolecular bonding properties within the substance matrix (Civeira 2019). The measurable water content is to be determined appropriately, and to run in an appropriate level of processing environment, the water content of the material is known as the moisture content in the testing and evaluation process of moisture analysis. Moisture content analysis is an important component of material quality and is essentially a function of quality control in most production and laboratory facilities. From biological research organizations and pharmaceutical manufacturers to food producers and packers, moisture content control greatly affects the physical properties and product quality of almost all substances and materials at all stages of processing and final product survival. Currently, several moisture analysis methods are available for commercial purposes. The primary methods of water content determination include spectroscopic, chemical, conductivity, and oven-dry methods. In this study, the method which is used for the determination of moisture content was the oven-dry method. In the soil moisture content test, an empty container is weighed as (W1). Then 50-100 grams of soil sample is collected in the container and is weighed as (W2). W2 will be the weight of the container plus wet soil. Then the container is kept in the oven which must be set at 100 Cº for 24 hours. After 24 hours take the container and weigh it again. Note the reading as W3, this will be the weight of the container plus the weight of dry soil. The weight of the moisture can be found by subtracting W3 from W2, i.e. (W2 – W3). Similarly, the weight of the dry soil can be found by subtracting W1 from W3, i.e. (W3 – W1). After finding these values the water content can be calculated using equation (3).

$$mc = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \quad \text{……………..} (3)$$

C. Specific Gravity

Specific gravity is the ratio of the density of a substance to the density of a reference substance equivalently; it is the ratio of the mass of a substance to the mass of a given volume (Hosni, Pauzi and Sharif-fuddin 2015). Apparent specific gravity is the ratio of the mass to the weight of a substance that is equal to the weight of the volume equal to the reference substance. The reference substance is always dense (4 ° C) water for liquids; for gases, it is air at room temperature (21 ° C). Nevertheless, temperature and pressure must be specified for both the sample and the reference. The pressure is almost always 1 atm (101.325 kPa). Temperatures for both sample and reference vary from industry to industry. In British Beer Brewing, the practice is to multiply it by 1000 for specific gravity as stated above. Specific gravity is commonly used in industry as a simple mean of obtaining information about solutions of various materials, or quality control for polymer materials: to evaluate material changes, or samples or to determine the degree of uniformity between lots. Specific gravity varies with temperature and pressure. The reference and sample must be compared at the same temperature and pressure, or it should be corrected to the standard reference temperature and pressure. Substances with a specific gravity of 1 are neutrally buoyant in water. Material with more than 1 SG is denser than water and will power, disregarding surface tension effects, drowning in it. Material with an SG of less than 1 is less dense than water and swims on it. Specific gravity can be performed using various techniques i.e. pycnometer method and digital density meters etc.In this study, the method is used for the determination of the specific gravity pycnometer method. In this method 200-250 grams of soil sample was taken in powdered form and weighed by digital balance alone and the weight is noted. Then an empty pycnometer is measured, and the weight is noted as W1. The pycnometer is then filled with the powdered soil sample and weighed again. This weight is then noted as W2. After taking weight (W2), the pycnometer with the powdered soil sample (200g) is filled with water till its mouth. Again, the weight is noted (pycnometer + soil + water) as (W3). Then the mixture (water + soil) is disposed of and again the pycnometer is filled, this time with water alone, and again weighed. The weight is measured as (W4). All these values can be put in equation (4) to obtain the specific gravity.

$$Gs = \frac{(W_2 - W_1)}{(W_2 - W_1) - (W_3 - W_4)} \quad \text{………...............} (4)$$

IV. RESULTS AND DISCUSSIONS

A. Compression Index

The experimental results demonstrate a notable reduction in the Cc value when polyurethane foam is incorporated. Specifically, the addition of 3% polyurethane foam yields a significant decrease of 20.8% in the Cc value as shown in table 1,2. This substantial reduction in Cc is a clear indication of enhanced consolidation control, which is the primary objective of this study. Furthermore, the results suggest that the optimal dosage of PU foam for achieving consolidation control is around 3%. Increasing the foam percentage beyond this threshold reverses the trend, implying that excessive foam addition can be counterproductive.

Table 1 Compression Index of soil without polyurethane

Soil sample	Initial Void ration	Final void Ratio	Initial effective stress (kg/cm^2)	Final effective stress (kg/cm^2)	Compression index(cc)
1	0.3015	0.2831	1	2	0.12

Table 2 Compressive Index of Soil with Polyurethane

Soil Sample	Initial Void Ratio	Final Void ratio	Initial effective stress (kg/cm^2)	Final effective stress (kg/cm^2)	Compression index (cc)	Polyurethane percentage
1	0.3271	0.3087	1	2	0.0095	3%
2	0.3015	0.2831	1	2	0.12	5%

B. *Coefficient of Volume Compressibility*

The incorporation of polyurethane foam into the soil sample has yielded a remarkable reduction in the value of Mv. Notably, the addition of PU foam has resulted in a decrease of greater than 50% in the Mv value as shown in Tables 3, and 4. This substantial reduction is highly encouraging, as it unequivocally indicates a significant enhancement in consolidation control. The pronounced decrease in Mv suggests that the polyurethane foam has effectively improved the soil's mechanical behavior, leading to enhanced stability and reduced settlement. This finding has important implications for geotechnical engineering applications, where controlling soil settlement and ensuring stability are paramount.

Table 3 Coefficient of volume compressibility of Different Soil Sample without polyurethane foam

Soil Sample	Av	Eav	Mv
1	0.0092	0.2923	1.98

Table 4 Coefficient of volume compressibility of Soil Sample with polyurethane foam

Soil Sample	av	Eav	Mv	Polyurethane percentage
1	0.0094	1.2716	0.82	3%
2	0,.01295	0.2486	1.41	5%

C. *Determination of Specific Gravity*

The specific gravity of the sample was determined using the pycnometer method. In this process, the weight of the empty pycnometer was determined to be 124 grams. After that, the soil sample was added to the pycnometer and weighed again, resulting in a weight of 174 grams. The pycnometer containing the soil sample was then filled with water up to the mark, shaken thoroughly, and weighed, showing a weight of 654 grams. Finally, the same pycnometer was filled with clean water only and weighed, resulting in a weight of 624 grams. Based on these measurements, the specific gravity of the soil sample was determined to be 2.5 as shown in table 5.

Table 5 Specific Gravity of Soil Sample

Soil Sample	Weight of empty pycnometer W1(g)	Weight of pycnometer and soil W2(g)	Weight of pycnometer with water and soil sample W3(g)	Weight of pycnometer with water W4(g)	Specific Gravity
1	124	174	654	624	2.5

D. Determination of Water Content

The water content of the soil sample was determined using the oven-dry method. Initially, the weight of the empty container was measured to be 10 grams. Then, the soil sample was added to the container and weighed again, resulting in a weight of 52 grams. The sample was subsequently placed in the oven for 24 hours, after which it was weighed again, showing a weight of 44 grams. Based on these measurements, the water content of the soil sample was determined to be 24% as shown in table 6.

Table 6 Moisture Content Calculation of Different Soil Samples

Serial no	Weight of empty container	Weight of container and wet soil	Weight of container and dry soil	Moisture Content (%)
1	10	52	44	24
2	13.5	50	40	38

E. Relationship between Effective Stress and Void Ratio

To study the consolidation behavior of soil a plot of void ratio is drawn against the applied stress. This plot helps in finding the value of Cc. The Cc value is observed both with and without foam samples. It was observed that the Cc value decreased significantly after foam was added and the results are encouraging. Figures 3, 4, and 5 show the relationship between the effective stress and void ratio of soil samples with and without foamed material.

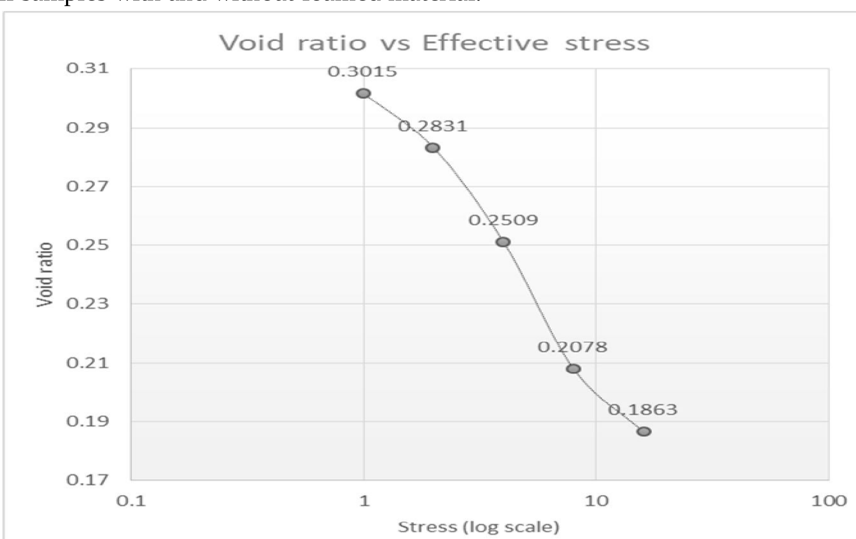

Figure 3 Void Ratio VS Effective Stress Graph without Polyurethane.

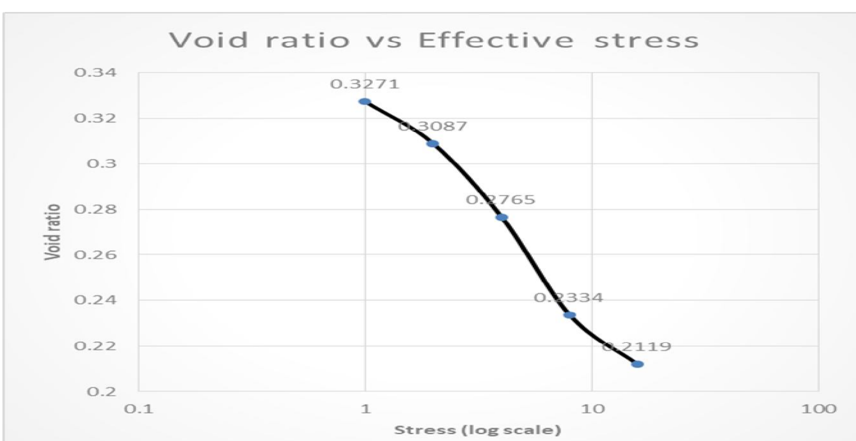

Figure 4 Void ratio VS Effective stress Graph with 3% Polyurethane

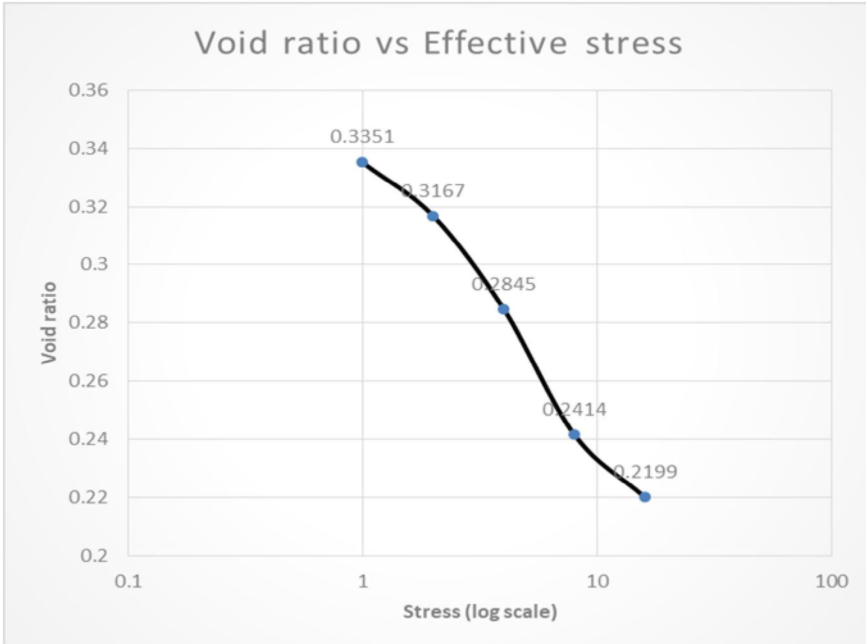

Figure 5 Void Ratio VS Effective Stress Graph With 5% Polyurethane

F. Deformation Vs Time Graph

In this study, it was initially observed that when a load was applied, water was removed at a faster rate as primary consolidation took place. Following primary consolidation, secondary consolidation began, which was significantly slower and smaller in magnitude. A plot of deformation against time was constructed for the same soil, facilitating the determination of the Mv value. The Mv values were observed for both samples, and a notable change in the value was observed in the direction of the project objectives. Figures 6, 7, and 8 show the deformation versus time graphs of soil samples with and without foamed material.

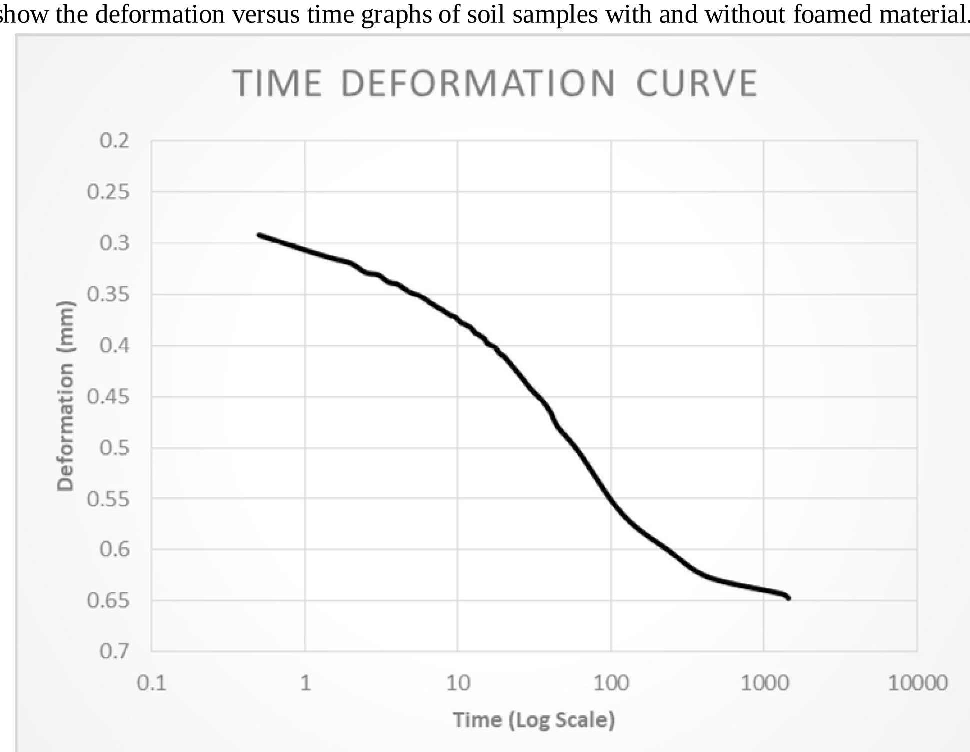

Figure 6 Time Deformation Curve Without Polyurethane

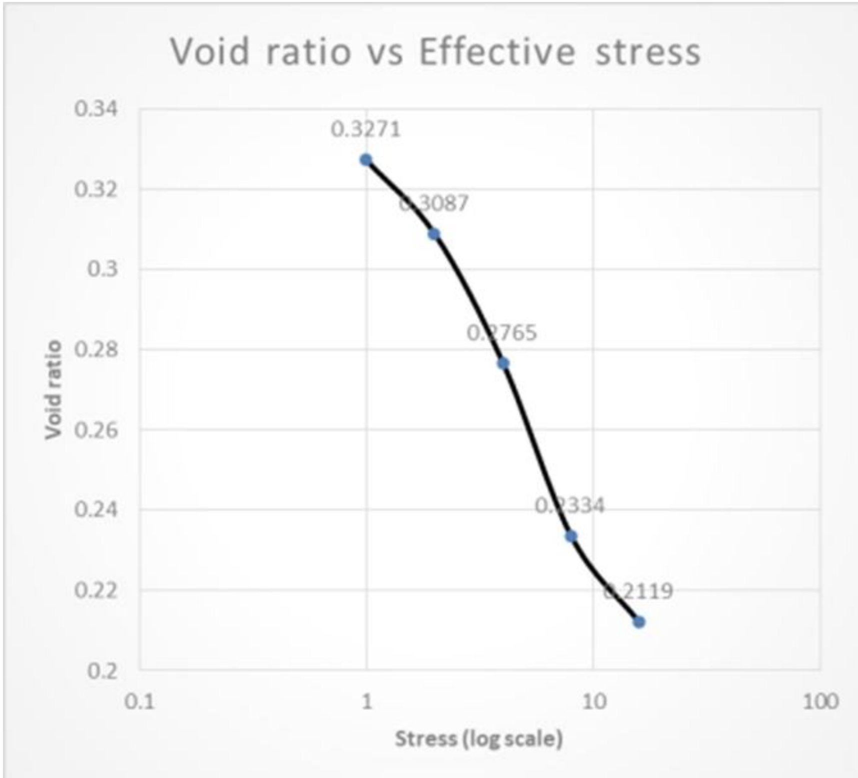

Figure 7 Time Deformation Curve With 3% Polyurethane

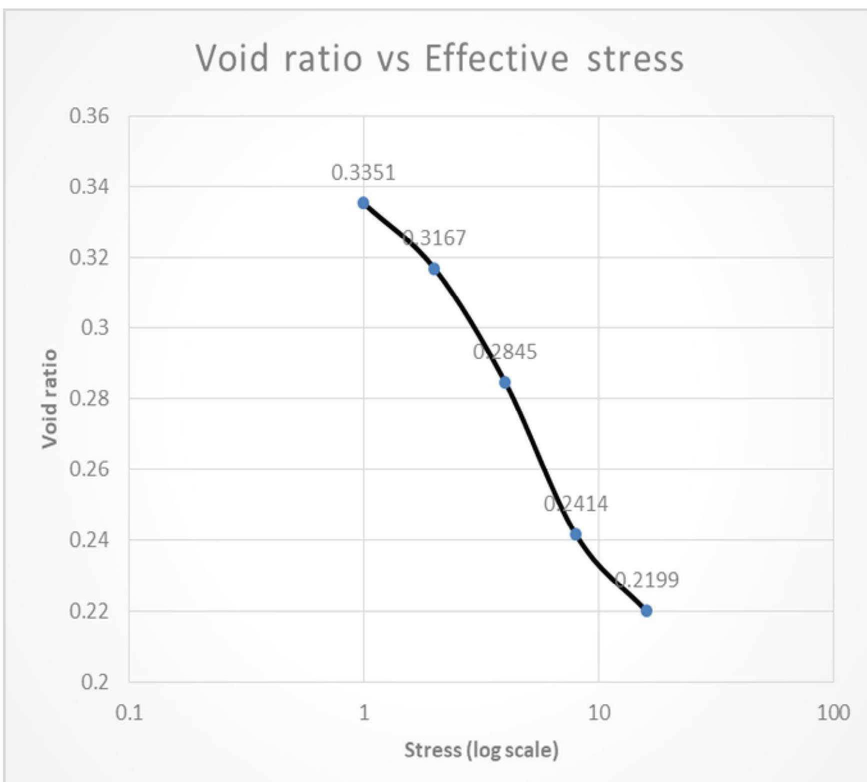

Figure 8 Time Deformation Curve With 5% Polyurethane

G. Comparison Chart

In this graph, the various properties of soil like compression index, coefficient of volume compressibility, and final deformation are compared as shown in the figure 8. It was found that all the values decreased for the soil when treated with foam. The decrease in the values is meeting the research objectives and is encouraging.

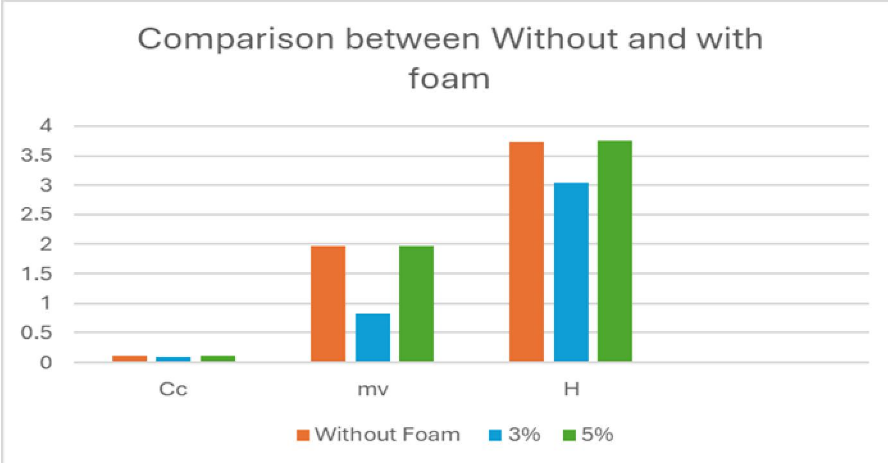

Figure 9 Camparison Chart

H. Discussion

The experimental results demonstrate that the incorporation of PU foam into saturated clay strata significantly reduces soil consolidation. The addition of 3% polyurethane foam yields a substantial decrease of 20.8% in the Cc value, indicating enhanced consolidation control. These findings are consistent with the notion that the introduction of foam into the soil matrix increases pore space and reduces soil density, thereby mitigating consolidation settlement. The optimal dosage of polyurethane foam for achieving consolidation control is determined to be around 3%, beyond which the trend reverses, suggesting that excessive foam addition can be counterproductive. The significant reduction in the Mv value, exceeding 50%, further underscores the efficacy of PU foam in enhancing consolidation control. This substantial reduction in Mv suggests that the polyurethane foam has effectively improved the soil's mechanical behavior, leading to enhanced stability and reduced settlement. The results of this study have important implications for geotechnical engineering applications, where controlling soil settlement and ensuring stability are paramount. The use of polyurethane foam as a soil amendment offers a promising solution for mitigating soil consolidation issues in saturated clay strata, and its optimal dosage can be tailored to specific site conditions. The results of the current study are supported by the literature (Sharif Ul Islam, 2022) By adding construction and demolition waste to weak soil liquid limit, plastic limit, and more significantly settlement is reduced by 30%of the original Soil. Construction and demolition waste addition increases the coefficient of permeability and pre-consolidation pressure. (Cheng, Zhu et al. 2020) conducted a comprehensive study investigating the influence of varying nano bentonite levels on key geotechnical parameters, including the compression coefficient, consolidation coefficient, secondary consolidation coefficient, and permeability coefficient. (Khalid and Siang 2021) conducted a comprehensive study to identify the most efficient chemical additives for enhancing the strength of clay soil. Lime, cement, and fly ash were investigated as potential additives within a range of 8% to 10% in the soil mixture. A comparative analysis was conducted among lime, cement, and fly ash mixtures to determine the most effective chemical for enhancing soil strength.(Jarushi and Talibullah 2023) results show that, the lime-treated soil up to 10% offers the optimum in most characteristics compared to other additives. In contrast, the influence of cement is evident with the inclusion of cement content as 15 and 20%. The permeability and coefficient of consolidation are associated with the variation of additives percentage. That is to say, the most significant improvement of both is observed with the inclusion of 5% cement and 20% lime. (Jarushi and Talibullah 2023)

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

This research study employed an experimental methodology, utilizing a laboratory-based investigation to examine the effectiveness of foamed materials in controlling consolidation settlement in soil. Soil samples of varying types were collected and prepared according to standards, then mixed with selected foamed materials and compacted it.

Consolidation tests were performed on treated and untreated soil samples using a consolidometer, and the resulting data were analyzed statistically to compare the consolidation settlement of soil with and without foamed materials. From the research carried out to check the effect of PU foam on the consolidation behavior of saturated clay after complete testing and analysis of results certain conclusions may be drawn. These concluding remarks are stated below.

1) After making the comparative analysis by adding PU foam the consolidation settlement was found to reduce significantly which is an encouraging sign as far as the stability of the foundation is concerned.
2) As it is clear from the previous studies PU can be successfully used for enhancing other properties of soil. Therefore, it is highly recommended for soil stabilization
3) The percentage of PU foam may not be increased beyond 3 % as it reverses the magnitude of deformation.

B. Recommendations

The following are the major recommendations made after the completion of this work to help the researchers extend this work.

1) An investigative study must be done for other saturated clay soil with different natural moisture content and pre-consolidation pressure.
2) The effects of different percentages of Polyurethane foam less than 3% and greater than 5% on consolidation control must be studied.
3) Soil properties such as Cc, Mv, final settlement, pre-consolidation pressure over consolidation ratio, etc must be studied for the above-mentioned amounts of PU foam.
4) Research must be done for economical comparison of PU foam and other materials used for consolidation control.

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Consent to Publish: The authors agree to publish in the journal.
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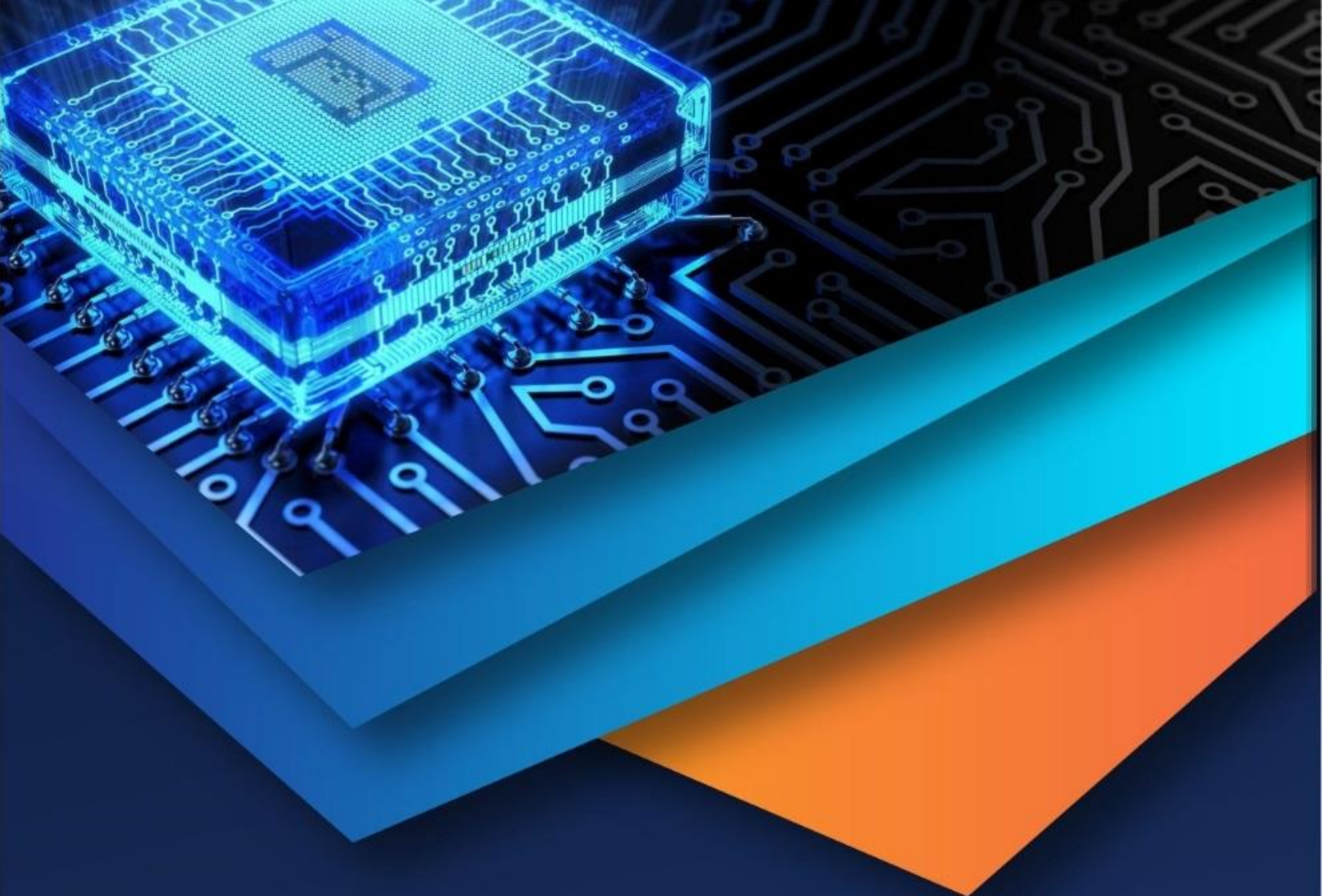

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IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429