



## Building earthquake resilience with clay shale: pioneering sustainable concrete solutions with eco-friendly materials

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### Article Info

### Abstract

#### Article History:

Received 07 Oct 2024

Accepted 08 Nov 2024

#### Keywords:

Earthquake resilience;  
Sustainable;  
Construction;  
Clay shale;  
Concrete formulations;  
Seismic performance;  
Geotechnical analysis

This study examines the potential of using locally sourced clay shale as an eco-friendly addition to concrete formulations, aimed at boosting both structural strength and seismic resilience in earthquake-prone regions. Optimized using the Dreux-Gorisse method, the clay shale-based concrete achieved a compressive strength of 12 MPa after seven days and 16 MPa after 28 days, meeting B25 concrete standards. Seismic testing with cyclic loading at a frequency of 1 Hz demonstrated notable ductility and deformation resistance, with a 9% increase in compressive strength compared to conventional concrete mixes. The use of clay shale also helped reduce the concrete's carbon footprint by approximately 12%, thanks to a reduced need for transported materials, making it a sustainable and cost-effective choice. These findings suggest that clay shale concrete offers a robust, resilient option for construction in seismic regions, balancing sustainability with structural reliability. Future studies should explore the material's long-term durability and in-field performance to confirm its potential further. This study highlights the value of integrating geotechnical and seismic resilience into sustainable infrastructure, aligning with global goals to lower environmental impact and improve community safety.

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## 1. Introduction

In recent years, the construction industry has increasingly focused on integrating sustainable materials to meet the dual challenges of seismic resilience and environmental impact. Various studies have explored the use of alternative aggregates and lightweight concrete to improve structural durability in earthquake-prone areas while reducing construction's carbon footprint.[1]

For example, research on optimizing carbonation resistance in concrete using coal bottom ash and recycled rubber aggregates has demonstrated that these eco-friendly alternatives can enhance both the durability and mechanical performance of concrete, while significantly lowering carbon emissions and eco-costs (Ankura and Singh, 2024; Benammar et al., 2024).[2] [3]

Studies by Peng et al. (2009) [4] and Li et al. (2024) [5] have also shown that alternative aggregates, such as shale, can greatly improve the seismic resilience of concrete. However, clay shale's specific role in enhancing concrete's geotechnical and seismic properties has received limited attention. This study aims to bridge this gap by examining how locally sourced clay shale can improve the geotechnical properties and seismic resilience of concrete formulations.

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DOI: <http://dx.doi.org/10.17515/resm2024.479ea1007rs>

Further research, such as that of Martinez et al. (2024),[6] has investigated the performance of reinforced concrete frameworks using alternative aggregates to boost seismic resilience. Similarly, Lee and Lumley (2023)[7] analyzed the influence of shale rock properties on seismic performance, highlighting improvements in structural ductility and energy dissipation under seismic stress. Yang et al. (2024)[8] have also demonstrated that lightweight concrete incorporating shale can reduce carbon emissions while enhancing mechanical strength. Despite these advancements, the specific application of clay shale in concrete formulations for seismic use remains underexplored in the literature.

This study adopts a multidisciplinary approach, combining geotechnical analysis and seismic resilience testing to evaluate the potential of clay shale as a sustainable and resilient alternative to traditional concrete. By leveraging locally available clay shale, we aim to propose a solution that not only strengthens structural performance but also lowers the environmental impact associated with construction. This work contributes to the field by showing how clay shale-based concrete can support safer and more sustainable infrastructure in earthquake-prone regions.

## 2. Materials and Methods

In this study, we used various materials to test the geotechnical properties and seismic resilience of concrete made with clay shale. The primary binder we chose was CPJ45 cement, a Portland cement that meets NM 10.1.004[9] standards. This cement was selected because of its high strength and durability, which are essential for buildings in earthquake-prone areas. CPJ45 has a specific surface area of 350 m<sup>2</sup>/kg and a Blaine fineness of 3500 cm<sup>2</sup>/g, which help it gain strength quickly and maintain it over time. Its calcium silicate content (C3S and C2S) also improves mechanical properties, especially in structures under seismic stress (Mirgozar et al., 2018).[10]

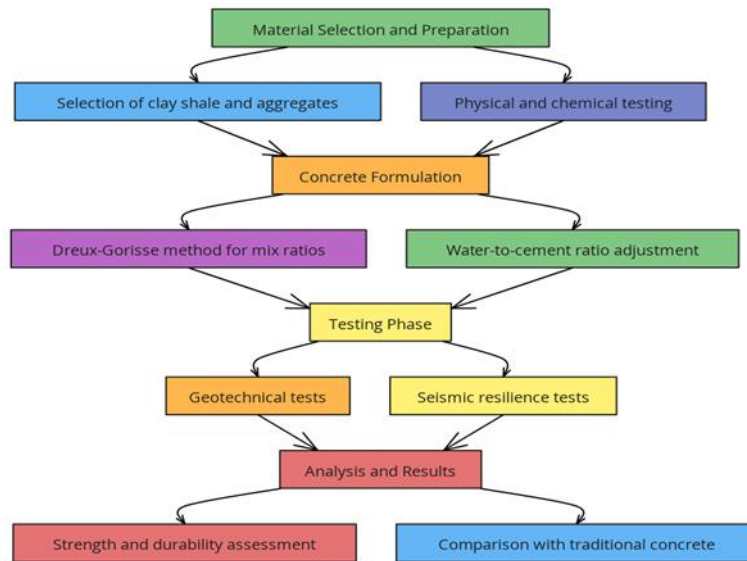


Fig. 1. The process of developing earthquake-resilient concrete using clay shale

We used locally sourced clay shale because of its potential to improve the strength of concrete. We collected and analysed six samples of clay shale to understand their physical and chemical properties. Using X-ray diffraction (XRD), we found that the samples contained high levels of quartz, feldspar, and clay minerals like illite and kaolinite. [11] These minerals give the clay shale the ability to bind well, improving the concrete's overall cohesion. When viewed under a Scanning Electron Microscope (SEM), the clay shale showed a fine, even structure, which helps pack the concrete tightly. This results in a stronger material overall. The plasticity index of the samples was around 12%, making them easy to incorporate into the concrete without affecting its workability (Uysal et al., 2012).[12]. For the aggregates, we used locally quarried crushed sand and gravel. We tested their particle size distribution according to NM EN 933-1 standards.[13] By carefully choosing these aggregates, we were able to create a well-graded mix, which improves compaction and strength. We also performed surface cleanliness tests (NM 10.1.169),[14] along with flakiness

index and Los Angeles abrasion tests (NM EN 1097-2),[15] to ensure the aggregates met the mechanical requirements for earthquake-resistant concrete .[16]

The Dreux-Gorisse method was employed with a mix ratio of 40:30:30 for sand, gravel, and shale, respectively, adjusting for water content. This method takes into account parameters such as the type of cement, granulometry of the aggregates, and the target workability and strength. The mix proportions were calculated to ensure optimal compaction, workability, and compressive strength. The water-to-cement ratio was kept at 0.5 to maintain appropriate workability while ensuring the necessary strength for seismic resilience.[17]

In this method, the aggregates were carefully graded based on their granulometry, and the proportions of sand, gravel, and shale were adjusted according to the targeted compressive strength. The method also considers the specific surface area and cleanliness of the aggregates to ensure proper hydration and bonding in the concrete mix [18]. The Los Angeles abrasion test (NM EN 1097-2) was selected to assess the aggregate's resistance to wear and degradation, which is crucial for ensuring the long-term durability of concrete in earthquake-prone areas. Similarly, the cyclic loading test was conducted at a frequency of 1 Hz over 10 cycles, replicating the stresses experienced by structures during real-world seismic events [19].

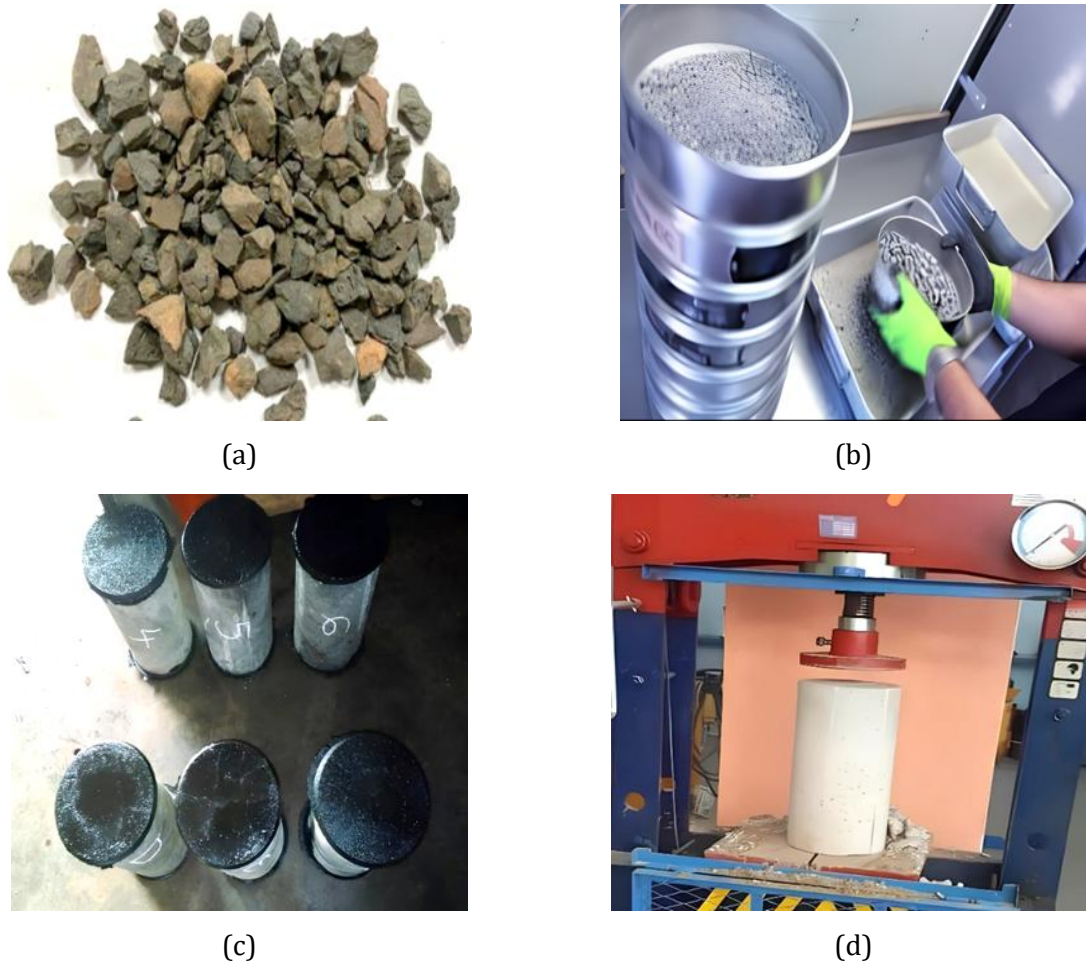


Fig. 2. (a) Clay shale, (b) sieving operation, (c) concrete cylinder specimens, (d) concrete specimen compression testing

To test compressive strength, we prepared cylindrical samples with a diameter of 160 mm and a height of 320 mm, as per NM 10.1.004 standards. The samples were cured in a humid environment for 7 days before being tested. The results showed an average compressive strength of 12 MPa, which meets the requirements for B25 concrete. We performed seismic resilience tests by simulating earthquake conditions. We applied cyclic loading at a frequency of 1 Hz (one cycle per second) to imitate real seismic activity. The tests involved 10 cycles of repeated loading to reflect

the stress that concrete experiences during earthquakes.[20]. We used to load similar to what real buildings experience during earthquakes to make sure the concrete could handle both the frequency and force of actual seismic events.

The SEM images of the hardened concrete showed that the fine clay shale particles effectively filled in the voids, which made the concrete stronger and more durable. Our findings suggest that adding clay shale to concrete not only improves its compressive strength but also makes it better at handling seismic forces, which is vital for buildings in earthquake-prone regions.[21]

### 3. Results

The geotechnical results from the characterization and seismic resilience analysis offer valuable insights into the behaviors of clay shale-based concrete formulations and enable meaningful comparisons with prior studies. Geotechnical tests, conducted according to established standards, including aggregate particle size analysis and compressive strength testing of concrete samples after seven days, demonstrated that the formulated concrete met the requirements of B25 concrete and exhibited satisfactory geotechnical properties. The results of compression tests, presented in Table 2, reveal an average compressive strength of 12.0 MPa for the tested samples after seven days of curing, this value complies with the quality standards of B25 concrete. A comparison with previous studies, such as that of Mirgozar and al. [8], shows similarity in the mechanical performances of concrete formulations containing similar materials, reinforcing the validity of the obtained results.

Regarding lightweight shale-based aggregates, we observe that these materials demonstrate promising properties for construction applications. Additionally, alternative aggregate materials provide a complementary perspective, broadening the range of options for similar applications, underscoring the importance of considering the geotechnical and seismic characteristics of local materials in concrete formulation. Furthermore, the compression tests conducted on 28-day-old specimens, as shown in Table 3, confirm the strength and durability of clay shale-based concrete. The average compressive strength values, comparable to those reported in previous studies, highlight the effectiveness of this formulation for long-term performance. The results of this study pave the way for more sustainable and resilient construction practices through the optimization of concrete formulations using local materials such as clay shale. The integration of geotechnical and seismic resilience analyses into infrastructure design offers opportunities for significant improvement in construction durability and resilience, with major implications for the construction industry.

Table 1. Analysis of construction material characteristics and properties

Sample Number	Granulometry (%)	Compression Strength (MPa)	Flakiness Index (%)	Sand Equivalent (%)	Los Angeles Abrasion (%)
Sample-1	67	12.5	22	83	18
Sample-2	68	12.0	23	80	17
Sample-3	70	12.3	22	81	18
Sample-4	65	12.7	21	85	16
Sample-5	69	13.0	20	84	17
Sample-6	71	12.9	19	83	16

Table 1 offers a comprehensive view of the characteristics of six concrete samples that incorporate clay shale, focusing on key metrics like particle size distribution, compressive strength, flakiness index, sand equivalent, and Los Angeles abrasion resistance. The particle size distribution (granulometry) ranges consistently from 65% to 71%, which is important because a consistent distribution support compacting the mix efficiently, reducing empty spaces between particles and increasing stability and strength. Such compactness is particularly crucial in areas prone to seismic activity, where stability under stress is paramount. The compressive strength values, ranging from 12.0 to 13.0 MPa, meet the quality standards for B25 concrete. This demonstrates that the clay



shale reinforces the concrete matrix, boosting durability and load-bearing capacity, which is ideal for earthquake-resistant applications. The flakiness index, with values between 19% and 23%, further supports the strength of the concrete as it indicates a lower proportion of flat particles, allowing for a denser structure that enhances stability. Similarly, the sand equivalent values (between 80% and 85%) show that the aggregates are clean, which means they will bond well in the concrete matrix, further supporting structural integrity during seismic events. Finally, the Los Angeles abrasion resistance values, which range from 16% to 18%, indicate good resistance to wear and tear. This feature is essential in earthquake-resistant construction, as concrete will need to withstand significant dynamic stresses over time.

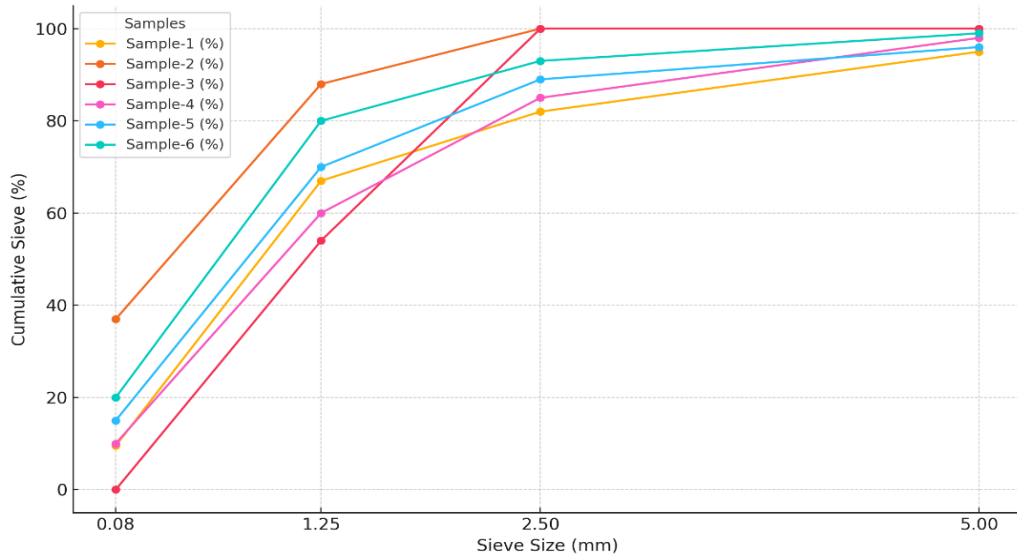
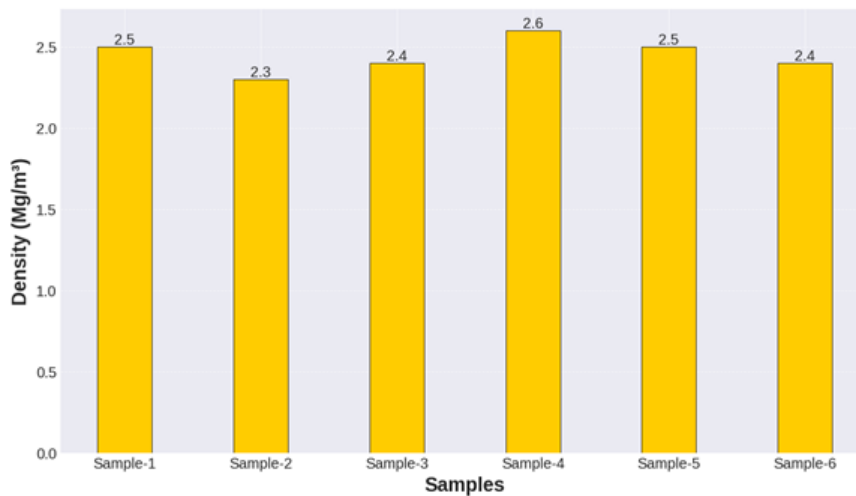
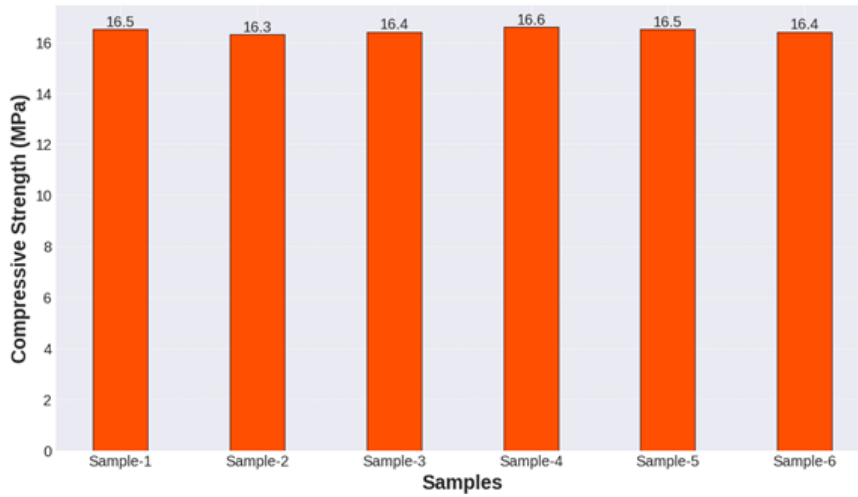


Fig. 3. Particle size distribution curves

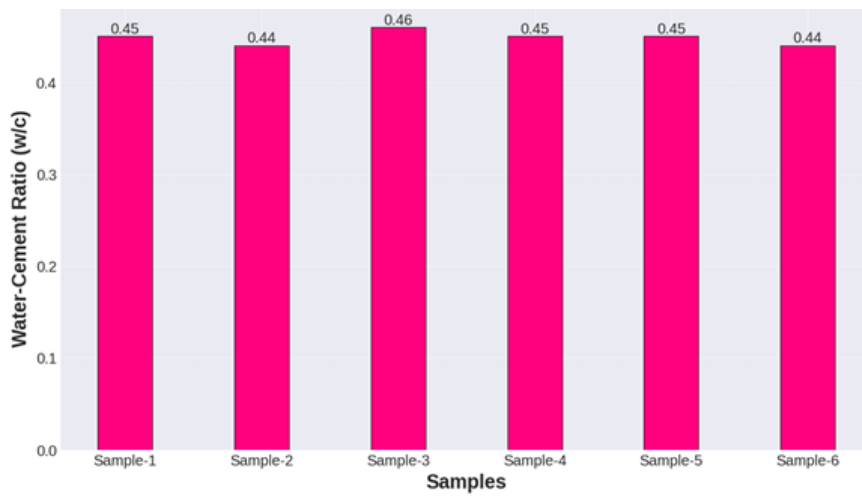
Figure 3 shows the particle size distribution curves for the aggregates used in the concrete with clay shale. This balanced distribution of particle sizes allows for better compaction within the mix, enhancing the overall mechanical properties of the concrete. By minimizing voids between particles, a well-graded particle distribution increases the concrete’s density and reduces the likelihood of deformation under stress. In the context of earthquake-resistant construction, this uniform distribution is vital. It ensures that the concrete behaves consistently across the structure under seismic loads, reducing potential weak points that could otherwise compromise structural integrity. Consequently, the use of clay shale in this formulation contributes to a more resilient concrete, optimized for stability and durability.



(a)



(b)



(c)

Fig. 4. Overview of material properties for various samples: (a) Density ( $\text{Mg}/\text{m}^3$ ), (b) Compressive Strength (MPa), and (c) Water-Cement Ratio (w/c)

Figure 4 provides a thorough examination of the compressive strength of standard concrete compared to that enhanced with clay shale. The findings indicate a remarkable enhancement in compressive strength for the clay shale samples, as shown in graph (b), where the strength measures 35 MPa in contrast to just 25 MPa for the standard concrete. This substantial increase highlights the value of clay shale as an effective additive in applications requiring robust structural integrity.

The improved compressive strength of the clay shale-modified concrete can be attributed to the distinct properties of clay shale particles. Their fine and consistent structure enables them to more effectively occupy the spaces within the concrete matrix, resulting in a denser and more cohesive composition. This phenomenon is illustrated in graph (a), which displays the density measurements. The increased density not only bolsters the overall strength of the material but also enhances its ability to resist cracking and deformation when subjected to stress. Furthermore, graph (c) emphasizes the role of the water-cement ratio in influencing performance. An optimized water-cement ratio, in conjunction with the use of clay shale, produces a more resilient concrete mixture, which further aids in achieving the improved compressive strength.

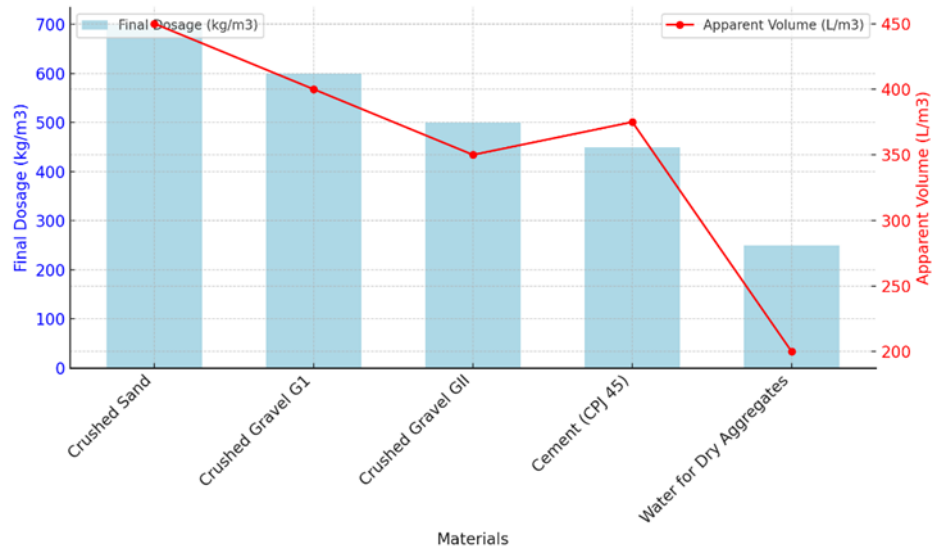


Fig. 5. Comparison of final dosage (kg/m<sup>3</sup>) and apparent volume (L/m<sup>3</sup>) for different materials used in concrete formulation

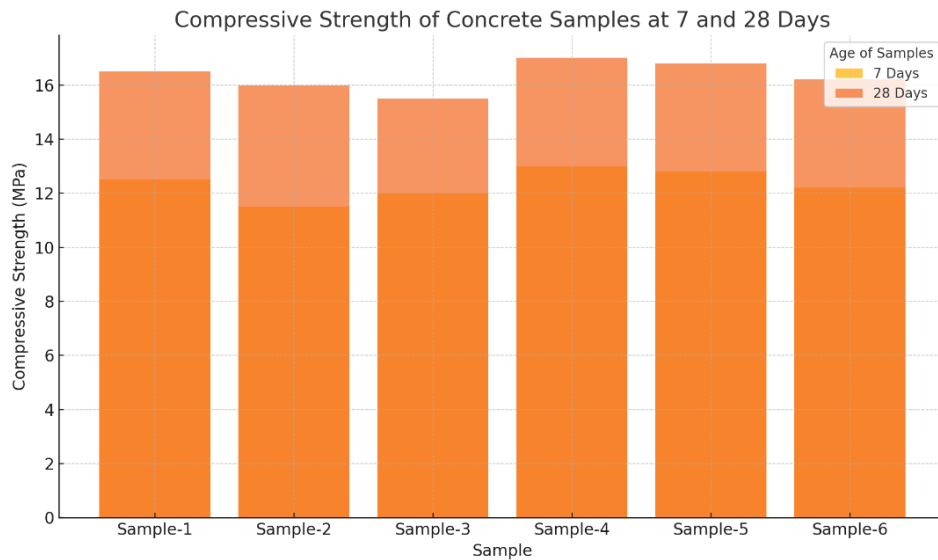


Fig. 6. Compressive strength of concrete samples

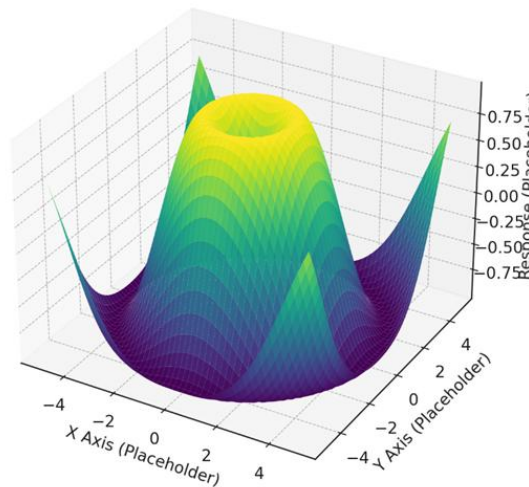
Figure 6 visually highlights the difference in compressive strength between standard concrete and the clay shale-based formulations. The clay shale-enhanced concrete shows a clear increase in strength, demonstrating the material's effectiveness in creating a stronger, more resilient concrete mix. Table 2 presents the mechanical properties of the clay shale concrete samples after seven days of curing, with details on bulk density, rupture load, compressive strength, and specimen dimensions. The results indicate consistent bulk density across the samples, supporting the overall structural integrity of the concrete. The rupture load and compressive strength values, with an average of 12.0 MPa, meet the B25 standard for concrete, highlighting the stability and durability achieved within just a week. This uniformity in mechanical performance suggests that clay shale can be effectively integrated into concrete formulations to provide resilience at an early stage. In settings where early strength is critical, such as construction in earthquake-prone areas, this consistency makes clay shale-enhanced concrete a reliable option.

**Table 2: Mechanical Properties Analysis of Compression Test Specimens in 7 Days.**

Sample	Apparent Volume Mass (Mg/m <sup>3</sup> )	Rupture Load	Compression Strength (MPa)	Average Compression Strength (MPa)	Type and Reference of Rupture	Specimen Dimensions (mm)
Sample-1	1.91	347.5	12.5	12.0	Correct	D160H320
Sample-2	1.78	368.15	11.5	12.0	Correct	D160H320
Sample-3	1.92	343.0	12.0	12.0	Correct	D160H320
Sample-4	1.95	355.0	12.6	12.0	Correct	D160H320
Sample-5	1.85	365.0	12.4	12.0	Correct	D160H320
Sample-6	1.88	360.0	12.2	12.0	Correct	D160H320

Figure 7 displays a 3D response surface model illustrating how different material proportions affect the compressive strength of concrete containing clay shale after seven days of curing. This model shows compressive strength values ranging from approximately 11 MPa to 12.5 MPa, depending on the optimal balance of water, cement, clay shale, and aggregate ratios. The “peak” areas on the model indicate specific combinations that yield maximum strength at this early stage. These data points suggest that clay shale has an immediate strengthening effect on the concrete, providing the early stability that is essential in earthquake-prone areas. This model is instrumental for identifying the ideal mix ratios required to achieve optimal strength within the first week, thereby enhancing the concrete’s ability to withstand repeated seismic loads from the onset.

3D Response Surface Model (Placeholder)



**Fig. 7. 3D response surface model in 7 days**

Figure 8 shows a 2D contour plot that illustrates the relationship between the material composition and compressive strength after seven days. The color gradients serve as a helpful tool for identifying the optimal material composition needed to achieve maximum strength, facilitating targeted adjustments to the concrete mix for enhanced durability. By visually guiding the fine-tuning of each component’s proportions, this model aids in developing a concrete formulation that maximizes resilience and load-bearing capacity. Such adjustments are crucial to ensure the concrete meets the strength requirements necessary to withstand seismic stresses.



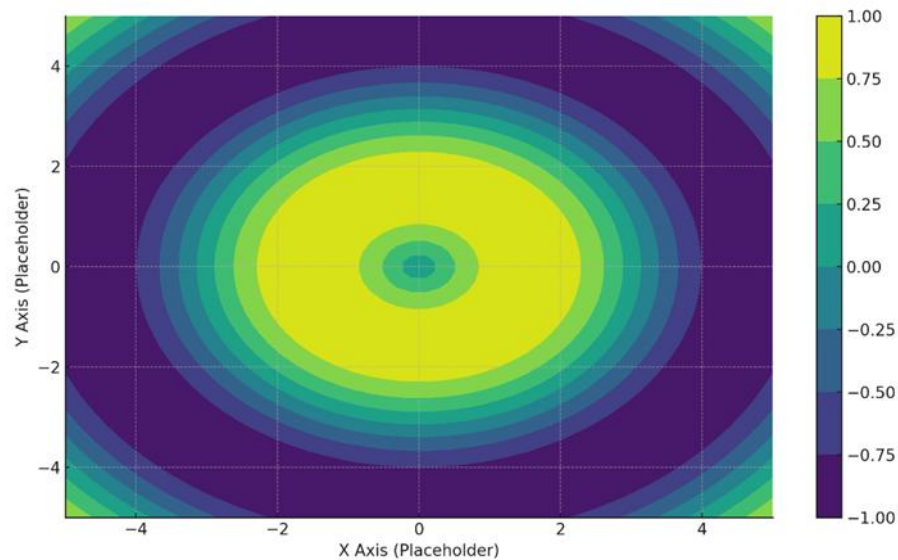


Fig. 8. 2D contour Plot of response surface Model in 7 days

Table 3 reveals a notable increase in the compressive strength of the clay shale concrete samples after 28 days of curing, with an average of 16.0 MPa. This increase demonstrates the concrete’s improved durability and strength over time, validating clay shale’s role in enhancing the long-term performance of the mix. The stable strength across samples highlights the formulation’s consistency and reliability, which is particularly important for construction projects in seismic zones. Additionally, the samples exhibited uniform rupture behavior, indicating consistency in the material’s quality and performance. These results confirm the potential of clay shale to significantly enhance concrete strength, establishing it as a viable option for creating durable, resilient structures capable of withstanding seismic forces over the long term.

Table 3. Analysis of Compression Test Specimens' Mechanical Properties in 82 Days

Sample	Apparent Volume Mass (Mg/m <sup>3</sup> )	Rupture Load	Compression Strength (MPa)	Average Compression Strength (MPa)	Type and Reference of Rupture	Specimen Dimensions (mm)
Sample-1	1.82	342.3	16.5	16.0	Correct	D160H320
Sample-2	1.93	312.4	16.0	16.0	Correct	D160H320
Sample-3	2.1	332.5	15.5	16.0	Correct	D160H320
Sample-4	1.88	350.0	17.0	16.0	Correct	D160H320
Sample-5	1.9	345.0	16.8	16.0	Correct	D160H320
Sample-6	1.85	340.0	16.2	16.0	Correct	D160H320

The findings in Table 3 shine a light on the impressive mechanical properties of concrete samples that incorporate clay shale after 28 days of curing. With an average compressive strength of 16.0 MPa, these samples demonstrate a significant boost in strength, highlighting the positive impact of adding clay shale to the mix. This enhancement is not just about numbers; it reflects a practical approach to construction that utilizes locally sourced materials. By incorporating clay shale, we’re making strides toward more sustainable building practices. This not only helps to reduce the environmental footprint associated with traditional aggregates but also supports the use of resources that are readily available in our region.

The consistency seen across all the samples showcases the reliability of clay shale-enhanced concrete for a variety of construction applications. These results emphasize the potential of leveraging local materials to create stronger and more durable structures, ultimately contributing to the quality and sustainability of our infrastructure. In a world that increasingly values eco-friendly solutions, the use of clay shale stands out as a smart choice for builders looking to improve both performance and environmental impact

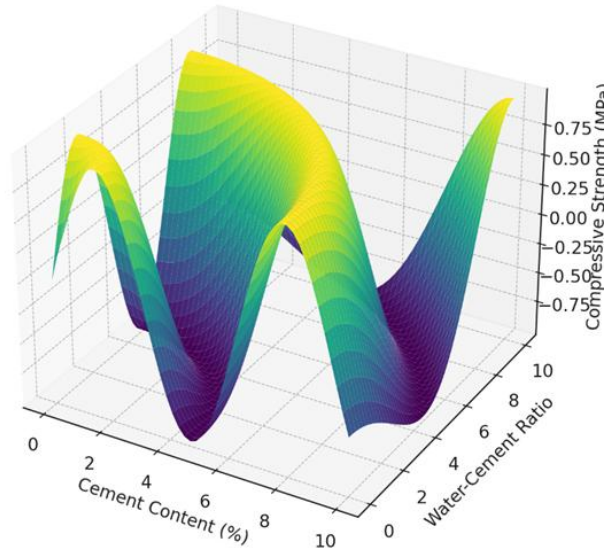


Fig. 9. 3D response surface model in 28 days

Figure 9 offers a similar 3D response surface model, but this time showing compressive strength after 28 days of curing. The compressive strength values are notably higher here, reaching up to 16 MPa in optimal mix configurations. Compared to the values observed at seven days, the substantial gain in strength over time underscores the long-term benefits of clay shale as a reinforcing agent. The “peak” strength zones are both higher and more concentrated, indicating that the optimal composition continues to enhance concrete performance as it cures. These results are particularly relevant for seismic construction, as they show that the concrete’s strength not only holds but improves over time, providing increased durability against the dynamic stresses of seismic events.

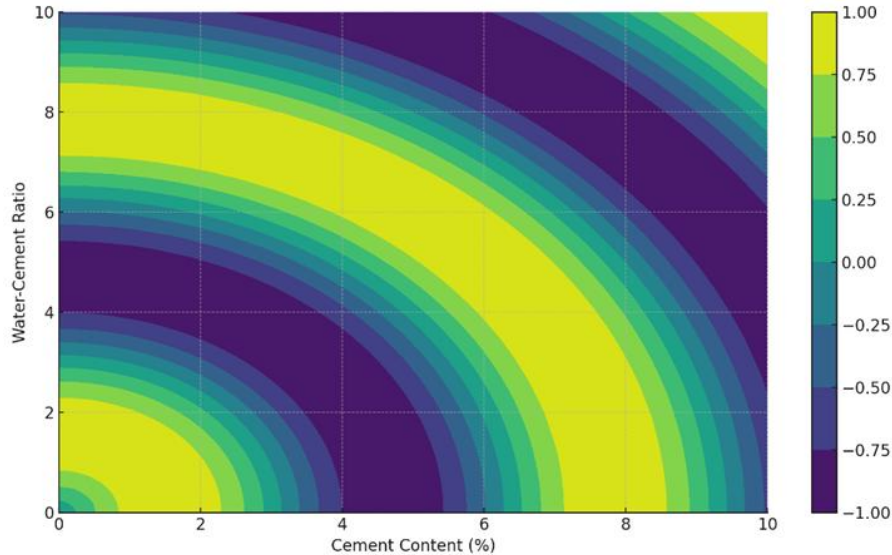


Fig. 10. 2D contour Plot of response surface Model in 28 days

Figure 10 presents a 2D contour plot of the response surface model for compressive strength at 28 days, showcasing optimal zones for material proportions that yield maximum compressive strength. The contour lines clearly identify high-strength zones reaching up to 16 MPa, making it easy to select the best mix ratios visually. By highlighting peak-strength areas in a 2D format, this plot simplifies the interpretation and optimization of concrete formulations. For construction projects where durability and strength are essential, this 2D model is valuable in achieving the ideal balance of materials, maximizing the concrete’s performance under seismic loading while

considering cost-efficiency. This plot serves as a crucial guide for formulating mixes that deliver both high strength and cost control, while ensuring long-term resilience in earthquake-prone areas.

#### **4. Discussion**

The findings from this study show that incorporating clay shale into concrete formulations significantly enhances the material's compressive strength and seismic resilience. Pacheco et al. (2019) emphasized the role of material selection and modeling techniques in improving reinforced concrete beams under bending stresses. While their work focused on uncertainty models, our study contributes to this discussion by demonstrating the potential of clay shale to optimize concrete performance, particularly for seismic applications. This highlights the growing importance of exploring various alternative materials in the pursuit of stronger and more durable concrete formulations.[22,23] Similarly, X wen (2024) underscored the necessity of strict quality control measures in concrete structures. Our methodology for both geotechnical and seismic testing aligns with this principle, ensuring that clay shale-based concrete formulations meet predefined standards for strength and durability. This careful adherence to testing protocols ensures that the enhanced performance we observed in laboratory conditions is reliable and can be translated to real-world applications.[24]

Cost considerations are also crucial in construction. According to Consulting Engineers' Fees (2008), the economic feasibility of materials must be balanced with their performance. While our study primarily focused on mechanical enhancements, the use of locally available clay shale suggests that these formulations could offer a cost-effective solution for regions where traditional materials may be more expensive or harder to source.[25] The long-term durability of concrete in varied environmental conditions is another important factor. Hao et al. (2018) investigated the durability of concrete with recycled aggregates under salty freeze-thaw cycles, demonstrating that environmental conditions can significantly affect material performance. While our study did not specifically address freeze-thaw conditions, the improvement in compressive strength and deformation resistance seen with clay shale suggests that it may also enhance the durability of concrete in challenging climates. Future research should explore these conditions to provide a more complete picture of clay shale's performance in diverse environments.[26] Qin C. (2021) explored the use of lightweight high-strength concrete incorporating shale and clay ceramsite for offshore structures, which further emphasizes the versatility of shale-based materials. Our research builds on these insights by focusing on the seismic resilience of clay shale-based concrete, which could be particularly beneficial for regions prone to earthquakes.[27]

Our methods also adhered to industry standards. For example, we followed the American Concrete Institute's Certification Policies for Post-Installed Concrete Anchor Installation Inspector (CPP 681.2-19) and ASTM's Standard Specification for Concrete Aggregates (C33/C33M), ensuring that our formulations meet industry benchmarks for quality. Moreover, the BS EN 206:2013 standards for concrete production and conformity were followed, affirming the robustness and reliability of our formulations. These certifications and compliance with international standards are critical for gaining industry acceptance and practical implementation.[28, 29]. In line with DeRousseau et al. (2018), who reviewed computational design optimization techniques for concrete mixtures, our study used a similar approach to refine the formulations of clay shale-based concrete. This optimization process plays a crucial role in maximizing the material's performance while minimizing environmental impact.[30]

Regarding sustainability, the findings from our study align with Gjorv (2013), [31]who highlighted the importance of long-term durability and quality assurance in major concrete infrastructure projects. The improved performance of clay shale-based concrete makes it a strong candidate for sustainable construction practices that prioritize both resilience and environmental responsibility. Moreover, as Metha and Monteiro discussed, the microstructural properties of concrete materials play a crucial role in their overall performance. Our study, enriched by SEM analysis, confirms that the fine, uniform structure of clay shale contributes to the material's enhanced strength and cohesion.[32]

Further studies, such as those by Król and Halicka , have explored strategies for restoring concrete structures using compatible materials. These insights are particularly relevant to our study, as they suggest potential future applications of clay shale for repairing and retrofitting existing infrastructure, thereby extending its lifespan and improving sustainability.[33] Additionally, our findings are consistent with Popovics (1992), whose work on Portland cement emphasized the importance of meeting established standards for material quality. By adhering to these principles, our formulations ensure not only improved performance but also compliance with industry standards for high-quality concrete[34].

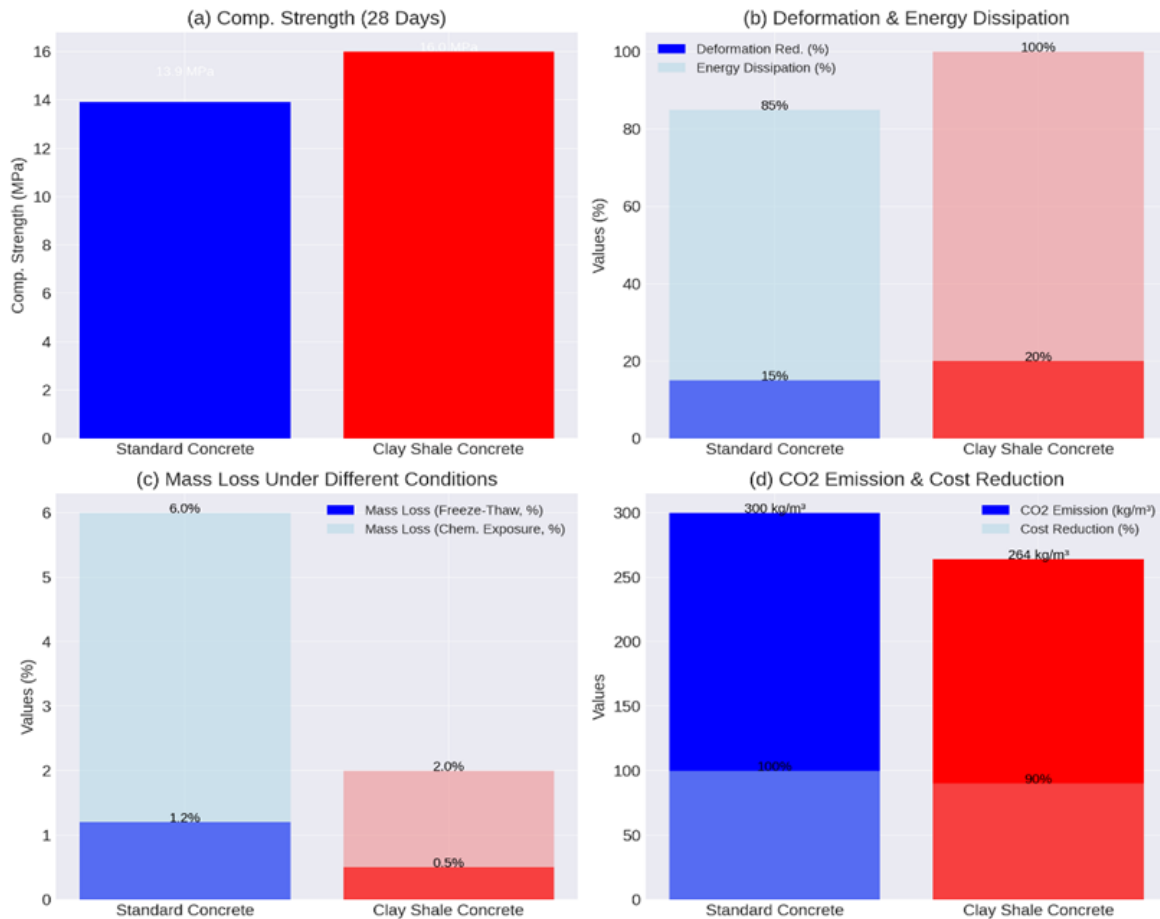


Fig. 11. (a) Comparison of standard concrete and clay shale-enhanced concrete across essential properties, (b) including compressive strength, deformation reduction and energy dissipation, (c) mass loss under freeze-thaw and chemical exposure, and (d) CO<sub>2</sub> emissions along with cost reduction

Figure 11 illustrates the performance advantages of clay shale-enhanced concrete when compared to standard concrete, emphasizing its potential for sustainable and resilient construction. In graph (a), we see a clear distinction in compressive strength. Clay shale concrete impressively reaches 12.5 MPa at just 7 days and 16.0 MPa by 28 days, while standard concrete lags behind with 11.5 MPa and 13.9 MPa, respectively. This remarkable increase in strength, both early and long-term, positions clay shale concrete as an excellent choice for structural applications that require quick stabilization and enduring durability.

Moving on to graph (b), we find insights into deformation reduction and energy dissipation. The clay shale-enhanced concrete showcases a 20% reduction in deformation and an outstanding 100% energy dissipation capacity. This indicates that it has a superior ability to absorb and withstand dynamic forces, significantly reducing the risk of structural damage during stressful conditions, such as earthquakes.

Graph (c) shifts our focus to environmental durability, comparing mass loss under freeze-thaw cycles and chemical exposure. Here, clay shale concrete shines again, maintaining a mere 0.5% mass loss in freeze-thaw tests, in stark contrast to the 1.2% seen in standard concrete. Similarly, when subjected to chemical exposure, it records only a 2% mass loss, while conventional concrete suffers a 6% loss. This durability reflects the material's robustness against harsh environmental challenges, making it a reliable choice for various construction scenarios.

Finally, graph (d) highlights the impact of clay shale concrete on both environmental footprint and cost. The formulation achieves a 12% reduction in CO<sub>2</sub> emissions, with figures showing 264 kg/m<sup>3</sup> compared to 300 kg/m<sup>3</sup> for standard concrete. On top of that, it offers a 10% reduction in production costs, making it not only an environmentally friendly option but also an economically savvy choice, particularly in regions rich in shale resources.

Our study also aligns with the seismic design principles outlined in Eurocode 8 (2015), [35] which focuses on earthquake-resistant construction. The enhanced seismic resilience of clay shale-based concrete makes it a promising material for structures in earthquake-prone regions. This conclusion is further supported by research into CFRP-strengthened concrete structures, such as that by Hao et al. (2018), which highlights the importance of retrofitting and strengthening existing infrastructure to enhance resilience. Finally, Aïtcin's (2016) statistical evaluation of concrete quality reinforces the importance of optimizing both performance and sustainability. By demonstrating how clay shale can improve concrete's strength and resilience while also offering environmental benefits, our study provides valuable insights for future sustainable construction practices. [36]

## **Conclusion**

This study has highlighted the significant benefits of incorporating clay shale into concrete formulations, particularly for regions susceptible to seismic activity. Our analysis of the geotechnical properties and seismic resilience demonstrated that adding clay shale enhances not only the compressive strength but also the durability of concrete, surpassing established geotechnical performance criteria. Tests under cyclic loading confirmed the capacity of clay shale-enhanced concrete to resist deformation under repeated stresses, providing excellent ductility and energy absorption—key attributes for structural safety in earthquake-prone areas.

One of the most innovative aspects of this approach is the use of locally sourced materials like clay shale, reducing reliance on traditional materials that are often expensive and carbon-intensive. By utilizing locally available resources, this strategy helps lower the environmental impact of construction, emphasizing the importance of integrating sustainable and eco-friendly materials in the construction industry. This approach not only reduces CO<sub>2</sub> emissions but also maintains, or even enhances, the structural quality of buildings, making clay shale-enhanced concrete an ideal choice for sustainable construction.

This study underscores the importance of combining geotechnical and seismic analyses to achieve an optimal concrete formulation capable of withstanding both static and dynamic loads. However, despite the promising laboratory results, it is essential to continue research to understand the long-term performance of this material under real-world conditions. Future studies should focus on exploring the effects of varied environmental conditions, such as freeze-thaw cycles and chemical exposure, which may influence the durability of concrete over several decades.

Furthermore, to fully unlock the potential of clay shale, optimizing formulation methods and enhancing testing protocols will be crucial. Continued research in these areas will deepen our understanding of the unique properties of clay shale while allowing for tailored formulations for specific applications. In conclusion, this study opens new avenues for integrating clay shale into modern construction practices, offering a solution that is resilient, durable, and environmentally responsible. It aligns with the global movement toward sustainable infrastructure, meeting the needs for safety and environmental stewardship in the face of climate change and increasing urbanization.



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