Library Progress International
Vol.44 No. 3, July-December 2024: P. 24418-24427

Print version ISSN 0970 1052
Online version ISSN 2320 317X

Original Article

Available online at www.bpasjournals.com

The Impact of Glass Powder on Concrete's Mechanical Properties: A Sustainable Approach

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How to cite this article: Y. Himath Kumar, Grandhi Jyothi Swaroop, P. Sai Krishna, D. Bahadur Thapa, Nadigatla Naveen Kumar (2024) The Impact of Glass Powder on Concrete's Mechanical Properties: A Sustainable Approach. *Library Progress International,* 44(3), 24418-24427

Abstract
This study investigates how concrete's mechanical qualities are affected when glass powder is used in part in place of cement. The effects of different glass powder percentages (0%, 3%, 6%, 9%, and 12%) on compressive strength, split tensile strength, and flexural strength over 7, 14, and 28-day curing times were examined. The findings show that adding up to 9% glass powder to concrete greatly increases its flexural, split tensile, and compressive strengths. Strength attributes were found to deteriorate beyond a replacement level of 9%, which was the maximum improvement. This study shows how glass powder can be used as a useful cement additive, supporting more environmentally friendly building methods.
Keywords: *Glass powder, Sustainable construction, green concrete, Supplementary cementitious materials, Mechanical properties of concrete.*

1. INTRODUCTION

In order to lessen its environmental effect while preserving concrete's effectiveness, the building industry is constantly looking for sustainable materials. The use of leftover glass powder as a partial cement substitute is one intriguing substance that has attracted a lot of interest. In addition to addressing the environmental problems related to glass disposal, using waste glass in the production of cement and concrete also helps to conserve resources and lower carbon emissions. Numerous studies have shown that adding leftover glass powder to concrete mixtures can improve the material's durability and mechanical qualities. This strategy emphasizes the need for environmentally friendly and financially feasible materials, which is in line with the larger objective of sustainable growth in the building industry.

1.1 Overview of the Construction Industry and Sustainable Practices

Because of its reliance on Portland cement, the building sector is one of the biggest users of natural resources and a major producer of carbon emissions worldwide. About 7–8% of the world's CO_2 emissions come from the manufacture of cement, which has raised awareness and prompted efforts to use more environmentally friendly building techniques. The hunt for environmentally suitable substitutes for cement in concrete has accelerated in recent years. The use of waste materials is one promising strategy that improves concrete's performance qualities while simultaneously lessening its negative effects on the environment. Waste glass powder has become a promising supplementary cementitious material (SCM) among these materials because of its pozzolanic qualities and capacity to lower the carbon concrete production.

1.2 Introduction to Glass Powder as a Supplementary Cementitious Material (SCM)

Glass powder is derived from finely ground waste glass, which is typically obtained from a variety of sources, including recycled bottles, window glass, and industrial by-products. The chemical composition of glass, primarily consisting of silica (SiO_2), makes it suitable for use as a pozzolan—a material that reacts with calcium hydroxide in the presence of water to form compounds that contribute to the strength and durability of concrete. When glass is ground to a fine powder, it exhibits higher pozzolanic activity
due to the increased surface area, which enhances its reactivity with the hydration

products of cement.
The use of glass powder in concrete not only provides a solution to the disposal problems associated with waste glass but also addresses the need to find alternatives to traditional cement. Traditional cement production is energy-intensive and relies heavily on the consumption of limestone, which leads to significant CO_2 emissions. By partially replacing cement with glass powder, it is possible to reduce these emissions, conserve natural resources, and improve the overall sustainability of construction practices.

1.3 Environmental and Economic Impacts of Using Waste Glass Powder

The addition of waste glass powder to concrete mixtures has significant positive environmental effects. The decrease in the amount of waste dumped in landfills is one of the biggest benefits. Each year, millions of tons of waste glass are produced, much of which cannot be recycled because of contamination or financial difficulties. By diverting this waste glass from landfills and using it as a raw material for concrete production, the environmental impact of waste disposal is lessened.

In the building sector, using leftover glass powder might result in financial savings. Glass powder can be produced from locally available waste glass at a relatively low cost compared to traditional SCMs like fly ash or silica fume. The lower production costs, coupled with reduced expenses related to waste disposal, make glass powder an attractive alternative for cementitious applications in concrete. Additionally, reducing the dependency on raw cement materials can lead to long-term cost benefits as the availability of natural resources becomes more limited.

1.4 Mechanism of Pozzolanic Reactions in Concrete with Glass Powder

The pozzolanic qualities of glass powder play a major role in how well it substitutes cement. The finely ground glass powder is added to a concrete mix and, upon reaction with calcium hydroxide, a by-product of cement hydration, forms extra calcium silicate hydrate (C-S-H), which is the compound that gives concrete its strength. Through the refinement of the pore structure and the reduction of permeability of the concrete matrix, this pozzolanic reaction not only improves the mechanical properties of the concrete but also increases its durability.

Particle size, glass type, and quantity of glass powder employed in the mixture all affect the pozzolanic activity of the powder. Because of their larger surface area, fine glass powder particles tend to be more reactive, enabling more effective chemical interactions with cement hydration products. Research has demonstrated that the use of glass powder with particles smaller than 75 micrometers can greatly increase the strength and durability of concrete, bringing it up to par or better than other widely used SCMs such as slag and fly ash.

1.5 Applications of Glass Powder in the Construction Industry

Concrete of all kinds, including high-performance, self-compacting, and structural concrete, can benefit from the use of glass powder. Applications requiring increased durability and resistance to chemical attacks benefit greatly from its use. For instance, concrete that has been mixed with glass powder has demonstrated increased resistance to sulfate attacks and penetration by chloride ions, two important elements in the durability of bridges, maritime constructions, and other infrastructure exposed to severe conditions.

Case studies and field applications have demonstrated the practicality of using glass powder in concrete for large-scale projects. In some regions, recycled glass powder has been successfully integrated into road construction, building foundations, and precast concrete products, highlighting its versatility and effectiveness in diverse construction scenarios.

1.6 Research Advances and Technological Developments

Significant progress has been made in the last ten years in the study and creation of glass powder as a cement substitute. The optimization of mix designs to attain the intended mechanical and durability qualities of concrete has been the subject of numerous studies. Analysis conducted in comparison with other SCMs has shed important light on the particular benefits and constraints associated with the use of glass powder in cementitious applications. In order to guarantee the durability and safety of glass powder-modified concrete in structural applications, researchers have also looked into the long-term performance of the material and how it behaves in different environmental settings.

2. Literature Review

Several researchers have explored the feasibility of using waste glass powder as a partial replacement for cement in concrete, examining its effects on the material's mechanical properties, durability, and microstructure. Du and Tan (2014) investigated the application of waste glass powder in concrete and concluded that it could effectively replace a portion of the cement without compromising the material's structural integrity, demonstrating a significant potential for sustainable construction practices [1].

Matos and Sousa-Coutinho (2012) focused on the durability aspects of mortar containing waste glass powder, revealing that this substitution enhances the resistance of concrete to chemical attacks, thus extending the lifespan of structures in aggressive environments [2]. Similarly, Schwarz and Neithalath (2008) compared the influence of fine glass powder on cement hydration to that of fly ash, providing insights into the pozzolanic activity of glass powder and its role in improving the degree of hydration [3].

Further studies by Aliabdo et al. (2016) highlighted the utilization of waste glass powder not only in enhancing the compressive strength of concrete but also in contributing to the production of a more sustainable building material by reducing the demand for conventional cement [4]. In another investigation, Schwarz et al. (2007) used electrical conductivity measurements to characterize the behaviour of cement pastes modified with coarse glass powder, illustrating its effectiveness in modifying the microstructural properties of the cementitious matrix [5].

Lee et al. (2017) evaluated the performance of concrete incorporating both glass powder and glass sludge, finding that these materials functioned well as supplementary cementing materials, thereby improving the mechanical properties of the concrete while also reducing waste [6]. Elaqra and Rustom (2018) explored the rheological and mechanical properties of cement paste containing glass powder, confirming its ability to improve workability and enhance early-age strength development [7].

The pozzolanic properties of glass powder were further substantiated by Tamanna et al. (2016), who demonstrated its effectiveness in reacting with calcium hydroxide to improve the durability and performance of cement paste [8]. Additionally, Afshinnia and Rangaraju (2016) investigated the combined use of ground glass powder and crushed glass aggregate, emphasizing the importance of optimized mix designs to achieve desired concrete properties [9].

Tamanna and Tuladhar (2020) examined the sustainable use of recycled glass powder as a cement replacement, focusing on its role in enhancing the environmental performance of concrete without compromising its structural capabilities [10]. Harbi et al. (2017) studied the combined effect of kaolin fillers, metakaolin, brick waste, and glass powder, illustrating the synergistic benefits of using multiple waste materials in cement composites [11].

3. Objective

This study's main goals are to determine whether it is feasible to substitute some of the cement in

concrete with waste glass powder and to assess how this substitution would affect the mixtures' durability and mechanical qualities. Particular objectives consist of:

1. Evaluating Mechanical Properties: To ascertain how various glass powder concentrations affect the concrete's tensile, flexural, and compressive strengths.
2. Comparative Analysis: To illustrate the special benefits and restrictions of utilizing glass powder, evaluate how well glass powder-modified concrete performs in comparison to regular concrete and other supplemental cementitious materials like fly ash, silica fume, and slag.
3. Sustainability Assessment: To assess the financial and environmental advantages of using waste glass powder in concrete, taking into account things like waste management strategies, a lower carbon footprint, and the preservation of natural resources.

4. Scope

The scope of this study encompasses the following aspects:

1. **Mix Design Optimization:** Development of various concrete mix designs incorporating different proportions of glass powder, ranging from 5% to 15% replacement levels, to identify the optimal mix that balances strength, durability, and workability.
2. **Laboratory Testing:** Conducting a series of laboratory tests to evaluate the mechanical properties (e.g., compressive strength, split tensile strength, flexural strength) of concrete containing glass powder.
3. **Comparative Analysis with Standard Materials:** Benchmarking the performance of glass powder-modified concrete against conventional cement-based concrete and concrete incorporating other supplementary cementitious materials (SCMs).
4. **Environmental Impact Assessment:** Examining how employing discarded glass powder might reduce greenhouse gas emissions, landfill trash, and the ecological footprint of producing concrete, among other environmental benefits.
5. **Field Applications and Case Studies:** Exploring the practical applications of glass powder in real-world construction projects, reviewing case studies to understand the challenges and best practices in its use.

5. Methodology

The purpose of this study's technique was to methodically evaluate how adding glass powder to concrete in place of some of the cement would affect the material's mechanical qualities. The process went as follows in detail:

1. **Materials Selection:**
   - Cement: Ordinary Portland Cement (OPC) served as the primary binding material.
   - Glass Powder: Waste glass was processed into a fine powder to achieve particle sizes comparable to that of cement, ensuring proper integration within the concrete mix.
   - Aggregates: Fine and coarse aggregates conforming to standard specifications were used in the concrete mix.
   - Water: Potable water was utilized for mixing and curing purposes to maintain consistency and reliability in the concrete properties.
2. **Mix Design:**
   - Concrete mixes were prepared with varying percentages of glass powder replacing cement at 0%, 3%, 6%, 9%, and 12%.
   - A consistent water-to-cement ratio was maintained for all mixes to ensure uniformity in workability and consistency.
3. **Specimen Preparation:**
   - Concrete specimens were cast for each percentage of glass powder replacement using standard moulds, specifically designed to meet the requirements for different mechanical tests.
   - Three sets of specimens were prepared to measure compressive strength, split tensile strength, and flexural strength at curing intervals of 7, 14, and 28 days.
   - After casting, the specimens were demolded after 24 hours and subjected to water curing until the specified testing age.

4. **Testing Procedures:**

- Compressive Strength Test: Conducted in accordance with ASTM standards using a compression testing machine on cubic specimens to assess the material's ability to withstand axial loads.
- Split Tensile Strength Test: Cylindrical specimens were evaluated using a compression testing machine to determine their tensile strength, which indicates the concrete's resistance to splitting under applied loads.
- Flexural Strength Test: Beam specimens underwent three-point bending tests to assess their flexural strength, reflecting the material's ability to resist bending and deformation.

5. **Data Collection and Analysis:**

- Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were recorded at 7, 14, and 28 days for each concrete mix.
- A comparative analysis was performed to determine the influence of different glass powder replacement levels on the strength properties of concrete.
- Statistical evaluations were conducted to identify the optimal percentage of glass powder

that provides the maximum enhancement in mechanical performance.

6.Experimental Analysis

One of the most popular building materials in the world, concrete is prized for its strength, adaptability, and durability. However, the increasing demand for cement—a primary ingredient in concrete—raises environmental concerns due to the high carbon emissions associated with its production. As a response

to these challenges, the construction industry is increasingly exploring supplementary materials that can partially replace cement, thereby enhancing concrete properties while promoting sustainability.
Glass powder, made from leftover recycled glass, is one viable substitute. Glass powder can be used to improve concrete's mechanical qualities in addition to solving waste management problems. An additional source of calcium silicate hydrate (C-S-H) is formed during the hydration process thanks to the pozzolanic behaviour of silica, which is present in glass powder. Improves in the concrete's overall durability, tensile strength, and compressive strength may result from this response.

Despite the promising attributes of glass powder, its effective incorporation into concrete requires a comprehensive understanding of the optimal replacement levels and the consequent effects on

mechanical properties. The effects of glass powder on concrete have been the subject of conflicting research in the past, with results frequently shifting according to parameters like particle size, replacement %, and curing conditions. Thus, the purpose of this experimental analysis is to systematically assess the impact of various glass powder percentages (0%, 3%, 6%, 9%, and 12%) on the concrete's compressive strength, split tensile strength, and flexural strength during the course of its 7, 14, and 28-day curing periods.

The study's conclusions will advance our knowledge of the more subtle applications of glass powder in concrete mixtures and provide light on the material's potential as an environmentally friendly, high-performing, sustainable building material.

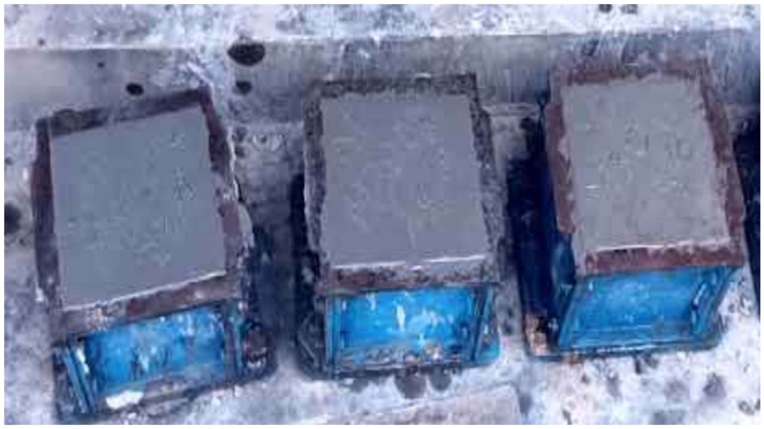

Fig-1: *Casting of Cubes*

	0%	3%	6%	9%	12%
7 Days	20.5	33.7	35.4	38.2	29.7
14 Days	23.8	34.1	36.7	39.8	31
28Days	27.4	35.6	37.4	40.5	33.5

Table -1: *Compression Strength for Glass powder with cement replacement (N/mm^2)*

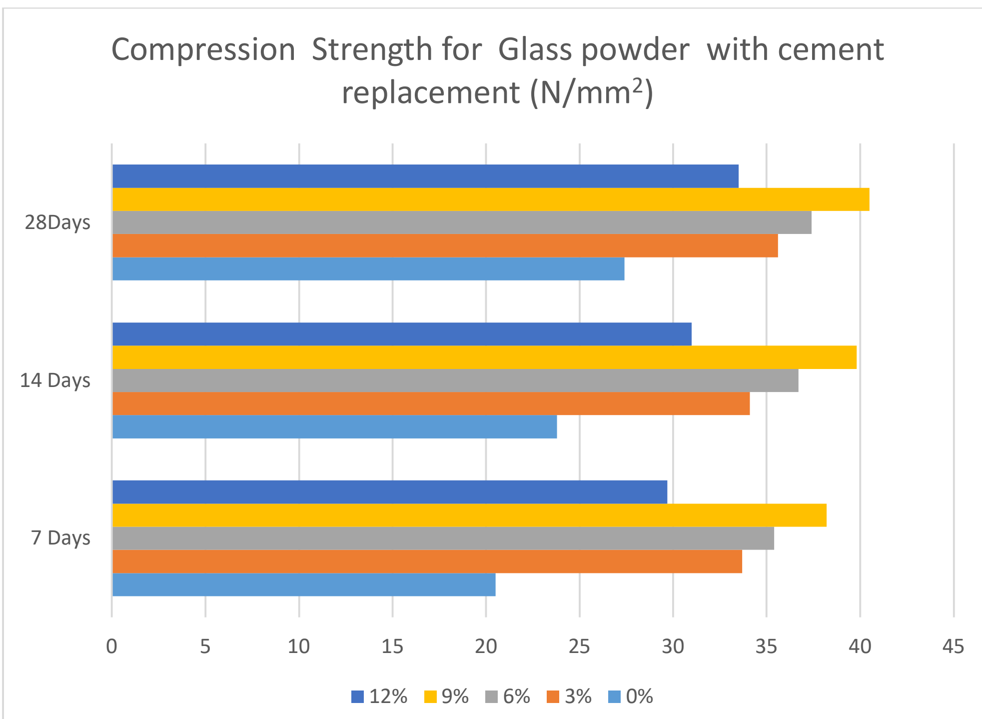

Fig-2*: Compression Strength for Glass powder with cement replacement (N/mm^2)*

Fig -3 *: Casting of split Tensile Beams*

	0%	3%	6%	9%	12%
7 Days	2.45	2.69	2.75	2.83	2.53
14 Days	2.5	2.71	2.79	2.85	2.62
28 Days	2.57	2.74	2.81	2.88	2.77

Table -2*: Split strength for Glass powder with cement replacement (N/mm^2)*

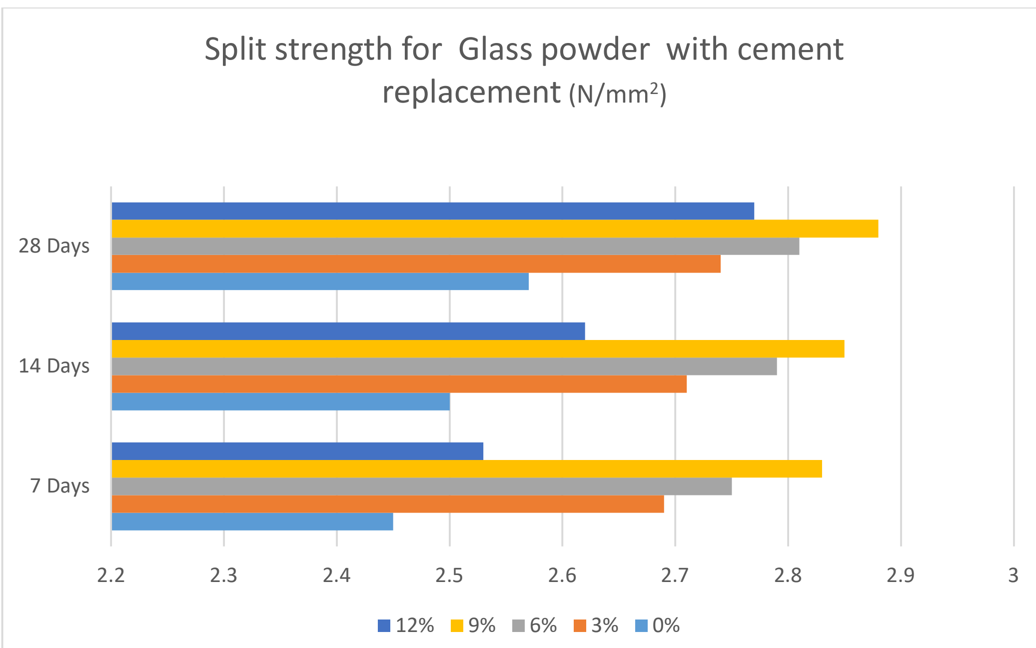

Fig-4: *Split strength for Glass powder with cement replacement (N/mm^2)*

Fig-5: *Flexural Strength*

	0%	3%	6%	9%	12%
7 Days	4.01	4.15	4.2	4.35	4.09
14 Days	4.04	4.17	4.23	4.38	4.12
28 Days	4.07	4.18	4.26	4.39	4.15

Table -3: *Flexural strength for Glass powder with cement replacement (N/mm^2)*

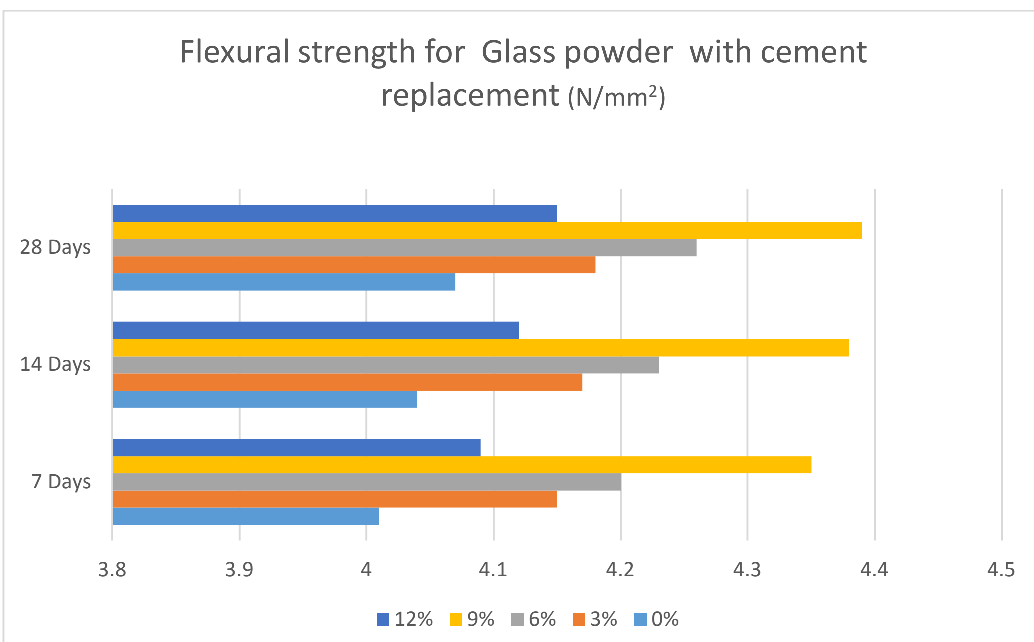

Fig-6: *Flexural strength for Glass powder with cement replacement (N/mm^2)*

7. Results and Discussion

Compressive Strength

From Table 1 and Figure 2, the compressive strength results demonstrate that the addition of glass powder significantly influences concrete performance. At 7 days, the compressive strength increased from 20.5 N/mm² for the control mix (0% glass powder) to a peak of 38.2 N/mm² at 9% glass powder replacement, reflecting an increase of over 85%. The trend continues at 14 days, where the strength at 9% glass powder reaches 39.8 N/mm², and at 28 days, it peaks at 40.5 N/mm². The higher percentages (12%) showed a decline in strength, indicating a possible limit to effective glass powder replacement.

Split Tensile Strength

Table 2 and Figure 4 illustrate the split tensile strength results. At 7 days, the control mix exhibits a split tensile strength of 2.45 N/mm², with the highest value of 2.83 N/mm² occurring at 9% glass powder replacement. Similar trends are observed at 14 and 28 days, where the tensile strength continues to improve with increasing glass powder percentages, although the maximum effectiveness is again noted at 9%.

Flexural Strength

The flexural strength results, shown in Table 3 and Figure 6, reveal that the addition of glass powder also enhances this property. At 7 days, the flexural strength for the control mix is 4.01 N/mm², while mixes with glass powder reach a maximum of 4.35 N/mm² at 9%. This positive trend persists through the curing periods, confirming that glass powder can effectively enhance flexural performance.

8. Conclusion

The results of the experimental research demonstrated that, up to a certain point, adding glass powder to concrete in lieu of some of the cement improves its mechanical qualities. The maximum values of compressive strength, split tensile strength, and flexural strength were found at 9%, which was determined to be the ideal replacement amount. The strength values decreased at 9% substitution, suggesting a saturation point for glass powder's advantageous effects. Consequently, it is advised to replace 9% of the glass powder in concrete in order to increase strength without sacrificing sustainability. This study emphasizes how glass powder can be used as a good substitute material in the building sector to support green practices without sacrificing the performance of concrete.

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