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Preliminary Investigation of the Effects of EICP on Compaction and Unconfined Compression Strength of Sandy Soil

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ABSTRACT

A laboratory study was conducted to examine the effect of enzyme-induced carbonate precipitation (EICP) on the compaction characteristics and unconfined compression strength (UCS) of clean sandy soil. The results were compared to both untreated soil and soil treated solely with calcium chloride ($CaCl_2$) to isolate the effect of the enzyme. The testing showed that EICP treatment increased the maximum dry density and decreased the optimum moisture content (OMC) compared to untreated soil. In contrast, $CaCl_2$ treatment had the opposite effect, reducing the maximum dry density and increasing the OMC. Furthermore, EICP treatment improved the peak stress by 79% and increased the elastic stiffness (i.e., the secant modulus at 50% of the failure stress) by over 440% compared to untreated soil. $CaCl_2$ improved the strength by 46% and increased the secant modulus by 106% relative to untreated soil.

INTRODUCTION

Enzyme-induced carbonate precipitation (EICP) has emerged as a promising bio-inspired technique for improving the geotechnical properties of soils (Arab et al., 2021; Almajed et al., 2021). EICP is a bio-cementation soil improvement technique in which calcium carbonate is precipitated by ureolysis in the presence of calcium ions (Almajed et al., 2018). The precipitation reaction is catalyzed by plant-extracted urease enzyme (Hamdan et al., 2013; Javadi et al., 2018; Khodadadi Tirkolaei et al., 2020). Growing interest in EICP stems from its potential to offer a more sustainable and environmentally friendly alternative to conventional soil stabilization methods, which often rely on energy-intensive processes or the use of potentially harmful chemicals.

Soil improvement methods play a fundamental role in geotechnical engineering, serving as essential techniques to enhance soil mechanical properties and meet the design requirements of various infrastructure projects. Soil improvement techniques have evolved significantly over the years, driven by the need for more efficient, cost-effective, and environmentally sustainable solutions. In recent years, bio-inspired and bio-mediated soil improvement methods have gained significant attention as promising alternatives to traditional chemical stabilization methods

(DeJong et al., 2010). These innovative approaches employ natural biological processes to modify soil properties and improve strength, stiffness and dilatancy (DeJong et al., 2006; Kavazanjian and Hamdan, 2015; Almajed et al., 2019), mitigate liquefaction potential (Kwon et al., 2024), and modify the hydraulic conductivity of soils (Woolley et al., 2020). Bio-mediated and bio-inspired techniques also offer potential advantages in terms of sustainability, reduced environmental impact, and increased compatibility with existing soil ecosystems (Raymond et al., 2021).

The impact of EICP treatment on soil compaction characteristics remains largely unexplored, despite compaction being a fundamental aspect of geotechnical applications. Compaction controls soil density, strength, and deformation behavior, all of which are critical for infrastructure design and construction. Therefore, understanding how EICP treatment affects soil compaction is important for predicting the performance of treated soils under different field conditions. However, the use of calcium chloride ($CaCl_2$) as a calcium source in EICP solutions introduces complexities into elucidating the soil-treatment interactions from EICP treatment that warrant investigation. $CaCl_2$ itself can affect soil properties through various mechanisms, including altering the soil electrical double layer (Abbaslou et al., 2020), influencing flocculation and dispersion of clay particles (Sharo et al., 2018; Almajed et al., 2023), and affecting the soil moisture retention characteristics (Sani et al., 2020). These effects can potentially alter soil responses to compaction and strength development, complicating the interpretation of EICP treatment outcomes. Therefore, examining these interactions individually is fundamental to developing effective EICP treatment strategies and accurately predicting the behavior of treated soils in different geotechnical applications.

This study aims to fill the knowledge gap on the effect of EICP on soil compaction characteristics by investigating the effects of EICP and $CaCl_2$ treatment on the compaction and UCS characteristics of a well graded coarse-grained soil (0% passing No. 100 sieve). By comparing the characteristics of EICP-treated soils with untreated soils and soils treated with $CaCl_2$, this study distinguishes the effects of carbonate precipitation from those of the salt ($CaCl_2$) in the EICP solution. This approach provides a more comprehensive understanding of the effects of EICP treatment on sandy soil.

MATERIALS AND METHODS

Materials. The soil used in this investigation can be described as clean, well-graded sandy soil, manufactured from naturally occurring silty sand in Arizona, USA. The original soil was subjected to dry sieving, followed by wet sieving, and then a final dry sieving to remove all fine particles and establish the particle size distribution curve. The procedure resulted in a well-graded sandy soil with particle sizes ranging from approximately 0.15 mm to 4.75 mm, as shown in Figure 1. The particle diameters corresponding to the 60%, 30%, and 10% of passing thresholds were determined to be 2.05 mm, 0.83 mm, and 0.32 mm, respectively. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) were calculated to be 6.4 and 1.05, respectively. Therefore, the manufactured fines-free sandy soil is classified as well-graded sand (SW) in accordance with the Unified Soil Classification System (USCS).

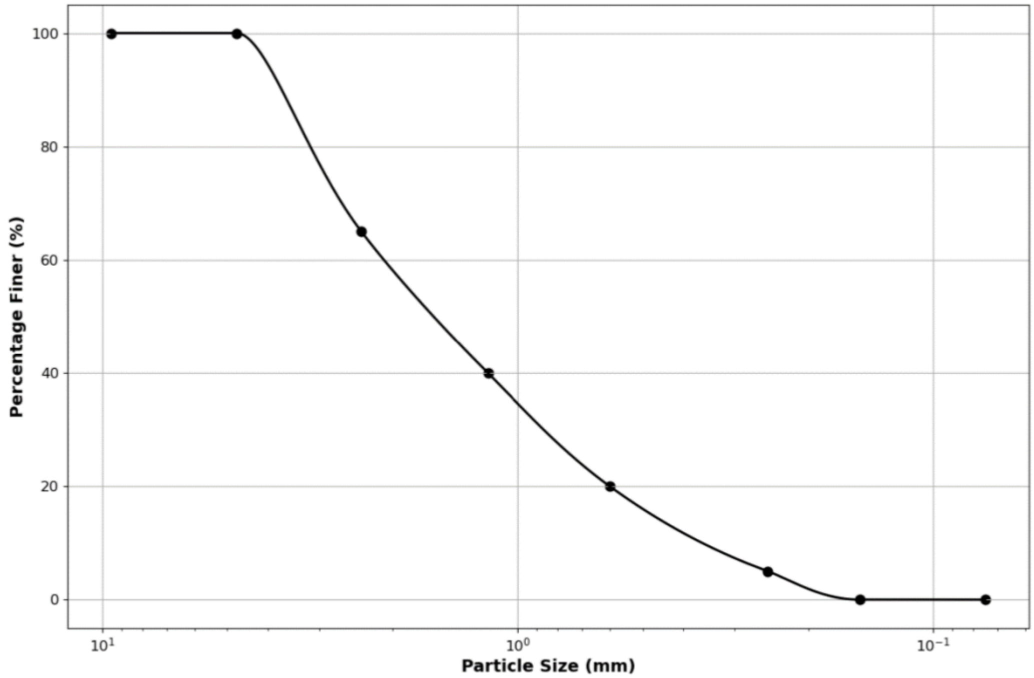

Figure 1. Particle size distribution curve for the manufactured soil

Soil Treatments. *EICP Treatment:* the soil was treated with an EICP solution through mixing and compaction. The solution consisted of 1.5 M urea, 1.5 M calcium chloride dihydrate ($CaCl_2.2H_2O$), 125 ml/L urease enzyme with an activity of 270 U/L, and 4 g/L non-fat dry milk. The urease enzyme, extracted from jack beans, was prepared using the soak-blend-filter method as reported by Khodadadi et al. (2020). A Urea-$CaCl_2$ solution was mixed with the soil first, and then a urease enzyme and non-fat dry milk solution was added to the soil mixture with a ratio of 1:1 by volume of Urea-$CaCl_2$ solution to the urease enzyme with dry non-fat milk solution.

$CaCl_2$ Treatment: the soil was treated using only a 1.5 M calcium chloride dihydrate ($CaCl_2.2H_2O$) solution. The solution was mixed with the soil first followed by compaction.

Compaction Testing. The soil was compacted using the Harvard Miniature Compaction Apparatus (HMCA) in accordance with the standard procedure outlined in the product manual (H-4165) by Humboldt (2014). A 20-pound spring tamper was used to compact the soil into a mold with dimensions of approximately 33.3 mm in diameter and 71.5 mm in height, resulting in a height to diameter ratio of 2.15. The soil was compacted at various target moisture contents, defined as the percentage of the added solution relative to the dry soil mass. The compacted untreated soil was weighed, extruded directly from the mold, and oven dried it in accordance with ASTM D2216. The compacted $CaCl_2$ and EICP treated samples were extruded from the mold, wraped in plastic film for at least 24 hours, and then weighed and oven dried.

Unconfined Compression Strength (UCS). Unconfined compression strength (UCS) tests were performed on compacted specimens of the untreated and treated sand following the ASTM D2166 standard procedure. Specimens were prepared using the HMCA at optimum moisture content and maximum dry unit weight for both untreated and treated specimens (EICP and $CaCl_2$). Three replicates were produced for each case. The untreated and treated specimens were wraped in plastic film for at least 24 hours prior to the strength testing to let the sample equilibrate and minime the associated suction changes. Each specimen was carefully placed in the loading frame, centered on the bottom platen and aligned with the loading device. Load was applied to produce a constant axial strain rate of 2.54 mm (0.1 inch) per minute. Load, deformation, and time values were recorded at regular intervals to define the stress-strain curve. The water content of each specimen was determined after testing. It should be noted that while ASTM D2166 is typically used for cohesive soils, this study also applied the method to the untreated well-graded sand. The cohesiveness of the untreated sand was likely due to its well-graded nature and dense particles packing at optimum moisture content, allowing for the formation of a stable structure under unconfined testing conditions. The treated specimens had additional cohesion (cementation) obtained from the treatments.

$CaCO_3$ Content. The calcium carbonate ($CaCO_3$) content was tested in accordance with NEN-ISO 10693 standards using the calcimeter (Eijkelkamp, 2021). The calcimeter measures carbonate content through a volumetric approach, wherein carbonate is converted to CO_2 by adding 4M hydrochloric acid (HCL) to 2–3 g of dry soil. The release of CO_2 causes the de-aired water level in the burette to rise and the difference in the water level is correlated to the quantity of CO_2 released. The equivalent calcium carbonate content ($CaCO_3$) is then calculated. In this study, the $CaCO_3$ content was evaluated using at least six replicates per specimen.

RESULTS AND DISCUSSIONS

$CaCO_3$. The calcium carbonate content of the treated and untreated specimens was measured at the end of the test. The carbonate content measurements were based on samples picked from random locations within each specimen. The EICP-treated specimens were additionally rinsed three times with deionized water. As illustrated in Figure 2, the box plot of the untreated specimens showed natural calcite content, with a mean value of approximately 7.6%. The mean values of the $CaCO_3$ for EICP-treated and EICP-treated rinsed specimens were 9.9% and 10.1%, respectively. These data indicate the added $CaCO_3$ due to the EICP treatment is nearly 2.4%, which is equal to 3.6 g of the total specimen weight. The data indicated a precipitation efficiency close to 100%.

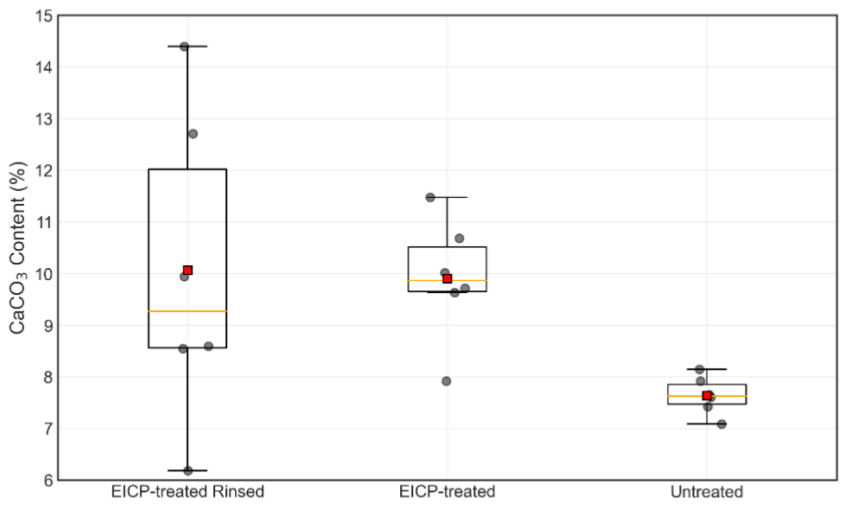

Figure 2. $CaCO_3$ content for the untreated, EICP-treated and EICP-treated rinsed specimens

Compaction Test Results. The compaction characteristics of the untreated soil and soil treated with EICP and $CaCl_2$ are shown in Figure 3. The untreated soil had a maximum dry unit weight of approximately 19.8 kN/m³ at an optimum moisture content of about 11.7%. The EICP-treated soil showed a slight increase in maximum dry unit weight, reaching approximately 20.2 kN/m³ at a lower optimum moisture content of 9.7%. In contrast, the $CaCl_2$ treated soil exhibited a reduction in maximum dry unit weight to approximately 19.2 kN/m³ with an increase in optimum moisture content to 12.5%.

The zero air voids line depicted in Figure 3 was estimated for the soil using a specific gravity of solids (G_s) of 2.7. The parallel lines on Figure 3 represent the theoretical maximum dry density achievable at different saturation levels: 100% saturation for the theoretical maximum, 95% saturation at optimum for the untreated specimen, 88% saturation at optimum for the specimen treated with $CaCl_2$, and 82% saturation at optimum for the specimen treated with EICP.

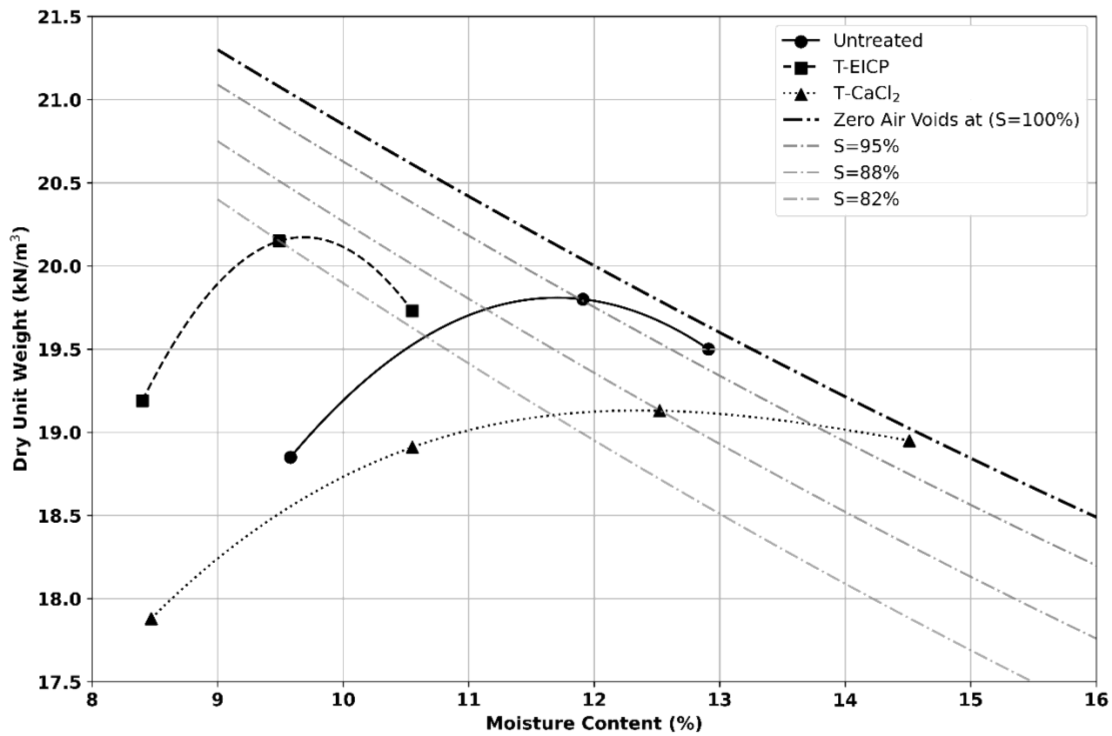

Figure 3. Compaction curves of untreated and treated soil using EICP and $CaCl_2$ treatments

The compaction curves reveal marginal differences in the soil's maximum dry unit weight but significant differences in the corresponding optimum moisture content due to the applied treatments. EICP treatment proved to be most efficient in improving the compaction characteristics (increasing the maximum dry density, reducing the optimum moisture content) of the treated soil. The increased maximum dry unit weight and reduced optimum moisture content suggest enhanced particle packing and potentially greater soil strength. This improvement may simply be due to the precipitated carbonate creating a denser structure.

$CaCl_2$ treatment resulted in a reduction in maximum dry unit weight alongside a slight increase in optimum moisture content compared to the untreated soil. This result is likely due to the hygroscopic properties of $CaCl_2$, which enhance water retention within the soil structure and promote greater flocculation between particles (resulting in a less dense material), thereby adversely affecting the compaction process. The flatter compaction curve observed when the sample was treated with $CaCl_2$ suggests that the treatment makes the soil less sensitive to moisture variations during compaction and results in a more rigid structure, a characteristic linked to flocculation (Mitchell and Soga, 2005).

Unconfined Compression Strength. The stress-strain response of the untreated soil and soil treated with EICP and with just $CaCl_2$ was evaluated through unconfined compression tests. Also, the matric suction was measured for the untreated and EICP-treated specimens using the pressure plate test at the tested degree of saturation. The results are illustrated in Figure 4. The untreated soil showed a gradual increase in stress with increasing axial strain, achieving a peak stress of 25 kPa at 4.5% strain. Figure 3 indicated the specimen was tested at 95% degree of saturation (matric suction of 5 kPa). In contrast, the soil subjected to EICP treatment reached a higher peak stress (47 kPa) at a lower strain of approximately 2%, and Figure 3 indicated the sample was tested at 82% degree of saturation (matric suction of 14 kPa). Soil treated with $CaCl_2$ yielded a peak stress of around 38 kPa at a 3.2% strain and Figure 3 indicates the sample tested at 88% degree of saturation.

Post-peak behavior varied significantly among the different samples: the EICP-treated soil demonstrated the most rapid decrease in stress whereas the untreated soil and $CaCl_2$-treated soil sustained their stress levels across a broader range of strain before exhibiting a gradual decline. This variation in stress response emphasizes the brittle failure mode associated with EICP treatment.

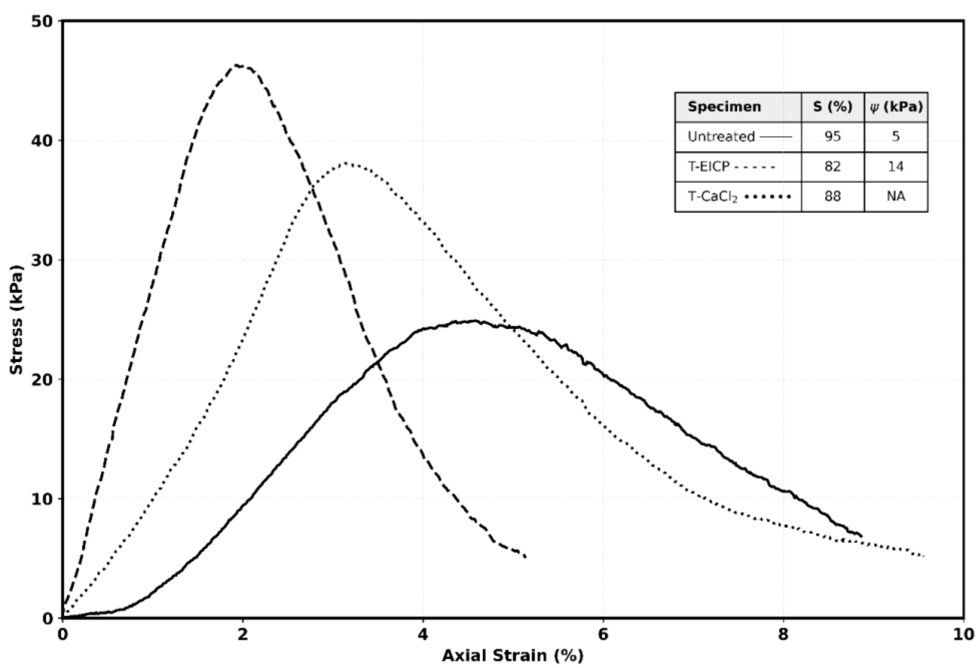

Figure 4. Stress-strain curves for the untreated and treated soil using EICP and $CaCl_2$ treatments

The elastic stiffness, referred to here as the secant modulus, was computed at the strain value corresponding to the 50% peak stress for each specimen. As illustrated in Table 1, the secant modulus increases substantially with both treatments. The untreated soil had a secant modulus of 0.52 MPa and served as the control soil. EICP treatment resulted in a substantial increase in the secant modulus, to 2.8 MPa, indicating a 440% enhancement. Similarly, $CaCl_2$-treated soil exhibited an increase in stiffness, achieving a secant modulus of 1.07 MPa, indicating a 106% stiffness increase compared to the untreated controlled soil.

Table 1. Unconfined Compression Test Results for Untreated and Treated Soil Specimens

Specimen	$CaCO_3$ (%)	Peak Stress (kPa)	Standard Deviation (kPa)	Mean (kPa)	Secant Modulus (MPa)	Strength Improvement (%)	Stiffness Enhancement (%)
Untreated	7.6	30.2	3.8	26.3	0.52	Control	Control
		22.5					
		26.3					
T-EICP	10.0	43.5	4.1	47.0	2.8	78.5	440.1
		46.0					
		51.5					
T-$CaCl_2$	7.6*	35.0	4.2	38.4	1.07	45.8	106.2
		43.1					
		37.0					

* The $CaCO_3$ for the T-$CaCl_2$ assumed to be the same as the untreated specimen.

The analysis of stress-strain curves showed significant variations in soil response due to the applied treatments. EICP treatment proved to be more effective in enhancing both the strength and stiffness of the soil compared to the $CaCl_2$-treated samples. Specifically, the peak stress observed in EICP-treated soil was approximately double that of the untreated soil, and its stiffness was four times greater. While the EICP treated soil had a higher matric suction (14 kPa) compared to the untreated soil (5 kPa), this difference in suction contributes only marginally to the overall strength enhancement as supported by Abd et al. (2020) findings. The enhancement is primarily attributed to the formation of cementation bonds, facilitated by calcium carbonate ($CaCO_3$), which develop between soil particles during the enzyme-induced precipitation process, resulting in a soil structure that is both stiffer and stronger. However, the decrease in stress following the peak stress indicates a brittle failure mode.

$CaCl_2$-treated soil exhibited a 45.8% improvement in soil strength and approximately double the stiffness compared to the untreated specimen. The moderate increase in peak stress and the corresponding strain at which this occurs suggest that calcium chloride modifies the soil structure, potentially through mechanisms such as flocculation of soil particles or changes in moisture retention characteristics. Furthermore, the post-peak stress reduction observed with the $CaCl_2$ treatment was more gradual compared to that of the EICP treatment, indicating a less brittle failure mode. The stress-strain curve of untreated soil shows the lowest peak stress but the most ductile behavior, maintaining its strength over a wider strain range.

CONCLUSION

This study examined the effects of enzyme induced carbonate precipitation (EICP) and calcium chloride ($CaCl_2$) treatments on the compaction properties and unconfined compressive strength of a well-graded clean sandy soil. The results show that EICP treatment has the greatest influence of soil behavior (compared to $CaCl_2$ treatment). EICP treatment resulted in an increase in maximum dry unit weight, a reduction in optimum moisture content, a doubling of the peak stress, and a stiffness approximately four times greater than that of untreated soil. These improvements are attributed to the formation of $CaCO_3$ bonds between soil particles. While $CaCl_2$ treatment was less effective than EICP with respect to strength and stiffness, it still resulted in a 46% increase in soil strength and a twofold increase in stiffness. However, it also led to a decrease in maximum dry unit weight and an increase in optimum moisture content, likely due to the hygroscopic nature of calcium chloride.

Overall, the findings of this study highlight the potential of EICP as a soil improvement technique, particularly for applications requiring significant increases in strength and stiffness. Further research is being conducted to assess the long-term stability of these treatments, their performance under varying environmental conditions, and their applicability to soils with varying fines content.

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