Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25007S

Next-Generation of readily biodegradable foaming agents for EPB TBMs

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Abstract: The paper presents a new class of readily biodegradable foaming agents specifically engineered for EPB TBM applications. These advanced formulations incorporate enhanced biodegradable chemistries beyond traditional raw materials, delivering superior foamability, increased stability over time, and improved control of the excavated soil's rheology. Crucially, these properties are achieved without increasing the Foam Injection Rate (FIR), thereby reducing overall chemical consumption. An important advantage of this Next Generation Technology is the ability to develop a reliable Soil Conditioning Plan early in the project; this includes accurately forecasting the volume of foaming agent required per geological section, which supports effective planning and real-time consumption control throughout the excavation process. This Next Generation Technology of foaming agents offers a robust, environmentally conscious solution tailored to the demands of modern EPB TBM tunneling. It facilitates greater process control, reduces waste, improves safety, and enhances the reliability of tunnel excavation through all types of ground conditions.

Keywords: EPB TBM; foaming agents; soil conditioning; biodegradability

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1. Introduction

1.1. Why is the Next Generation Technology of foaming agents needed

The application of Earth Pressure Balance Tunnel Boring Machines (EPB TBMs) has expanded significantly in recent years, particularly in projects involving cohesionless soils located below the groundwater table. Under these geotechnical conditions, the use of foaming agents with superior stability is critical to maintain chamber pressure, improve face support, and enable controlled and continuous spoil removal.

To meet these demands, foaming agents must demonstrate enhanced rheological control of the soil over time while minimizing overall foam consumption. Temporal stability of the foam has emerged as a key parameter in soil conditioning: extended foam life directly contributes to improved excavation efficiency and reduced resource utilization.

Recent developments in foam chemistry have introduced a Next Generation Technology of readily biodegradable foaming agents specifically engineered to address these challenges. These formulations exhibit increased surface tension and improved bubble stability, allowing the foam to remain functional over longer periods within the excavation chamber. This sustained performance not only enhances soil conditioning quality but also contributes to a measurable reduction in total foam volume required compared to conventional products.

As a result, higher Foam Expansion Ratios (FER) can be achieved in conjunction with lower Foam Injection Ratios (FIR), without compromising the mechanical behavior of the conditioned ground. The implementation of this Next Generation Technology contributes to a more stable and efficient

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excavation process, enabling optimization of the TBM mining cycle and supporting adherence to project schedules in complex tunneling environments.

2. Basics of soil conditioning – Old Technology

2.1. Foam generation

A soil conditioner is a chemical product which is added to a soil, together with water, to improve soil physical and mechanical properties. Soil conditioning is the process to achieve this, and heavily depends from the generation of foam and the quality of the foaming system used.

The generation of foam, whether done in laboratory or in TBM, is divisible in two separate steps:

- Step 1: the surfactant is mixed with water at a certain concentration rate (Cf), creating the foaming agent.
- Step 2: the foaming agent is then mixed with air to create the foam.

The standard foams in the TBM industry are based on a surfactant, or tensioactive, called Sodium Lauryl Ether Sulfate (commercial name is SLES). As per Fig. 1, SLES is an ionic tensioactive that, when enters in contact with water, its molecules work like an emulsifier, bonding the water with its chemical structure.

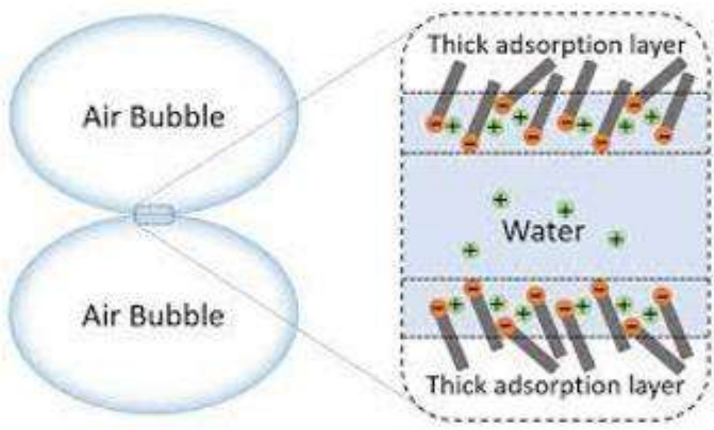

Fig. 1. Thick adsorption layers of SLES mixed with water, acting on air bubbles (Source: Peng et al., 2020).

SLES works on the surface of the bubbles favoring the stabilization of the air-liquid interface by developing the surface tension that allows the air bubbles to be generated. Initially once the foam is generated, bubbles are in small size but, with the passing of time, these tend to increase in their size in a simultaneous effect with the reduction of the surface tension applied on the external layer of the air bubbles.

The reduction of the surface tension on the external layer of the air bubble results at a certain point in the air bubble to implode, which effect is detrimental to the stability of the foam and its ability to work when mixed with a soil.

Therefore, the concept of time, which until now has not been properly addressed by the industry, is now a vital parameter that must be taken in consideration when we condition a soil in a TBM.

2.2. Foam parameters

Foams are generated and used through the control of these three essential parameters:

- Concentration (Cf), expressed in percentage as the rate of tenside inside the foaming agent; the higher the Cf, the stronger the foam from the chemical and mechanical point of view.
- Foam Expansion Rate (FER), as the ratio between the volume of air and liquid; the higher the FER, the drier the foam; FER is the indication of quality of the foam and the indication of how much air is trapped inside the bubbles; as a matter of example, a foaming agent foamed at FER 10 means that it expands its volume ten times.

Fig. 2. Example of one foam at same Cf expanded at three different FER (Source: Sposetti, 2023).

- Foam Injection Rate (FIR), expressed in percentage as the ratio between the volume of the foam and the volume of the soil; the higher the FIR, the higher the volume of the foam injected into the ground and, therefore, higher the consumption.

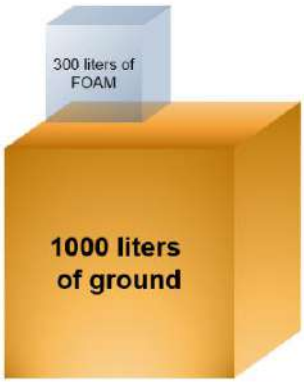

Fig. 3. Example of FIR 30%. The total volume in play is 1300 liters (Source: Sposetti, 2023).

3. Quality control

Historically, soil conditioning in Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) operations has been performed using foaming agents composed primarily of sodium lauryl ether sulfate

(SLES) and water, commonly referred to as the conventional or Old Technology. While these formulations were initially effective under basic tunneling conditions, their limitations have become increasingly apparent in modern tunneling applications, particularly those involving heterogeneous soft ground strata with variable permeability profiles.

When operating EPB TBMs through such complex geological environments, maintaining control over soil rheology and face pressure becomes critical. Under these conditions, conventional SLES-based foams demonstrate a performance plateau when the Foam Expansion Ratio (FER) exceeds approximately 10. Beyond this threshold, the foam tends to lose structural stability, leading to reduced control over conditioned soil behavior. To compensate, contractors are often required to significantly increase foam injection rates, resulting in higher material consumption and suboptimal operational efficiency.

This degradation in foam performance has been quantitatively verified through standardized laboratory tests. One such test, the Half-Life Time (HLT) test, is defined by the Specification and Guidelines for the Use of Specialist Products for Mechanized Tunnelling (TBM) in Soft Ground and Hard Rock (EFNARC, 2005). The test assesses foam drainage stability under controlled conditions by measuring the time required for 80 grams of foam, generated at a specific foaming agent concentration (Cf) and FER, to drain 40 mL of liquid through a synthetic fleece into a graduated cylinder. The foam is generated using a laboratory foam gun calibrated to replicate those used in TBM operations. A schematic representation of the HLT test is shown in Figure 4.

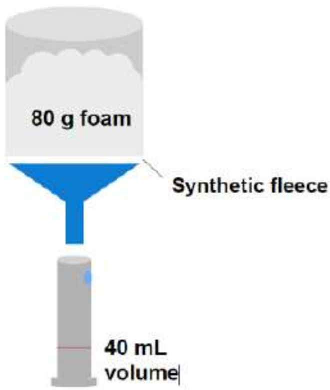

Fig. 4. Schematic diagram of the Half-Life Time test (EFNARC, 2005).

In typical tests of conventional SLES-based foaming agents, the recorded Half-Life Time ranges from 5 to 7 minutes. This limited drainage stability illustrates the inability of the Old Technology to maintain foam integrity at high FER values, reinforcing its inadequacy for advanced tunneling applications. As a result, foam utilization is constrained to a narrow operational window, limiting both its technical effectiveness and economic efficiency.

In addition to HLT testing, the Mechanical Resistance Test offers further insights into foam performance, particularly its structural resilience over time. Although not yet standardized, this test provides a practical evaluation of foam strength by measuring the time required for a water-filled ping-pong ball (approximately 18 grams) to descend vertically through a column of foam placed inside a transparent plastic cylinder. As with the HLT test, the foam is generated using a representative TBM foam gun. A schematic of the setup is shown in Figure 5.

The duration of the ball's descent serves as a proxy for the foam's internal resistance to deformation. A longer penetration time indicates a stronger foam matrix capable of better supporting the conditioned soil. Comparative data between conventional and Next-Generation foaming technologies, presented in Figures 6 and 7, respectively, clearly illustrate the performance gap in both drainage stability and mechanical resistance.

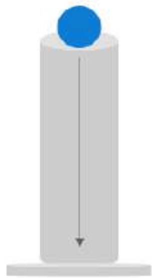

Fig. 5. Schematic diagram of the unstandardized Mechanical Resistance test (Source: Sposetti, 2023).

In summary, while SLES-based soil conditioners remain in widespread use, their limitations in modern EPB TBM operations are well-documented. Their inability to maintain stability and performance beyond FER 10 restricts their applicability in complex geologies, increases operational costs, and limits tunneling efficiency. These challenges underscore the need for advanced soil conditioning technologies capable of meeting contemporary performance standards.

4. Next Generation Technology – Sika Stabilizer-1215, 1219, 1515 TBM

Recent innovations in soil conditioning foaming agents have enabled a significant advancement in EPB TBM operations: the ability to consistently produce stable foam above the previously limiting Foam Expansion Ratio (FER) threshold of 10. This development marks the removal of what was long considered a practical upper limit, and introduces new flexibility in foam generation and management, resulting in more effective and efficient soil conditioning in varied ground conditions.

- The Next Generation Technology represents a new class of high-performance, readily biodegradable foaming agents, fully compliant with OECD biodegradability standards. These formulations offer substantially improved stability and foaming capacity while maintaining compatibility with standard TBM foaming systems. Using identical procedures for foam generation and standard operating parameters, including foaming agent concentration (Cf), FER, and Foam Injection Ratio (FIR), these agents are capable of producing highly stable foams at FER values significantly exceeding 10, without compromising performance or operational safety.
- Enhanced foam stability correlates with improved performance during TBM operation. As FER increases, the air bubbles formed within the foam exhibit a reinforced surface tension at their outer layer, maintaining structural integrity over extended periods. This prolonged stability ensures improved rheological control of the conditioned soil, enhancing face support and optimizing pressure management in the excavation chamber.

4.1. Technical and operational advantages

- Compared to conventional SLES-based foaming agents (Old Technology), the Next Generation Technology offers a broad spectrum of technical and operational benefits:
- Improved Drainage Stability: Significantly prolonged Half-Life Time (HLT) enhances foam durability during extended excavation cycles.
- High FER Compatibility: High foaming capacity enables operation at elevated FER levels without foam collapse, overcoming a key limitation of conventional agents.

- Optimized FIR Utilization: Lower FIR values can be employed to achieve desired soil rheology, reducing overall chemical consumption.
- Sustained Face Support: The high foam stability contributes to the maintenance of EPB chamber pressure, enhancing excavation control and reducing the likelihood of over-excavation or surface settlement.
- Enhanced Soil Conditioning:
  - Improved plastic deformation properties and cohesion of the excavated soil.
  - Reduced permeability, supporting better pressurization and spoil extraction.
  - Improved behavior in fine-grained soils, with reduced stickiness and clogging potential.
- Reduced Cutterhead Wear and Shield Friction: Lower internal friction and abrasiveness of the conditioned ground contributes to prolonged tool life and reduced energy consumption.
- These advantages translate into improved machine performance, reduced downtime, and lower environmental and operational costs. The enhanced rheological control, combined with the agent's biodegradable formulation, positions the Next Generation Technology as a significant step forward in the sustainable and efficient execution of mechanized tunneling projects.

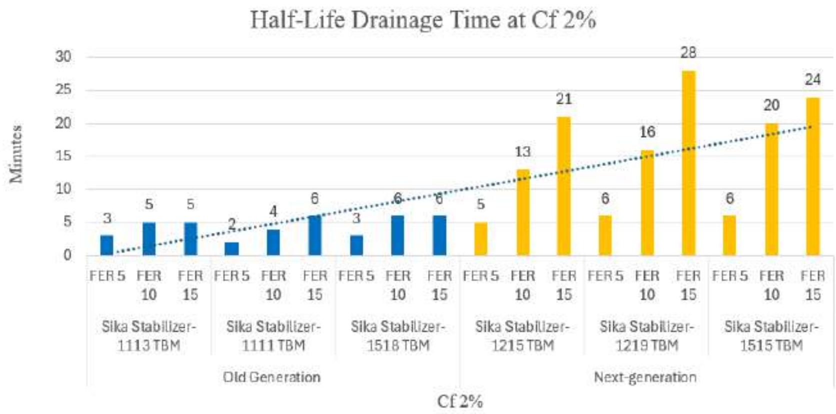

Fig. 6. Old and Next Generation Technology comparison HLT at Cf 2%.

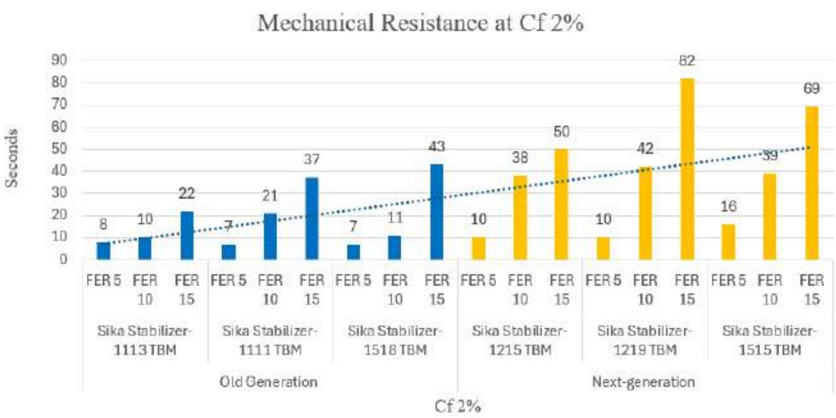

Fig. 7. Old and Next Generation Technology comparison Mechanical Resistance at Cf 2%.

5. Interpretation of results

To provide a robust and scientifically sound interpretation of laboratory test results—specifically the Half-Life Time (HLT) and Mechanical Resistance performance of Next Generation foaming agents, a comparative benchmarking framework was developed. This high-level technical evaluation includes a broad spectrum of commercially available foaming agents currently in use in the TBM industry, enabling a direct and rigorous assessment of relative performance.

This benchmarking exercise offers critical validation of the superior properties of the Next Generation Technology and underscores the growing performance gap between modern formulations and traditional SLES-based (Old Technology) foaming agents.

In 2020, the Department of Structural and Geotechnical Engineering and the Department of Chemical Engineering, Materials and Environment at *La Sapienza University of Rome* (Italy) introduced a novel classification system for foaming agents based on foam stability (Sebastiani et al., 2019). This system organizes foaming products into five classes, where Class I represents the highest level of performance in terms of foam durability and stability, and Class V denotes the weakest performing formulations.

The classification was established using HLT data at a foaming agent concentration of 2% (*Cf*) and a Foam Expansion Ratio (FER) of 10. In this work, traditional SLES-based foaming agents were plotted using HLT (Y-axis) versus FER (X-axis), as shown in Figure 8 (dark dots). These agents were predominantly clustered within Classes III to V, indicating limited drainage stability and durability.

In 2024, the same departments incorporated results from newly developed products—Sika Stabilizer-1215 TBM, Sika Stabilizer-1219 TBM, and Sika Stabilizer-1515 TBM—which belong to the Next Generation Technology. These products demonstrated significantly higher HLT values under the same testing conditions and were represented by star markers in Figure 8. Due to their distinctly superior performance, these foaming agents could not be placed within the pre-existing classification system, prompting the creation of a new, superior class beyond Class I.

It is also noteworthy that the earlier-generation Sika Stabilizer-1113 TBM, based on Old Technology, is included in the classification and falls into Class III, labeled as “Considerable Stability.”

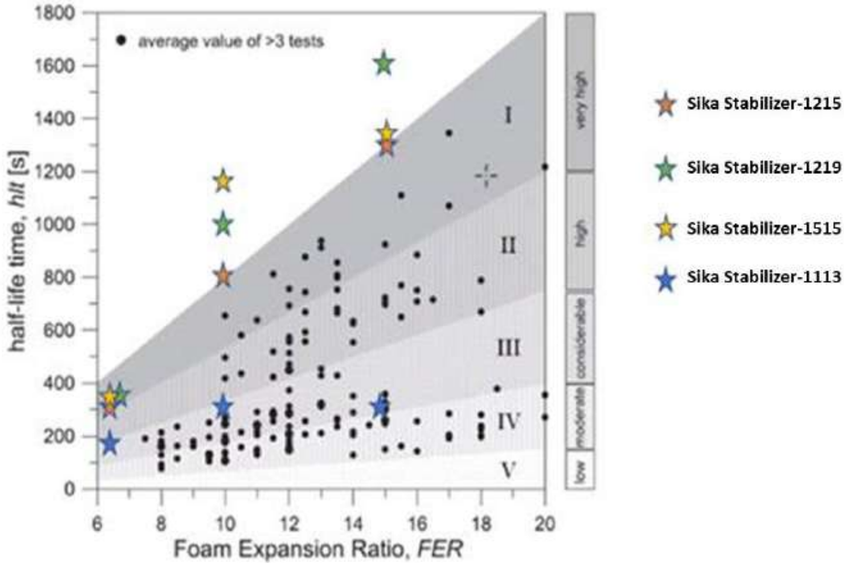

Fig. 8. Foaming products classification based on the stability of the generated foam.

To further reinforce the classification results, a second benchmarking analysis was conducted comparing HLT and Mechanical Resistance performance across four products: the Next Generation Technology (orange), Old Technology (blue), and two other commercially available foaming agents (red). Results were evaluated at three concentration levels (Cf = 1%, 2%, and 3%) with FER fixed at 10. The outcomes are presented in Figures 9 and 10, showing a clear and consistent performance advantage of the Next Generation foaming agents in both stability and mechanical integrity. Figure 9 illustrates HLT benchmarks, demonstrating significantly extended foam stability for Next Generation products at all tested concentrations. Figure 10 presents Mechanical Resistance test results, with longer penetration times indicating superior foam structural strength and cohesion.

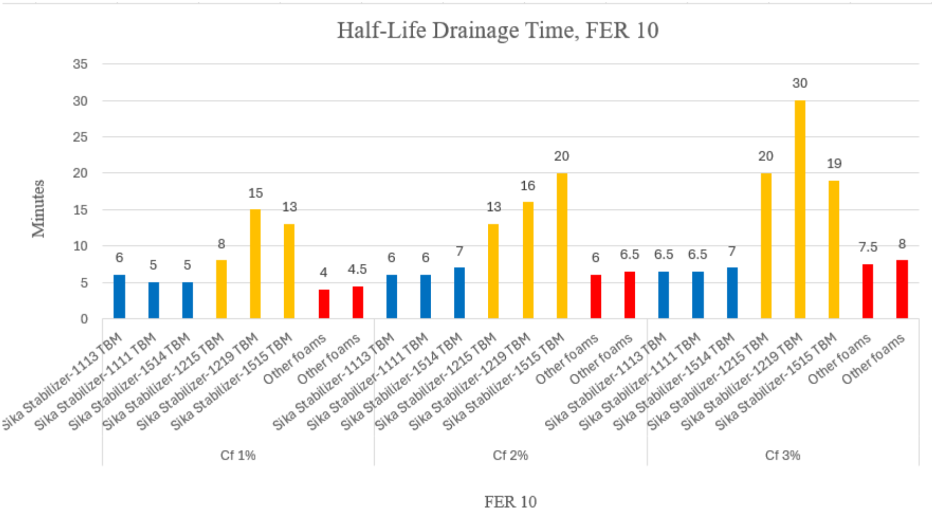

Fig. 9. Half-Life Time benchmark, FER 10.

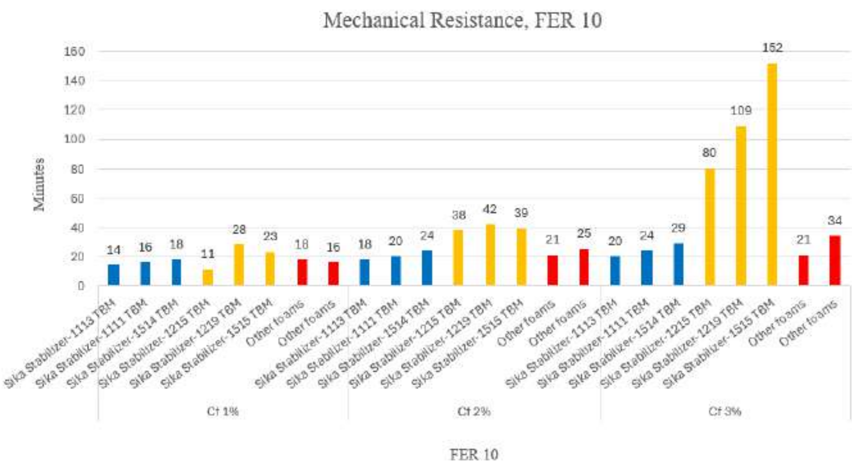

Fig. 10. Mechanical Resistance benchmark, FER 10.

5.1. Conclusions from benchmarking

The benchmarking and classification studies lead to the following key conclusions:

- The Next Generation Technology exhibits markedly higher drainage stability than all other tested foaming agents.
- Foam stability increases with FER, a behavior not observed in traditional products, which tend to destabilize beyond FER 10.
- No other foaming agents currently available in the TBM industry demonstrate comparable performance across both drainage and mechanical stability metrics.

These findings provide compelling scientific validation of the enhanced performance of Next Generation foaming agents and support their application in advanced EPB TBM operations requiring high reliability, extended stability, and optimized soil conditioning.

6. Conclusions

This study has presented and validated the performance of a newly developed class of soil conditioning agents, referred to as the Next Generation Technology, specifically engineered for use in EPB TBM operations. These advanced foaming agents represent a significant departure from traditional SLES-based formulations (Old Technology), offering substantial improvements in foam stability, rheological control, and environmental performance.

The Next Generation of foaming agents enables extended control over soil rheology, reducing the need for frequent reinjection of low-stability foams into the excavation chamber. This enhancement results in a measurable reduction in foam consumption, yielding both economic benefits and improved operational efficiency. The benefits are particularly pronounced in heterogeneous soils with variable permeability and in large-diameter TBMs (> 9 meters), where the excavation volume and stabilization demands are significantly higher.

The improved foam stability contributes to a more consistent excavation cycle, with enhanced control of face pressure, reduced risk of surface settlements, and minimized operational downtime. Additionally, the reduced quantity of active chemical agents in the excavated spoil, due to the high efficiency and lower required dosage of the Next Generation foams, represents a clear environmental advantage.

These technological improvements are especially relevant in the context of modern tunneling projects, which are trending toward increased tunnel diameters and longer excavation cycles. In such scenarios, the time factor becomes critical, as the ability of the foam to maintain stability over extended periods directly supports face pressure regulation and soil plasticity throughout the mining and ring-building phases.

From a practical perspective, the adoption of Next Generation Technology enables more predictable planning and control of the soil conditioning process. Contractors can now operate at higher Foam Expansion Ratios (FER) and lower Foam Injection Ratios (FIR), allowing for optimized foam usage and better forecasting of total conditioning costs.

In summary, the Next Generation foaming agents offer a comprehensive improvement over conventional products, supporting more sustainable, efficient, and cost-effective EPB TBM tunneling across a wide range of geological conditions.

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