# Breakage and permeability reduction of tailings sand under high-pressure oedometric compression and creep

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## ABSTRACT

Tailings dams are constructed as a means of containing the byproducts of mining operations. They are often built using the coarser fraction of the tailings referred to as the tailings underflow or tailings sand. Due to the expected high overburden pressure, grain crushing may occur at the base of tall tailings dams. This may result in reduced hydraulic conductivity or drainage capability, thus undermining the long-term performance of the dam. To accurately evaluate the safety margin when designing tall tailings dams, it is important to understand the evolution of the hydromechanical behavior of the tailings sand. In this paper, laboratory-scale high-stress compression tests were conducted, and hydraulic conductivity measurements were taken using a specially designed oedometer cell. The experimental results were then analyzed using an enhanced continuum breakage mechanics model. The results indicate that an increase in stress from 5 to 40 MPa can result in an increase in fines content (mass percentage of particles smaller than 0.075mm) from 11% to 17% and a corresponding decrease in hydraulic conductivity of up to one order of magnitude for the tested materials. We also report the preliminary results of a 3-month creep test on tailings sand subjected to 3 MPa confining pressure to study the time effect associated with grain crushing.

## INTRODUCTION

Tailings Storage Facility (TSF) is a structure designed for long-term storage of mining waste. In TSF, tailings are deposited in isolated impoundments behind the so-called tailings dams. These dams typically are constructed starting with a relatively small dam, referred to as a starter dam, that gradually grows in height as the storage demand increases over the operational life of the facility. The evolution of the engineering properties of the materials in a TSF can increase the risk of instability. Specifically, the coarse fraction of raw tailings (often called tailings sand or tailings underflow) is commonly used to build and raise the dam because of its relatively high strength, low compressibility, and high hydraulic conductivity. Due to the high hydraulic head in the upstream, as well as the application of construction water from the underflow slurry deposition, maintaining good drainage conditions inside the dam is critical to avoid saturation of the underflow material, thereby minimizing liquefaction potential. To achieve this, tailings underflow must meet strict quality control standards, typically requiring less than about 15% - 18% of fines by weight (Valenzuela, 2018; Barrera et al., 2011). However, even if such a requirement is satisfied at the time of construction, the gradation of the underflow can evolve over time due to sustained mechanical and environmental (e.g., hydraulic, chemical, and thermal) loadings. As the TSF height increases, stresses at the base can lead to grain crushing, effectively increasing the fines content, pore clogging, and reduced hydraulic conductivity, ultimately compromising the stability of the dam.

For these reasons, there is a pressing need to better understand the hydromechanical behavior of tailings sand in the context of grain crushing. Only a few experimental studies have been reported in this regard. Riemer et al. (2008) conducted monotonic and cyclic triaxial compression tests on an underflow material from an active TSF and showed that the fines content increased by 5~6% when consolidated from 0 to 5.5 MPa. The sample also appeared to be substantially more contractive and less cyclically resistant at high stress due to grain crushing. Fourie and Papageorgiou (2001) conducted a series of undrained triaxial compression tests and revealed the possible steady-state line for tailings with different fines content, demonstrating the possibility of static liquefaction in the case of Merriespruit tailings dams in South Africa. Bedin et al. (2012) showed the possibility of flow instability at low stress levels due to the pronounced contractive behavior exhibited by gold tailings (a low- or non-plastic silty sand) at low stress levels. These studies, however, have extensively focused on the mechanical aspect. Little is known about the co-evolution of hydraulic conductivity with respect to grain crushing and porosity reduction for tailings underflow. Such information is important in estimating the phreatic level and moisture distribution in the TSF prior to any stability or deformation analysis.

This study aims to: 1) quantify the effect of compaction and grain crushing on the hydraulic conductivity of tailings sand, and 2) explore an experimental procedure to probe the long-term response of tailings sand subjected to in-situ fluid chemistries. To achieve this goal, a series of high-stress oedometer tests coupled with simultaneous hydraulic conductivity measurements on tailings sand are performed using a customized oedometer cell. The degree of grain crushing is quantified at the end of each test via sieve analysis. Finally, the same oedometer cell was used in a dead-weight creep test for several months to probe the effect of time on the deformation and hydraulic conductivity of tailings sand. The experimental results and possible improvements of the testing setup are discussed at the end.

## MATERIALS AND METHODS

The soils being investigated in this study are underflow tailings and filter material from an active mine site. The underflow sand is the coarse fraction of tailings obtained from the cycloning process and is the main component of the tailings dam. The filter material is located at the interface between the drainage system and the tailings sand at the bottom of the dam and is produced from crushed igneous intrusive rocks such as granodiorite. The grain size distributions (GSDs) of the specimens are determined through sieve analysis for the coarse fraction ($d$ > 0.075mm) and hydrometer test ($d \leq$ 0.075mm) for fines and the results are shown in Fig. 1, respectively. The underflow has an initial fines content of 19%, coefficient of uniformity ($C_u$) of 16.36, and coefficient of curvature ($C_c$) of 5.05. The filter sand has an initial fines content of 6%, coefficient of uniformity ($C_u$) of 7.69, and coefficient of curvature ($C_c$) of 1.55. The underflow tailings has an overall smaller grain sizes with more angular shapes compared to the filter sand.

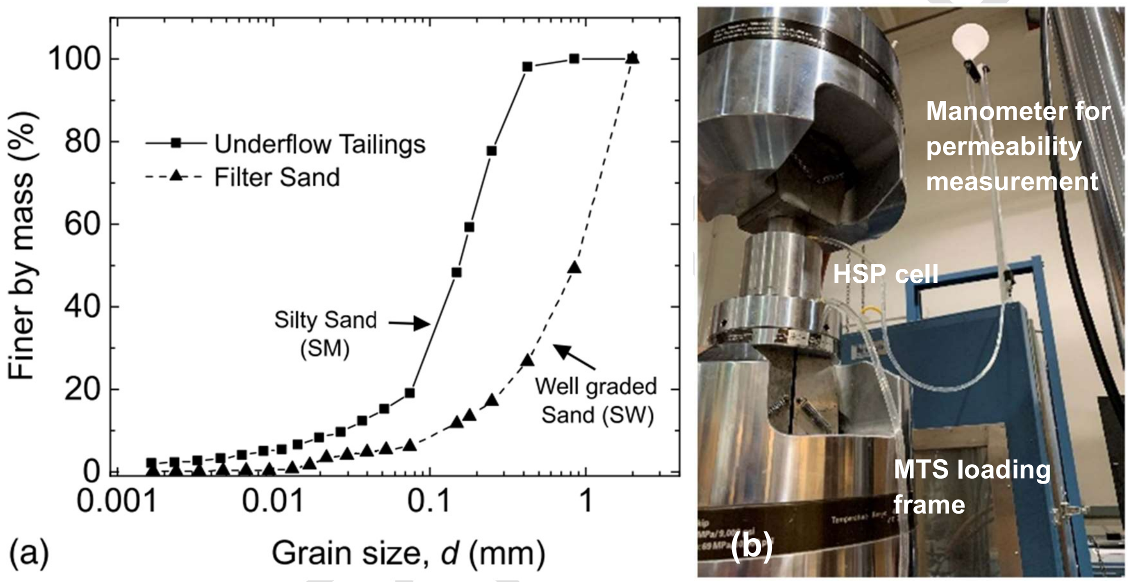


**Figure 1. (a) GSDs of the tested materials; (b) testing setup.**

The test program included 10 oedometer tests, loaded to different maximum vertical stresses ranging from 3.5 MPa to 120 MPa, combined with in-test hydraulic conductivity measurements and post-test GSD analyses. Although stresses greater than 5 MPa, which is equivalent to 333 m-high overburden with dry unit weight of 15 kN/m$^3$ (Obermeyer and Alexieva, 2011), are rare in tailings dams, loading to extended stress level allows for the examination of post-crushing compressibility which is useful for calibrating constitutive models. All oedometer tests were performed using a specially designed high-stress permeability (HSP) oedometer cell to accommodate elevated stresses of up to 160 MPa and permit the measurement of hydraulic conductivity without unloading the specimen. Please refer to Singh et al. (2021) for more details of the HSP cell. Vertical loading is provided by a 500-kN MTS universal testing machine. The combined oedometric compression and hydraulic conductivity tests are performed at five vertical stress levels (3.5 MPa, 5 MPa, 10 MPa, 40 MPa and 120 MPa) for both underflow tailings and filter sand. After each test, the specimen was subjected to wet sieve analysis (ASTM D1140-17) to obtain the post-loading GSD curve.

Specimens were carefully prepared using the wet pluviation method to ensure full saturation at the beginning of all tests. Before pouring the sand, the cell was filled with water and the base outlet was flushed and closed to ensure the drainage lines were free of entrapped air bubbles (ASTM D5856-15). Soils were gradually poured and compacted by gently tamping each layer in multiple layers of similar height to achieve uniform density. Both the underflow tailings and filter sand specimens were prepared to around 80% relative density in the HSP cell. The top drainage line was kept open to allow water drainage during oedometric compression. The assembled oedometer cell was then carefully placed on the loading platform (Fig. 1b). Prior to loading, the inlet was kept open with the outlet valve closed. Compression was conducted at a loading rate of 4.5 kN/min which was sufficiently slow to allow full drainage of the specimen. After reaching the target stress level, the test was paused, and the inlet valve was connected to the manometer for measuring the hydraulic conductivity using the falling head method.

## EXPERIMENTAL RESULTS

Results of the combined compression and hydraulic conductivity tests and the GSDs of post-loaded specimens for the underflow tailings and the filter sand are shown in Fig. 2. The compression curves in Fig. 2a and Fig. 2c exhibit two distinct slopes at low- and high-stress levels. This response is typical for granular soils undergoing grain crushing (Hendron Jr, 1963; Pestana and Whittle, 1995; Nakata et al., 2001). The transition point (i.e., the point of maximum curvature) corresponds to the onset of massive grain breakage and is often referred to as clastic yielding (McDowell et al., 1996). Theoretical and experimental studies have shown that the clastic yield stress $\sigma_{vc}$ is higher for soils with stronger particles, smaller grains, and denser packing (McDowell, 2002; Nakata et al., 2001; Zhang et al., 2016). Here, however, the yield stress for both soils is about the same at 5 MPa, despite the smaller average grain size ($d_{50}$ = 0.15 mm) of the underflow tailings relative to that ($d_{50}$ = 0.85 mm) of the filter sand. Considering these tests are conducted at the same relative density, the comprising minerals for the underflow tailings can be inferred to be much weaker than that of the filter sand. Petrography examinations indeed confirmed that the underflow tailings grains comprise quartz (~50%), muscovite and plagioclase, whereas the filter grains comprise predominately quartz (>90%). Also, the yielding transition is slightly more gradual for the underflow tailings compared to the filter sand. This difference is because the filter sand grains are more rounded and relatively brittle. Once stressed beyond the breakage threshold, sudden fracturing and comminution occurs, which is manifested as a sharp transition at the yielding point. For the underflow tailings with more angular and smaller grains, the failure may involve local plastic sliding and deformation at the grain-to-grain contacts which blurs the clastic yielding transition. These observations are consistent with those by Nakata et al. (2001) and Zhang et al. (2017).

From the GSD curves in Fig. 2b and Fig. 2d, grain crushing apparently has already occurred at a stress level as low as 3.5 MPa before the apparent yielding stress of 5 MPa for both soils. The shifting in the GSD is more significant for the filter sand (Fig. 2d) due to a larger average grain size relative to that for the underflow tailings (see Fig. 1). The maximum grain size $d_M$ for both materials stays the same during loading because of the so-called cushioning effect referring to the protection of larger grains from breakage due to distributed supports from the neighboring smaller grains (Tsoungui et al., 1999; Mair and Abe, 2008). Inspection of the hydraulic conductivity data shows that the reduction of hydraulic conductivity is quite small before clastic yielding for both soils. This portion of hydraulic conductivity is mainly attributed to soil compaction and, thus, the reduction in porosity. After yielding, the hydraulic conductivity decreases significantly, caused by the combined effects of porosity reduction and fines generation. For example, from 5 MPa to 40 MPa, the void ratio of filter sand decreased from 0.48 to 0.3 and the fines content increased from 11% to 17%, respectively, resulting in a hydraulic conductivity reduction by one order of magnitude. The reduction in hydraulic conductivity decreases at high stress levels where the void ratio, $e$, reaches about 0.1~0.2.

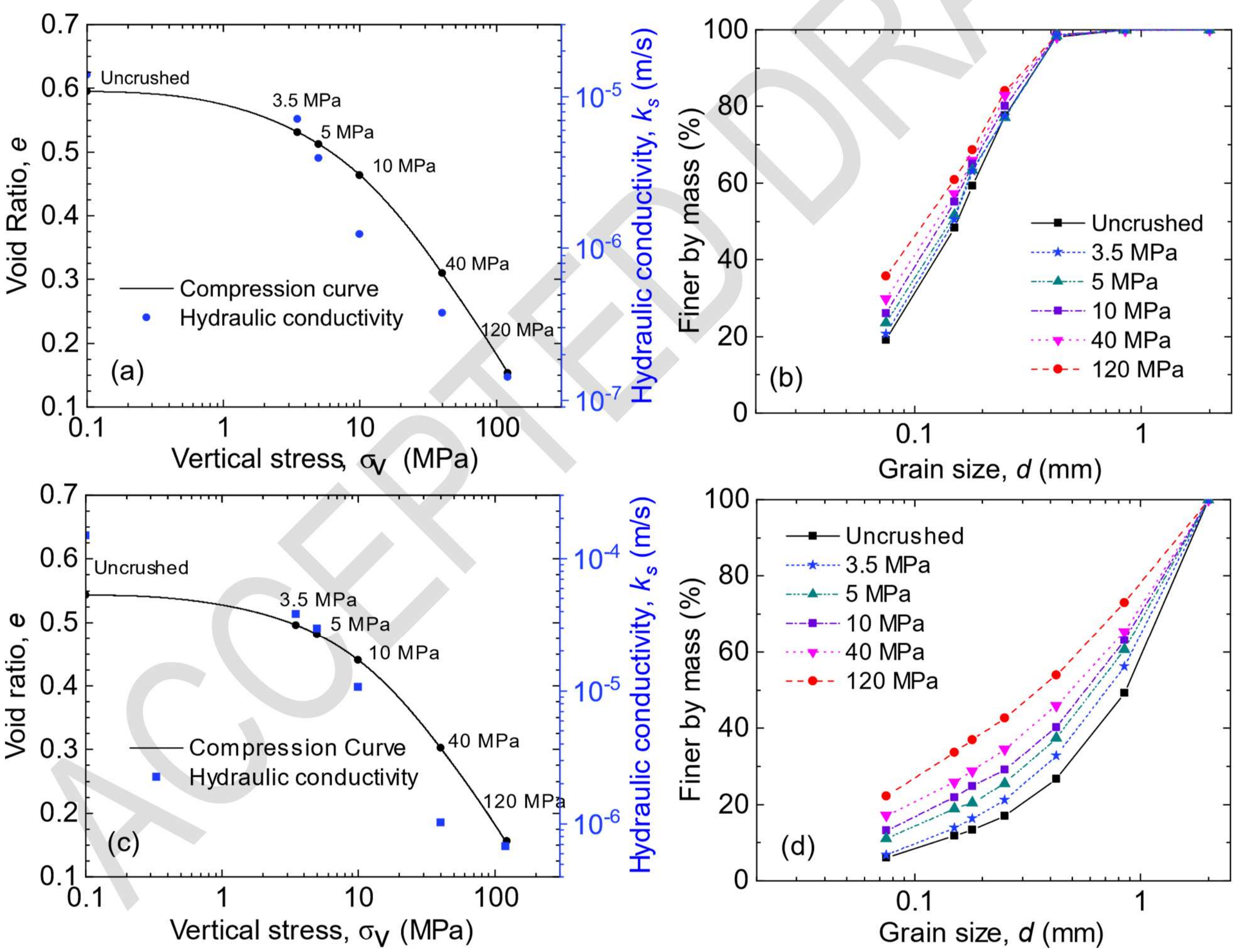


**Figure 2. Compression curve, hydraulic conductivity, and GSD curves at different stress levels for (a, b) underflow tailings and (c, d) filter sands**

## A PILOT CREEP TEST ON TAILINGS SAND

A 3-month creep test was conducted to investigate the evolution of permeability of tailings sand under sustained loading and to prepare for a 2-year creep tests under planning. Fig.3 presents the experimental setup that consists of the same HSP cell, an LVDT for measuring the axial strain, a deadweight loading system, a manometer tube for permeability measures, and a data acquisition desktop. Specimen is prepared using the wet pluviation method to ensure full saturation. The initial density of the specimen is 1.732 g/cm$^3$ ($e_0$ = 0.530) with height of the specimen being 3 cm. An axial stress of 3 MPa is applied to the specimen at once to start the creep test. The axial displacement is constantly monitored through the LVDT. Falling-head permeability tests are conducted twice every week in the first two months but reduced to once every two weeks after that. To better replicate the in-situ environment, the specimen is initially saturated and then frequently flushed with water retrieved from the same TSF where the tailing sand is sourced. The specimen is flushed twice per week by the tailings water for at least 100mL under an initial head difference of about 1m, taking a few hours to complete the flushing process.

The evolution of axial strain and hydraulic conductivity $k_s$ is presented in Fig. 4a. The axial strain increases significantly at the beginning and becomes relatively stable after 20 days. The final axial strain after approximately 3 months of creep is 8.76% (void ratio reduction of 0.13). The $k_s$, on the other hand, shows an abnormal increase during the first 20 days and then gradually decreases to the initial $k_s = 2.9\times10^{-5}$ cm/s. This observation will be discussed in detail in the next paragraph. The initial and the post-test GSDs are presented in Fig. 4b. There is a slight shift of the GSD with the fines content increased from 18.62% to 19.75% under 3 MPa stress after 3-month creep. This is not quite negligible given 3 months is only a tiny fraction of the planned service life of the TSF.

The increase of $k_s$ is unexpected given the lowered void ratio and the increased fines content of the specimen. We postulate that the non-uniformity of the specimen during sample preparation as well as the large hydraulic gradient used in flushing the soil is the cause of such abnormal results. This specimen was prepared by initially filling the HSP cell with tailings water, then the tailings sand was poured and mixed by a glass rod until air bubble disappears. Since fine grain deposits are slower than the coarse grain in water, a thin layer of fines may have formed at the top of the specimen, leading to an initially low value of $k_s$. The flushing operation with the relatively large hydraulic gradient may have mobilized the top layer of fines towards the matrix downstream and thus increased the apparent hydraulic conductivity $k_s$. After approximately 3 weeks with 6 times of flushing, the redistribution of grains induced by flushing may have stabilized, and $k_s$ reaches the maximum. The decrease of $k_s$ afterwards reflects the combined effect of void ratio reduction and grain breakage under sustained loading.

Overall, the effect of creep and particle breakage on $k_s$ is coupled with the effect of high-gradient flushing and sample nonuniformity in this pilot study, making it difficult to postulate the evolution of $k_s$ in real TSF operation conditions. The following improvements should be made in future long-term creep test of tailings sands: 1) premix the tailings material with water before depositing to the HSP cell for a more rigorous wet pluviation procedure; 2) a fully automated water flushing system shall be implemented to provide continuous flushing under minimal hydraulic gradient to prevent perturbation to the sample's internal fabric. Besides, although not observed in this test, the stainless-steel porous disc in the HSP cell may rust during long-term creep tests that span multiple years. Effort can be made to find a material with higher rusting resistance and strength. Ultimately, advanced imaging techniques such as X-ray tomography may combine with an X-ray transparent version of the HSP cell to permit the tracking of the particle spatial distribution and GSD evolution during creep.

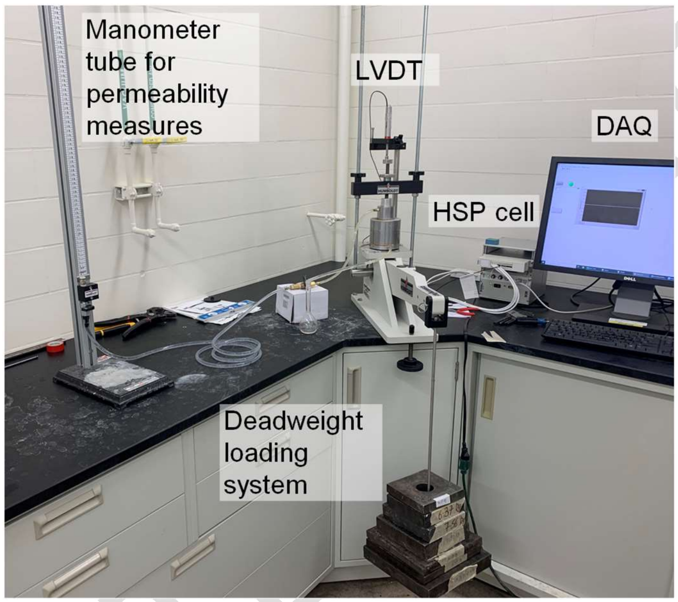


**Figure 3. Creep test setup**

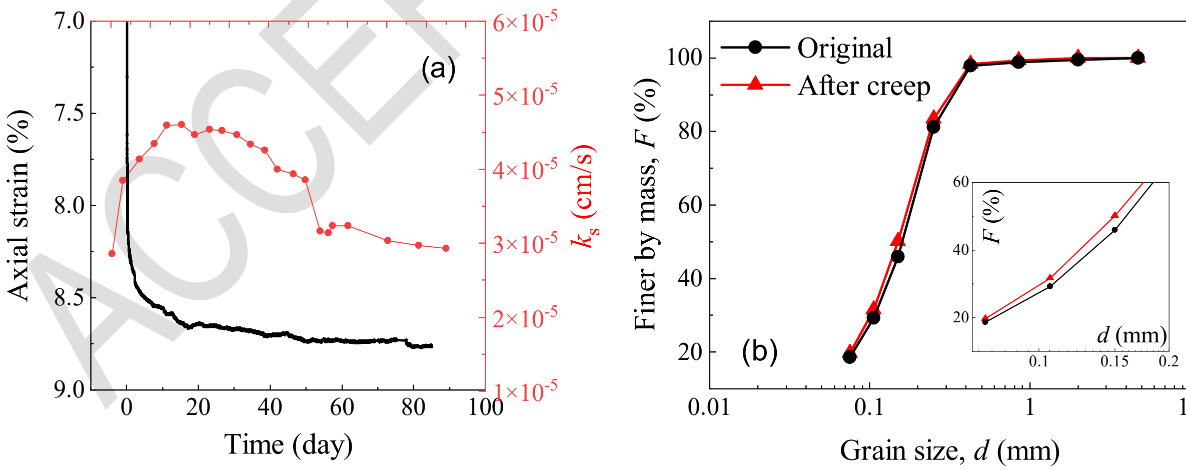


**Figure 4. Creep test results: a) time evolution of creep strain and hydraulic conductivity; b) GSD before and after the test.**

## CONCLUSION

The findings of this study showcase the outcomes of a sequence of coupled high-stress oedometric compression and laboratory-scale hydraulic conductivity tests on tailings sand and filter sand. A new oedometer cell (HSP) was specifically devised and created for this study. Two types of granular soils, underflow tailings and filter sand obtained from a presently operating tailings dam, were assessed. The outcomes reveal that the decrease in hydraulic conductivity during compression is considerably amplified if the stresses were high enough to cause grain breakage, primarily because of the increased fines content in the soil matrix and reduction in void ratio. Our experimental results suggest that increasing the stress from 5 MPa to 40 MPa can result in a reduction in hydraulic conductivity by one order of magnitude for both materials. This reduction in hydraulic conductivity could cause heightened saturation and an elevated phreatic surface within the tailings dam, increasing the likelihood of liquefaction and structural failure in response to mechanical excitations such as earthquakes.

We also performed a pilot 3-month creep test on the tailing sand specimen using the same oedometer cell. After the 3 months of 3 MPa creep loading, the specimen registers an axial strain of 8.76% (void ratio reduction of 0.13), and its fines content increased more than 1%. An abnormal rise of hydraulic conductivity prior to the expected reduction is observed. It is postulated that the initial sample nonuniformity combined with the high-hydraulic head flushing is the cause of this phenomena. Based on the results of this pilot test, multiple improvements to the testing system and protocol are proposed and will be implemented in a 2-year creep test currently under planning.



## ACKNOWLEDGEMENT

This research was supported by the U.S. National Science Foundation (NSF) under NSF CMMI Award No. 2237332. The Predictive Science Academic Alliance Program (PSAAP) under Award Number DE-NA0003962 is also gratefully acknowledged.

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