

Title: Mechanical effects of nanomaterials on the residual shear strength of dry sandy mixtures: implication for the high mobility of rock avalanches

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- The shear strength of silica nanomaterial (SN) depends on the applied normal stress
- Shear velocity has no significant impact on the shear strength of SN
- The shear strength of the mixtures of sand with SN depends on the SN content
- Powder roll formation regulates the shear strength of mixtures with high SN content

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Abstract

Nanoparticles found in rock avalanches and natural faults were inferred to be the reason for the ultra-low shear resistance of the materials along the shear surface. Nevertheless, this inference has not been physically verified yet. To investigate the role of nanoparticles in the shear behavior of granular materials, we conducted a series of ring shear tests on silicon dioxide nanoparticles (SN), silica sand (S8), and mixtures of the S8 with different contents of SN, under varying normal stresses (σ) and shear velocities (V). Our results showed that the shear strength (μ) of SN is high when σ is small (≤ 215 kPa at our test range), even though the maximum shear velocity is about 210 cm/s, but shows a great decrease under higher σ (≥ 619 kPa). The shear strength of mixtures varied with SN content. For S8 (M0) and the mixture of 10% SN (M10), when sheared under small σ , μ first decreased slightly with increasing V when V is smaller than 1 cm/s, after that it increased slightly with further increase of V . Nevertheless, this kind of shear-rate dependent behavior was not observed in the tests under higher σ . When the content of SN in the mixture was less than 20%, μ increased with the increase of SN content. However, with further increase of SN content, μ decreased. Under high normal stress conditions, distinctive powder rolls were observed on the shear surface formed on the tests. When the mixtures with lower SN content ($\leq 50\%$), the powder rolls were not observed. We inferred that powder rolls can be produced under high SN content and high normal stress conditions, and this structure altered the particle movement mode from sliding friction to rolling resistance, resulting in a significant decrease in the shear strength. These findings provide valuable insights into the shear behavior of granular materials with nanoparticles and then provide evidence for a better understanding of the high mobility of rock avalanches.

Keywords: Rock avalanches, High mobility, Nanomaterials, Shear behavior, Powder rolls

1. Introduction

Rock avalanche is a common type of mass movement where the sliding materials are fragmented dry rock or ice at low temperatures prior to or during slope failure (Hung, 2001). It is normally characterized by its large volume, high velocity, and long sliding displacement (Heim, 1932; Hsü et al., 1978; Legros, 2002; Lucas et al., 2014; Pudasaini and Miller, 2013). These features could be exemplified by some rock avalanche events, in which it has been reported that the displaced materials can move at a very high speed exceeding 200 m/s (Evans, 1989), and extend as far as 43 km (Crandell et al., 1984). Therefore, rock avalanche often results in devastating damage to the local properties and great loss of life (Delaney and Evans, 2015; Mitchell et al., 2020; Xu et al., 2012). To prevent or mitigate this kind of disaster, extensive efforts have been made to better understand the mechanisms behind the high mobility of rock avalanches.

For evaluating the mobility of rock avalanches, Heim (1932) proposed a ratio (hereinafter termed Heim's ratio) between the vertical drop height and the horizontal movement distance of the sliding rock mass. This ratio was later termed an equivalent friction coefficient by Shreve (1968a) and Scheidegger (1973) and was widely used in the evaluation of landslide mobility (Corominas, 1996; Legros, 2002; Lucas et al., 2014; Mitchell et al., 2020). By now, numerous studies have revealed that Heim's ratio has an inverse relationship with the volume of the rock avalanche (i.e., Corominas, 1996; Legros, 2002; Lucas et al., 2014; Mitchell et al., 2020, among others). When the volume is approximately smaller than 10^6 m^3 the Heim's ratio consistently ranges approximately from 0.4 to 0.7. However, as the volume increases beyond 10^9 m^3 , it decreases to a small value, sometimes dipping below 0.1 (Pudasaini and Miller, 2013; Lucas et al., 2014). So far as one of the essential prerequisites for the rapid movements of those rock avalanches, several hypotheses, such as air lubrication (Shreve, 1968b), self-lubrication by transformed rock (Campbell, 1989; Erismann, 1979), lubrication by undrained loading of saturated substrates (Sassa, 1988; Wang et al., 2014), acoustic fluidization (Melosh, 1979, 1996), mechanical fluidization (McSaveney, 1978; Davies, 1982), dynamic rock fragmentation (Davies and McSaveney, 1999), and normal stress-dependent

frictional weakening (Wang et al., 2018) had been proposed from the point of view of lowered shear strength of the displaced materials. Nevertheless, while these assumptions may sound reasonable, none of them has gained widespread acceptance due to a lack of supporting evidence from field investigations or experimental results.

Recent studies revealed that nanoparticles (with particle diameters ranging from 1 to 100 nanometers) exist in rock avalanche deposits or fault rupture surfaces (Chester et al., 2005; Dubovskoi et al., 2008; Fondriest et al., 2013; Green et al., 2015; McSaveney and Hu, 2022; Reznichenko et al., 2012), probably resulting from particle fragmentation (Strom and Abdrakhmatov, 2018; Wang et al., 2017; Hu et al., 2020) or mineral decomposition (De Paola et al., 2011; Han et al., 2007, 2010; Spagnuolo et al., 2015; Zhang et al., 2022). It is also reported that nanoparticles could be generated in laboratory shear tests conducted for simulating the fault slip movements (Han et al., 2007, 2010; Hu et al., 2022; Wang et al., 2017).

Numerous laboratory shear tests on fault gauges or different types of rocks have revealed that the tested materials could present extra-low shear strength under certain conditions (such as high normal stress or high shear rate). As the possible reasons for the presence of extra-low shear strength, in addition to frictional melting (Di Toro et al., 2006; Hirose and Shimamoto, 2005; Tsutsumi and Shimamoto, 1997), thermal pressurization (Han et al., 2007; Rice, 2006; Wibberley and Shimamoto, 2005), flash heating (Goldsby and Tullis, 2011; Rice, 2006; Spagnuolo et al., 2015), and thermal decomposition (Hu et al., 2018; Mitchell et al., 2015), possible lubricant by the presence of nanoparticles (Han et al., 2010, 2011; Reches and Lockner, 2010; Tisato et al., 2012) had also been raised. Therefore, it will be reasonable to infer that the presence of nanomaterials in rock avalanches may also substantially diminish the shear resistance of displaced materials and elevate the mobility of rock avalanches. However, it remains unclear whether the formation of nanomaterials affects the shear behavior of the displaced materials in rock avalanches. Further, considering that the displaced materials of the rock avalanches may have varying thicknesses, sliding velocity, or different nanomaterial contents, clarifying the effects of these factors, if any, on the shear strength of sliding materials will be important for better understanding the dynamics of rock

avalanches.

Therefore, in this study, we conducted a series of ring shear tests on the mixture of silica sand with different contents of silica nanoparticles (SN) under different normal stresses and shear velocities. Considering that in rock avalanches the displaced materials are basically in dry conditions (Hungr et al., 2001), all the samples were sheared under dry conditions. On the other hand, due to the mobility and runout of rock avalanches are mainly controlled by the residual shear strength of the displaced landslide materials, in this study we mainly focus on examining the residual shear strength. We also observed the sliding surfaces formed after tests. Based on the results, we examine the mechanical effects of this nanomaterial on the shear behavior of the sand mixtures and discuss the implications for the enhanced mobility of rock avalanches. This investigation provides valuable insights into the role of nanoparticles in mechanically altering the shear strength of displaced materials and their potential impact on related geophysical phenomena.

2. Materials and methods

2.1 Materials

To investigate whether the nanoparticles can work as lubricants, resulting in a significant reduction in the shear strength of geomaterials, we utilized Silicon dioxide (SiO_2) nanoparticles (SN), fine-silica sand (S8), and the mixtures of S8 with different contents of SN as the test materials. SN (Fig. 1a) consists of nano-scale particles with a spherical microstructure, each having a diameter of approximately 50 nanometers (observed using the TEM image presented in Fig. 1b). S8 is uniform sand produced artificially by crushing natural rocks and sieving, mainly composed of subangular to angular quartz grains (Figs. 1c and 1d) (Wang and Sassa, 2003). The particle size distribution of S8 is presented in Fig. 1e, which was measured following the standard of the Japanese Geotechnical Society (2015). The specific gravities of SN and S8 are measured as 2.20 and 2.63, respectively. It is noted that we selected SN and S8 for this study because their physical properties are relatively stable when the temperature

remains within a certain range (typically below 1200°C) (Zihms et al., 2013; Davenport et al., 2022). In our tests, although the temperature within the samples may increase due to the shear friction, it did not reach such a high degree. This was confirmed because the rubber edge (heat resistant is 300 °C at maximum) as the interface between the lower and upper parts of the shear box did not melt during the shearing. Additionally, we prepared mixtures of S8 with 10%, 20%, and 50% of SN, respectively (hereinafter term these mixtures as M10, M20, and M50, respectively). For consistency, we also term S8 and SN as M0 and M100, respectively.

2.2 Methods

In this research, to shear the samples under different normal stresses at different shear rates, we employed three different types of ring shear apparatuses (DPRI-No.5, DPRI-No.6, and DPRI-No.7) developed at Kyoto University (Sassa et al., 2004; Wang et al., 2010; Wang and Sassa, 2002). Some typical features of these apparatuses are summarized in Table. 1. In all the tests, all the materials were oven-dried at 105 °C for 24 hours to eliminate the possible influence of thermo-pressure (excess pore pressure) on the test results. For the tests on SN, we used a small spoon to load the oven-dried SN into the shear box, ensuring that the samples were uniform in the shear box for each test. For the tests on the mixtures, we mixed the oven-dried samples in small amounts and then filled them into the shear box in batches. The tests were conducted under different normal stresses ($\sigma_n = 107$ kPa, 161 kPa, 215 kPa, 619 kPa, and 1030 kPa, respectively). It is also noted that we encountered difficulty in achieving uniform initial density among samples, as they were consolidated under varying normal stresses, while the procedures for placing the samples into the shear box remained consistent. Nevertheless, considering that differences in the initial densities of the samples are likely to impact only the peak shear strength of the samples (Schofield and Wroth, 1968), while our study primarily focuses on residual shear strength, we did not allocate additional effort to examining the potential effects of sample initial density.

After consolidation was completed, the samples were sheared either by the shear-stress controlled method

(for obtaining more details on the variation of shear strength with progress of shearing) or by the shear-velocity controlled method (for examining the shear rate dependency). In the shear stress-controlled tests, the shear stress was increased at a rate of 1 kPa/s from zero to failure of the sample (peak shear strength) until the sample reached its residual state (residual shear strength). For the shear velocity-controlled method, the samples were initially sheared slowly to reach their residual state (inferred as the pre-shear stage) and then sheared by increasing the velocity to different target values. The shear was stopped after the shear strength was stable at the given shear velocity. In all the tests, the shear velocities were changed in a large range among 0.1 ~ 220 cm/s. It is noted that due to the problem in the sever-control system in DPRI-6, the shear tests with shear velocities exceeding 30 cm/s were conducted by changing the shear rate manually.

After the shear tests were finished, we opened the shear box and observed the sliding surfaces. For those tests with identifiable sliding surfaces, a small part (about 2 mm long and 2 mm wide) containing the sliding surface was sampled and then was further observed by using a scanning electron microscope (SEM) (type: ZEISS Ultra-55) without conductive metal coating. In addition, a transmission electron microscope (TEM) (type: JEM-2200FS) was used to observe the microstructure of SN.

The shear resistances for all the tested samples are presented in terms of the stress ratio (μ), the value of monitored shear strength (τ) divided by the applied normal stress (σ_n). The main conditions and results for the ring shear tests are summarized in Table. 2.

3. Results

3.1 Shear behavior of SN

To investigate the shear behavior of pure nanomaterials, we first conducted shear tests on SN under different normal stresses of 107, 161, 215, 619, and 1030 kPa, respectively. In all these tests, the shear stress-controlled method was employed, and the final shear velocity in each test was smaller than 0.4 cm/s. The results are depicted

in Fig. 2a in the form of the shear stress ratio against the shear displacement. From Fig. 2a, it is seen that the shear displacement before reaching the peak shear strength (occurrence of shear failure) differs for different tests, probably due to the different initial sample densities. The shear stress ratios at peak for all the tests are summarized in Table 2. As expected, samples of different initial densities would have different shear stiffness, which will affect the peak shear strength. At normal stresses of 107, 161, and 215 kPa, the stress ratios at the residual state are greater than 0.53. These values closely align with the shear strength of typical natural soils (Keaton, 2017), suggesting that SN itself possesses high shear strength. However, as shown in Fig. 2a, the stress ratio of SN is also dependent on the normal stress. It decreased to 0.34 and 0.25 approximately under the normal stresses of 619 and 1030 kPa, respectively. It is worth noting that the large oscillation could be observed in the test under the normal stress of 619 kPa. A detailed discussion of this phenomenon will be presented in the following section.

A series of tests were conducted on SN by using ring shear apparatus DPRI-No.6 to examine the possible shear rate effect on the shear resistance of SN in a larger velocity range. As an example, Fig. 2b presents the time series data of stress ratio and shear velocity for one test under normal stress of 161 kPa. In this test, the shear velocity was initially raised to 0.11 m/s and held for approximately 10 seconds. Subsequently, it was gradually raised to 2.1 m/s, and the sample was sheared for 5 approximately seconds at this velocity, and finally, the velocity was lowered gradually to zero. From Fig. 2b, it can be noticed that after the occurrence of shear failure, the stress ratio remains relatively consistent (around 0.52~0.63) and presents no significant variation even under the shear velocity of 210 cm/s. It is worth noting that in this test, the total shear displacement is about 30 m, which is significantly longer than the tests mentioned in Fig. 2a.

Fig. 2c illustrates the change in the residual stress ratio at different shear velocities under normal stresses of 161, 619, and 1030 kPa, respectively. It is noted that these tests were carried out using DPRI-No.5. This apparatus enables the application of high normal stress, but it has a small maximum shear velocity (about 10 cm/s). From Fig. 2c, it is noticed that in the tested range of shear velocities, the stress ratio of SN at residual state presents

strong dependence on the normal stress, but at each normal stress level, it does not show significant variation with the shear velocity.

3.2 Shear behavior of mixtures of S8 with SN

The results of a series of shear stress-controlled tests conducted on S8 under various normal stresses are summarized in Fig. 3. From Fig. 3a, it is observed that S8 consistently exhibits a stable shear stress ratio of about 0.67, irrespective of the difference in the applied normal stress. Fig. 3b presents the results of tests on S8 subjected to different shear velocities (V) under normal stress of 161 and 1030 kPa, respectively. It is noted that we employed multistage testing in these shear velocity-controlled tests. Specifically, the sample was sheared until it reached its residual state at a specified shear velocity. Afterward, the shear test was paused while the sample was consolidated under the same normal stress. Subsequently, the sample was re-sheared at a different shear velocity. From Fig. 3b, it can be noticed that S8 exhibits rate dependency, although the shear resistance varies slightly with shear velocity. There is an inflection point in the shear velocity (around 1 cm/s), at which the strength reaches its minimum. Below this velocity, the sample exhibits rate-weakening behavior, while above this velocity the sample shows rate-strengthening. The results shown in Fig. 3b present good consistency with those reported by Jiang et al (2017).

To investigate whether the presence of nanomaterials in the sandy materials can affect the shear behavior, a series of shear tests were conducted on the mixtures of S8 with different SN contents. These tests were performed under the normal stresses of 161 kPa and 1030 kPa, respectively, and at different shear velocities. The stress ratios at the residual states are summarized in Figs. 4a and 4b against the shear velocity for the tests under the normal stresses of 161 and 1030 kPa, respectively. From Fig. 4a, it is noted that when the stress ratios for M50 and M100 range from 0.52 to 0.61, while those for M0, M10, and M20 from 0.66 to 0.78, indicating that introducing SN to S8 can change the shear behavior of the mixtures. However, the shear strength increases with the increase of SN in the mixture when the content of SN is less than 20%, while a further increase in the content of SN (such as 50%

in this study) results in a decrease in the shear resistance. For M10 and M50, the shear strength shows a varying tendency with the shear velocity (V) similar to that of S8. For M20 and M100, the shear strength does not show a significant dependence on V when $V \leq 1$ cm/s; however, when $V \geq 1$ cm/s, the shear strength increases with increasing V . Fig. 4b represents the results for the mixtures under higher normal stress conditions. In this case, it is noticed that in all the mixtures the stress ratio does not show significant change with the variation of the shear velocity. In general, the mixtures with small SN content (M0, M10, M20) present high shear strength, while those with high content of SN exhibit significantly lower values.

3.3. Microphysical features of shear surface

It is noted that in all the tests a shear zone with a sliding surface was formed. To better understand the different shear behaviors of samples under different shear test conditions, after the shear tests were finished we observed the shear surface. We also took sample blocks with sliding surfaces from the shear zone and conducted SEM observation on the sliding surface. The results are presented in Figs. 5-7.

Fig. 5a shows the shear surface obtained after the shear test on SN under normal stress of 1030 kPa, from which the scratches can be seen clearly. Although the surface from this photo seems to be smoothly formed, detailed observations by the SEM shown in Fig. 5b show that there are many aggregates of SN particles on the sliding surface. Further zoomed views shown in Figs. 5c and 5d indicate that some of the SN particles (originally spherically shaped as shown in Fig. 1b) have formed particle aggregates resembling rolls, and the long-axis of these rolls are approximately parallel to each other but perpendicular to the sliding direction, with some broken rolls being smeared on the slip surfaces.

The SEM images of the sliding surface formed in the shear test on SN under the normal stress of 619 kPa are presented in Fig. 6, from which it can be noticed that aggregates of SN particles were also formed on the sliding surface with their longitudinal axis being approximately perpendicular to the sliding direction, but number of rolls

is less than those shown in Figs. 5b-d. Additionally, it is apparent that the shear surface formed (Fig. 6) under lower normal stress exhibits relatively greater roughness compared to that formed under higher normal stress (Fig. 5). This discrepancy likely accounts for the variability in shear behavior observed under normal stress of 619 kPa. Fig. 7 presents the SEM image for the test on M50 under the same normal stress of 1030 kPa. As revealed by Fig. 6, aggregates with different shapes of SN were formed, but the powder rolls were less than those formed in the test on SN (as shown in Figs. 5b-d), suggesting that the sliding surface may be affected by the contents of SN. This was verified by the SEM images shown in Fig. 7, from which no powder rolls could be discovered. These results as shown in Figs. 5-7 indicate that the microstructure of the sliding surface can be affected by the normal stress and also by the content of SN in the mixture. It is noted that we failed to take block samples for SEM observation from the shear zone formed in the tests under the normal stress of 161 kPa, because the shear zone was not densely compacted probably due to the small normal stress. Considering that the nanoparticles are very sensitive to liquid, we also gave up using liquid to bond the shear zone (as normally used in the geological slices).

4. Discussion

4.1. Normal stress-dependent shear behavior of SN

As revealed by Fig. 2a, the residual stress ratios of SN under lower normal stresses (107, 161, 215 kPa) remain relatively high and consistent, while they decrease greatly under higher normal stresses (619 and 1030 kPa). S8 does not show this kind of normal stress-dependent shear behavior (as shown in Fig. 3) although it has the same mineral ingredients as SN. As shown in Figs. 5, for the test under the normal stress of 1030 kPa, SN particles aggregate to form distinctive powder rolls on the shear surface with the long-axis direction of these rolls being approximately perpendicular to the shear direction. Therefore, we infer that the presence of these powder rolls results in a change in the shear mode from sliding to rolling and then results in a decrease in the shear strength.

It is noted that the powder rolls shown in Fig. 5 present similar features as those debris' rolls reported in the

shear tests on different materials for the studies of fault dynamics (Boch et al., 1989; Dong et al., 1991; Zanolari et al., 1995a, b; Hayashi and Tsutsumi, 2010; Nakamura et al., 2012; Chen et al., 2017a, 2017b). In these studies, it is inferred that the rolling of powder rolls facilitates fault slip along the smooth patches of the principal shear zone, contributing to overall weakening and reduced friction. Concerning the formation mechanism of these powder rolls in the shear tests, Chen et al. (2017a, b) present a comprehensive explanation as follows. Namely, the frictional heating resulting from the friction and possible grain-size reduction within the principal slip zone (PSZ) with the progress of shearing may lead to grain compaction, agglomeration, local sintering, and atmospheric water absorption, and then result in the formation of cohesive gouge flakes with smooth, continuous shear surfaces on the top of PSZ. The debris finally agglomerates into powder rolls through the shear-induced torque generated between the opposing slipping surfaces of PSZ, with the axes of the powder rolls being perpendicular to the slip direction. The rolling action of powder contributes to cleaning the surface of the principal shear zone by incorporating encountered particles. However, when these rolls encounter rough or debris-laden areas, they become susceptible to damage, leading to collapse and fracturing. The debris from failed rolls undergoes re-agglomeration, forming new rolls and smooth surfaces until a dynamic balance is achieved between formation and destruction. It has also been addressed that the cohesive behavior of the debris will be key for the formation of powder rolls because they were observed exclusively on cohesive gouge flakes.

The nanoparticles used in this study are no-cohesive. However, flash heating during the shearing may temporally result in the local melting of nanoparticles near the shear surface and then make these nanoparticles cohesive. Based on Rice (2006), Chen et al (2017a) re-formulated the equation for the temperature rise at a contacting asperity, which writes as:

$$\Delta T = \frac{\tau_a V t}{\rho c \sqrt{\pi a_t h \ell}} \quad (1)$$

Here, τ_a : shear stress on the asperity; V : slip velocity; t : time spent at the contact; ρc : the thermal capacity; α_{th} : thermal diffusivity.

Although in this study, we did not make detailed calculations for the possible increase of temperature resulting from the shearing, from equation (1), it will be reasonable to infer that the shear test under higher normal stress would result in greater shear stress on the asperity on the shear surface, and then lead to a higher increase in the temperature. The highly increased temperature would favor the formation of cohesive grains and then enhance the formation of powder rolls under shearing. This may be the reason why the tests under the normal stress of 1030 showed distinguished and much more power rolls on the shear surface (as shown in Fig. 5) with smaller stress ratios, while few formed in the tests under the normal stress of 619 kPa (shown in Fig. 6) with greater stress ratios.

Zanoria et al (1995a, b) produced tribological rolls composed of amorphous silica by the ball-on-flat linear reciprocating sliding of self-mated silicon and examined the effects of length, diameter, and population density (number of rolls per unit area) of tribological rolls on the friction under various loads and environmental conditions. They reported that in all their tests under different loading, humid, and temperature conditions, the coefficients of friction showed identical tendency with the progress of sliding, namely, and were initially relatively high (0.45 ~ 0.65) and then decreased rapidly to a steady value of about 0.13 with the formation and involvement of rolls. They reported that the temperature plays a key role in regulating the length, diameter, and population density of the rolls (as shown in Fig. 8), while the load can only affect the length, and humidity has no significant effect on either of these three items. They further inferred that the balancing influence of changes in length, diameter, and population density results in a consistent coefficient of friction at the steady state. Although inferring the stress ratio from the length, diameter, and population density of the rolls is not the main purpose of this study, to clarify the effects of rolls on the shear strength of SN in our tests, we also examined the population densities of rolls presented in Figs. 5 and 6. Our results show that the tests under 1030 kPa and 619 kPa produced rolls with their population densities being about $4 \times 10^{11} \text{ m}^{-2}$ and $6 \times 10^{10} \text{ m}^{-2}$, respectively, presenting the same order as those shown in Fig. 8c. Therefore, although we failed to measure the temperature that might result from the shearing, it will be reasonable to infer that the formation of rolls during the shear in our tests made key contribution to the decrease of shear strength.

4.2. Shear-velocity dependent shear behavior

The shear velocity (V) dependency of the shear resistance of geomaterials has been widely recognized and reported. It has been pointed out that the mobilized friction angle of soils during shearing is a consequence of both physical friction and the interlocking of soil grains (Lambe and Whitman, 1969). The friction and interlocking are mainly influenced by the orientation of soil grains and shear modes (including sliding mode, transitional mode, and turbulent mode) (Tika et al., 1996), while the shear modes may change with V , leading to variations in residual shear strength (τ_r) (Kenney, 1977; Lupini et al., 1981; Osipov et al., 1984; Tika, 1989; Tika et al., 1996; Suzuki et al., 2004; Duong et al., 2018; Wang et al., 2023).

By now, based on the shear behavior of clayey soils, three distinct types of $\tau_r \sim V$ behavior have been documented: namely, with an increase in V , τ_r remains unchanged (neutral rate effect), exhibits an increase (positive rate effect), and a decrease (negative rate effect) (i.e., Tika, 1989; Tika et al., 1996; Suzuki et al., 2004, among others). Recently, another type (hereinafter called N-P type) had also been reported, which shows that with an increase of V , τ_r decreases at first, but there is an inflection point of V_c at which τ_r reaches its minimum, after that it increases with a further increase of V (Scaringi et al., 2018; Kang et al., 2022; Wang et al., 2023). As the reasons for these $\tau_r \sim V$ modes, two primary assumptions have been proposed. First, alterations in V may lead to the accumulation of excess pore water pressure, resulting in a change in residual shear strength (Japanese Geotechnical Society, 1987). Second, variations in V induce changes in shear modes, resulting in a corresponding alteration in the internal friction angle of soils (Skempton, 1985; Tika et al., 1996).

The shear-velocity-dependent shear behavior of sands has not been of great concern by now, probably because the variation of shear strength with shear velocity is not significant. For example, Hung and Morgenstern (1984) conducted shear tests on different types of coarse sand, mixtures of sand-rock flour, and polystyrene beads under different shear velocities, and concluded that the frictional behavior of these sandy materials was not influenced by either velocity or normal stress over the entire range of shear velocities (0.1~98 cm/s). On the other hand,

Duttine et al (2009) conducted a series of direct shear tests on Toyoura sand (a poorly-graded relatively angular quartz-rich sand) under air-dried conditions and found that the residual shear strength decreases with an increase in shear rate (within the tested rate range of 100 mm/min). Kuwano et al (2013) sheared glass beads with a mean diameter of 270 μm under different normal stresses (10 ~ 30 kPa) and shear velocities ($1 \times 10^{-5} \sim 3$ m/s), and found the characteristic shear velocity at which the least friction is realized. Jiang et al. (2017) performed a series of ring shear tests on silica sands (2.0 ~ 2.5 mm) and glass beads of different sizes (0.11 ~ 0.15 mm and 1.0 ~ 1.4 mm, respectively), and reported the presence of N-P type of shear behavior for all these material within the tested velocity range (0.05~ 50 mm/s). Our tests on M0 and M10 under different shear velocities (shown in Fig. 3b and Fig. 4a) showed a type of N-P, similar to Jiang et al. (2017), although the tendency is insignificant. Concerning these inconsistencies in the shear velocity dependency of shear behavior for these sandy materials, it may result from the differences in the tested velocity ranges and normal stress levels. Concerning the presence of the N-P type shear behavior in these tested samples under dry conditions, Kuwano et al (2013) stated that it may result from the competition between frictional healing and anelasticity. On the other hand, as reported by Skempton (1985) and Tika et al. (1996), changes in the shear modes with velocity could also be one of the reasons. Nevertheless, further study on this issue will be needed to make a conclusive interpretation.

As found in some previous studies (e.g. Han et al., 2007, 2010, 2011; Noda and Shimamoto, 2005; Wang et al., 2017, among others), the residual friction coefficients of some tested samples (such as natural rocks, fault gouges, and nanoparticles) decreased to an extra-low value (less than 0.1) when subjected to rapid shearing (up to 2 m/s approximately). Nevertheless, our results of shear tests on M50 and M100 under the normal stress less than 215 kPa suggest that the shear velocity does not affect the residual shear strength significantly, even when the shear velocity reaches approximately 210 cm/s (as shown in Fig. 2b). On the other hand, our tests showed that the M50 and M100 present smaller shear strength under the normal stresses of 619 and 1030, respectively, possibly due to the formation of rolls on the sliding surface. Therefore, we inferred that for these tests on M100 under the

stress ≤ 215 , although the rapid shearing may favor the generation of high temperature such that more cohesive grains and then more powder rolls could be formed, stronger turbulence during the fast shearing may result in the quick vanish of the powder rolls, if any (Chen et al. 2017b), such that no significant reduction of shear strength could be generated.

4.3. Effect of SN on the shear behavior of the mixtures

Hungr and Morgenstern (1984) conducted a series of ring shear tests on sand-rock flour mixtures and reported that the mixture with 20% of rock flour presented higher shear strength than its host sand, but the shear strength of the mixture did not show significant change with further increase in the flour content. They inferred that the introduction of rock flour to the mixture in a small amount will fill the void spaces in the mixture and then lead to enhanced contact areas between the host sand grains and, consequently, elevate the shear strength. However, the shear behavior of the mixture with higher rock flour will be mainly dominated by the shear behavior of the rock flour.

Our results presented in Fig. 4 show that for the tests on M0, M10, and M20 under the normal stress of 161 kPa, when the shear velocities are the same, the shear strength becomes greater with an increase of SN in the mixture. However, there is no significant difference between M50 and M100. In this sense, our results show good consistency with Hungr and Morgenstern (1984). Namely, the introduction of SN to the mixture below a certain amount will enhance the contact areas of grains and elevate the shear strength; after that, the shear behavior will be mainly controlled by the shear behavior of SN.

For the tests under higher normal stress of 1030 kPa, the shear behavior of M0 ~ M20 will be mainly controlled by the sliding resistance, while those for M50 and M100 will be controlled by the rolling resistance due to the formation of powder rolls. Therefore, for the sliding-controlled shearing, the differences among these samples of M0 ~ M20 became smaller, while that between M50 and M100 became greater because more powder rolls

would be formed in the tests on M100 (as revealed by Figs. 5 and 6). It will be expected that with the increase of SN on the mixture, the sliding surface will become smoother, with in return will elevate the formation of more powder rolls and their longevity.

In the sliding progress of natural rock avalanches, rock particles could gradually become smaller due to dynamic disintegration and frictional abrasion (Perinotto et al., 2015), resulting in the formation of nanoparticles (Strom and Abdrakhmatov, 2018; Wang et al., 2017; Hu et al., 2020). As revealed by our test results, although nanoparticles may not directly work as the lubricate to lower the shear resistance of the mixtures, powder rolls could be formed by the nanoparticles with the progress of shearing when the normal stress and the content of nanoparticles in the mixtures are high enough. Considering that large volume is a general feature of rock avalanches, it will be reasonable to infer that the normal stress loading on the sliding materials could be great enough (say, greater than the normal stress applied in this study). Concerning the content of nanoparticles in the landsliding materials of rock avalanches, although few records are available, it will be able to expect that with the progress of landsliding, more nanoparticles could be produced and accumulated. When the nanoparticle content reaches a certain threshold, the nanoparticles may play a significant role in affecting the structure of the sliding surface with the formation of powder rolls, resulting in the significant reduction of the shear strength and then elevating the mobility of rock avalanches. We further infer that the threshold of nanoparticle content may depend on the applied normal stress and also on the types of nanoparticles. Nevertheless, concerning this inference, further study (including field investigation and laboratory tests under higher normal stress) will be needed for a conclusive remark.

5. Conclusions

To clarify the role of nanoparticles in shear behavior and investigate their potential as lubricants to weaken shear strength during high-velocity shearing, we conducted a series of ring shear tests on SN, S8, and mixtures of

the two, under varying normal stresses and shear velocities. The following conclusions can be drawn from our study:

1. The shear resistance of pure nanomaterial SN is high and stable at lower normal stress levels, even though the maximum shear velocity is approximately 210 cm/s. However, with the increase of applied normal stress (619 and 1030 kPa in this study), the shear resistance decreases significantly.
2. The shear strength of the mixtures of S8 depends on the SN content. When the SN content is less than 20%, the shear strength of the mixture increases with SN content. However, a further increase of SN in the mixture will result in a significant reduction in the shear strength. These results indicate the different roles of SN in the shear behavior of the mixture, namely, the SN with less content will reduce the void space, resulting in the increase in the contacting areas of grains, while further increase of SN in the mixture will result in the fact that the main shear behavior will be mainly controlled by the nanoparticles.
3. The SEM observation on the shear surfaces formed in the tests on SN and mixtures of S8 with high content of SN under higher normal stress (619 and 1030 kPa) revealed the formation of powder rolls laying above the sliding surface and being perpendicular to the sliding direction. When the applied normal stress or the content of SN in the mixtures is higher, the presence of powder rolls becomes denser. Therefore, it is inferred that the significantly lowered shear strength of SN or mixtures with higher content of SN under higher normal stress results from the formation of these powder rolls, which enable the particle movement mode from sliding to rolling.

Finally, it is noted that although our test results showed that the shear resistance of the mixtures can suffer from significant reduction when the applied normal stress or the content of nanoparticles is high enough, the application of our test results to natural rock avalanches needs further scrutiny. In most cases the rock avalanches featured by large scale enable the displaced materials to be loaded by high normal stress during the transportation due to the great thickness, however, the content of nanoparticles in the sliding mass (or along the sliding zone)

will be a key issue in affecting whether the weakening mechanism as shown in Fig. 5 can occur or not. Nevertheless, our results provide insight into understanding the possible roles of nanoparticles in the hypermobility of rock avalanches, because the threshold of nanoparticle content in the mixture could be different under differing normal stress, and the content of nanoparticles may increase due to the continuous pulverization of rocks with the progress of movement. The threshold of nanoparticle content may also be differing for different types of nanoparticles. Concerning this, further study by using different types of nanoparticles will be necessary and are undergoing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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References

- Boch, P., Platon, F., Kapelski, G. (1989). Tribological and interfacial phenomena in Al₂O₃/SiC and SiC/SiC couples at high temperature. *Journal of the European Ceramic Society*, 5(4), 223-228.
- Campbell, C. S. (1989). Self-lubrication for long runout landslides. *The Journal of Geology*, 97(6), 653-665. <https://doi.org/10.1086/629350>.
- Chen, Xiaofeng, Andrew S. Elwood Madden, Ze'ev Reches. (2017a). Friction evolution of granitic faults: heating controlled transition from powder lubrication to frictional melt. *Journal of Geophysical Research: Solid Earth*, 122.11: 9275-9289. <https://doi.org/10.1002/2017JB014462>.
- Chen, Xiaofeng, Andrew S. Elwood Madden, Ze'ev Reches. (2017b). Powder rolling as a mechanism of dynamic fault weakening. *Fault zone dynamic processes: Evolution of fault properties during seismic rupture*: 133-150. <https://doi.org/10.1002/9781119156895.ch7>.
- Chester, J. S., Chester, F. M., Kronenberg, A. K. (2005). Fracture surface energy of the Punchbowl fault, San Andreas system. *Nature*, 437(7055), 133-136. <https://doi.org/10.1038/nature03942>.
- Corominas, J. (1996). The angle of reach as a mobility index for small and large landslides. *Canadian Geotechnical Journal*, 33(2), 260-271. <https://doi.org/10.1139/t96-005>.
- Crandell, D. R., Miller, C. D., Glicken, H. X., Christiansen, R. L., Newhall, C. G. (1984). Catastrophic debris avalanche from ancestral Mount Shasta volcano, California. *Geology*, 12(3), 143-146. [https://doi.org/10.1130/0091-7613\(1984\)12<143:CDAFAM>2.0.CO;2](https://doi.org/10.1130/0091-7613(1984)12<143:CDAFAM>2.0.CO;2).
- Davenport, P., Ma, Z.W., Nation, W., Schirck, J., Morris, A., Lambert, M. (2022): Thermal Stability of Silica for Application in Thermal Energy Storage. *AIP Conference Proceedings* 2445(1), 160003. <https://doi.org/10.1063/5.0085641>.
- Davies, T.R.H. (1982). The spreading of rock avalanche debris by mechanical fluidization. *Rock Mechanics*, 15: 9-24. <https://doi.org/10.1007/BF01239474>.
- Davies, T. R., McSaveney, M. J. (1999). Runout of dry granular avalanches. *Canadian Geotechnical Journal*, 36(2), 313-320. <https://doi.org/10.1139/t98-108>.
- Delaney, K. B., Evans, S. G. (2015). The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: Review, remote sensing analysis, and process modelling. *Geomorphology*, 246, 377-393. <https://doi.org/10.1016/j.geomorph.2015.06.020>.
- De Paola, N., Holdsworth, R.E., Viti, C., Collettini, C., Bullock, R. (2015), Can grain size sensitive flow lubricate faults during the initial stages of earthquake propagation? *Earth and Planetary Science Letters*, 431, 48-58. <https://doi.org/10.1016/j.epsl.2015.09.002>.

- Di Toro, G., Hirose, T., Nielsen, S., Pennacchioni, G., Shimamoto, T. (2006). Natural and experimental evidence of melt lubrication of faults during earthquakes. *Science*, 311(5761), 647–649. <https://doi.org/10.1126/science.1121012>.
- Dong, X., Jahanmir, S., Hsu, S. M. (1991). Tribological characteristics of α -Alumina at elevated temperatures. *Journal of the American Ceramic Society*, 74(5), 1036–1044.
- Dubovskoi, A. N., Pernik, L. M., Strom, A. L. (2008). Experimental simulation of rockslide fragmentation. *Journal of Mining Science*, 44(2), 123–130. <https://doi.org/10.1007/s10913-008-0025-y>.
- Duttine, A., & Tatsuoka, F. (2009). Viscous properties of granular materials having different particle shapes in direct shear. *Soils and foundations*, 49(5), 777–796. <https://doi.org/10.3208/sandf.49.777>.
- Duong, N.T., Suzuki, M., Hai, N.V., 2018. Rate and acceleration effects on residual strength of kaolin and kaolin–bentonite mixtures in ring shearing. *Soils Found.* 58 (5), 1153–1172.
- Erismann, T. H. (1979). Mechanisms of large landslides. *Rock Mechanics*, 12(1), 15–46. Mechanisms of large landslides. *Rock Mechanics* 12(1), 15–46. <https://doi.org/10.1007/BF01241087>.
- Evans, S. G. (1989). Rock avalanche run-up record. *Nature (London)*, 340(6231). <https://doi.org/10.1038/340271a0>.
- Fondriest, M., Smith, S. A., Candela, T., Nielsen, S. B., Mair, K., Di Toro, G. (2013). Mirror-like faults and power dissipation during earthquakes. *Geology*, 41(11), 1175–1178. <https://doi.org/10.1130/G34641.1>.
- Goldsby, D. L., Tullis, T. E. (2011). Flash heating leads to low frictional strength of crustal rocks at earthquake slip rates. *Science*, 334(6053), 216–218. <https://doi.org/10.1126/science.1207902>.
- Green II, H. W., Shi, F., Bozhilov, K., Xia, G., Reches, A. Z. (2015). Phase transformation and nanometric flow cause extreme weakening during fault slip. *Nature Geoscience*, 8(6), 484–489. <https://doi.org/10.1038/ngeo2436>.
- Han, R., Hirose, T., Shimamoto, T. (2010). Strong velocity weakening and powder lubrication of simulated carbonate faults at seismic slip rates. *Journal of Geophysical Research: Solid Earth*, 115(B3). <https://doi.org/10.1029/2008JB006136>.
- Han, R., Hirose, T., Shimamoto, T., Lee, Y., Ando, J. I. (2011). Granular nanoparticles lubricate faults during seismic slip. *Geology*, 39(6), 599–602. <https://doi.org/10.1130/G31842.1>.
- Han, R., Shimamoto, T., Hirose, T., Ree, J. H., Ando, J. I. (2007). Ultralow friction of carbonate faults caused by thermal decomposition. *Science*, 316(5826), 878–881. <https://doi.org/10.1126/science.1139763>.
- Hayashi, N., & Tsutsumi, A. (2010). Deformation textures and mechanical behavior of a hydrated amorphous silica formed along an experimentally produced fault in chert. *Geophysical Research Letters*, 37(12).

504 <https://doi.org/10.1029/2010GL042943>.

505 Heim, A., (1932) *Bergsturz und Menschleben*. Fretz and Wasmuth, Zurich. 218 pp.

506 Hirose, T., Shimamoto, T. (2005). Growth of molten zone as a mechanism of slip weakening of simulated faults in
 507 gabbro during frictional melting. *Journal of Geophysical Research: Solid Earth*, 110(B5).
 508 <https://doi.org/10.1029/2004JB003207>.

509 Hsü, K. J., Voight, B. (1978). Albert Heim: observations on landslides and relevance to modern interpretations.
 510 *Natural Phenomena*, 1, 70-93.

511 Hu, W., Chang, C. S., McSaveney, M., Huang, R., Xu, Q., Zheng, Y., Yu, J. (2020). A Weakening Rheology of Dry
 512 Granular Flows With Extensive Brittle Grain Damage in High-Speed Rotary Shear Experiments.
 513 *Geophysical Research Letters*, 47(11), 1–10. <https://doi.org/10.1029/2020GL087763>.

514 Hu, W., Huang, R., McSaveney, M., Zhang, X. hui, Yao, L., Shimamoto, T. (2018). Mineral changes quantify
 515 frictional heating during a large low-friction landslide. *Geology*, 46(3), 223–226.
 516 <https://doi.org/10.1130/G39662.1>.

517 Hu, W., Xu, Q., Mcsaveney, M., Huang, R., Wang, Y., Chang, C. S., Gou, H., Zheng, Y. (2022). The intrinsic
 518 mobility of very dense grain flows. *Earth and Planetary Science Letters*, 580, 117389.
 519 <https://doi.org/10.1016/j.epsl.2022.117389>.

520 Hungr, O., Morgenstern, N. R. (1984). High velocity ring shear tests on sand. *Geotechnique*, 34(3), 415-421.
 521 <https://doi.org/10.1680/geot.1984.34.3.415>.

522 Hungr, O., Evans, S. G., Bovis, M., Hutchinson, J.N. (2001) Review of the classification of landslides of the flow
 523 type. *Environ Engineering Geoscience* VII:221–238

524 Japanese Geotechnical Society, 2015. Japanese Geotechnical Society Standard (JGS 0051–2009): Method of
 525 Classification of Geomaterials for Engineering Purposes, vol. 1. The Japanese Geotechnical Society
 526 Standards: Laboratory Testing Standards of Geomaterial.

527 Jiang, Y., Wang, G., & Kamai, T. (2017). Fast shear behavior of granular materials in ring-shear tests and
 528 implications for rapid landslides. *Acta Geotechnica*, 12, 645-655. <https://doi.10.1007/s11440-016-0508-y>.

529 Kang, X., Wang, S., Wu, W., & Xu, G. (2022). Residual state rate effects of shear-zone soil regulating slow-to-fast
 530 transition of catastrophic landslides. *Engineering Geology*, 304, 106692.
 531 <https://doi.org/10.1016/j.enggeo.2022.106692>.

532 Keaton, J.R. (2017). Angle of Internal Friction. In: Bobrowsky, P., Marker, B. (eds) *Encyclopedia of Engineering*
 533 *Geology*. Encyclopedia of Earth Sciences Series. Springer, Cham. [https://doi-org.kyoto-](https://doi-org.kyoto-u.idm.oclc.org/10.1007/978-3-319-12127-7_16-1)
 534 [u.idm.oclc.org/10.1007/978-3-319-12127-7_16-1](https://doi-org.kyoto-u.idm.oclc.org/10.1007/978-3-319-12127-7_16-1).

535 Kenney, T.C., (1977). Residual strength of mineral mixtures. In: Proc. of the 9th ICSMFE, pp. 155–160.

536 Kuwano, O., Ando, R., & Hatano, T. (2013). Crossover from negative to positive shear rate dependence in granular
537 friction. *Geophysical research letters*, 40(7), 1295-1299. <https://doi.org/10.1002/grl.50311>.

538 Lambe, T. W., and Whitman, R. V. (1969). Soil mechanics. John Wiley and Sons, Inc., New York, N.Y.

539 Legros, F. (2002). The mobility of long-runout landslides. *Engineering Geology*, 63(3–4), 301–331.
540 [https://doi.org/10.1016/S0013-7952\(01\)00090-4](https://doi.org/10.1016/S0013-7952(01)00090-4).

541 Lucas, A., Mangeney, A., Ampuero, J. P. (2014). Frictional velocity-weakening in landslides on Earth and on other
542 planetary bodies. *Nature Communications*, 5(1), 1-9. <https://doi.org/10.1038/ncomms4417>.

543 Lupini, J.F., Skinner, A.E., Vaughan, P.R., (1981). The drained residual strength of cohesive soils. *Geotechnique*,
544 31 (2), 181–213. <https://doi.org/10.1680/geot.1981.31.2.181>.

545 McSaveney, M. J. (1978). "Sherman glacier rock avalanche, Alaska, USA." *Developments in Geotechnical*
546 *Engineering*. Vol. 14, pp. 197-258.

547 McSaveney, M., Hu, W. (2022). Nanoparticles in the 2008 Yangjiagou rock avalanche. Short Papers and Extended
548 Abstracts, Geological Society of America Penrose Conference Penrose Conference: Progressive Failure of
549 Brittle Rocks. PRF2022. Flat Rock, N.C., 20-24 June, 2022. <https://doi.org/10.1130/abs/2022PR-376041>.

550 Melosh, H. J. (1979). Acoustic fluidization: a new geologic process? *Journal of Geophysical Research*, 84(B13),
551 7513–7520. <https://doi.org/10.1029/JB084iB13p07513>.

552 Melosh, H. J. (1996). Dynamical weakening of faults by acoustic fluidization. *Nature*, 379(6566), 601–606.
553 <https://doi.org/10.1038/379601a0>.

554 Mitchell, A., McDougall, S., Aaron, J., Brideau, M. A. (2020). Rock avalanche-generated sediment mass flows:
555 Definitions and hazard. *Frontiers in Earth Science*, 8, 543937. <https://doi.org/10.3389/feart.2020.543937>.

556 Mitchell, T. M., Smith, S. A. F., Anders, M. H., Di Toro, G., Nielsen, S., Cavallo, A., Beard, A. D. (2015).
557 Catastrophic emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming.
558 *Earth and Planetary Science Letters*, 411, 199–207. <https://doi.org/10.1016/j.epsl.2014.10.051>.

559 Nakamura, Y., Muto, J., Nagahama, H., Shimizu, I., Miura, T., and Arakawa, I. (2012). Amorphization of quartz
560 by friction: Implication to silica-gel lubrication of fault surfaces. *Geophysical Research Letters*, 39(21).
561 <https://doi.org/10.1029/2012GL053228>.

562 Noda, H., & Shimamoto, T. (2005). Thermal pressurization and slip-weakening distance of a fault: an example of
563 the Hanaore fault, southwest Japan. *Bulletin of the Seismological Society of America*, 95(4), 1224–1233.
564 <https://doi.org/10.1785/0120040089>.

565 Osipov, V.I., Nikolaeva, S.K., Sokolov, V.N., 1984. Microstructural changes associated with thixotropic

phenomena in clay soils. *Geotechnique*, 34 (2), 293–303.

Perinotto, H., Schneider, J. L., Bachèlery, P., Le Bourdonnec, F. X., Famin, V., & Michon, L. (2015). The extreme mobility of debris avalanches: A new model of transport mechanism. *Journal of Geophysical Research: Solid Earth*, 120(12), 8110–8119. <https://doi.org/10.1002/2015JB011994>.

Pudasaini, S. P., Miller, S. A. (2013). The hypermobility of huge landslides and avalanches. *Engineering Geology*, 157, 124–132. <https://doi.org/10.1016/j.enggeo.2013.01.012>.

Reches, Z., Lockner, D. A. (2010). Fault weakening and earthquake instability by powder lubrication. *Nature*, 467(7314), 452–455. <https://doi.org/10.1038/nature09348>.

Reznichenko, N. V., Davies, T. R. H., Shulmeister, J., Larsen, S. H. (2012). A new technique for identifying rock avalanche-sourced sediment in moraines and some paleoclimatic implications. *Geology*, 40(4), 319–322. <https://doi.org/10.1130/G32684.1>.

Rice, J. R. (2006). Heating and weakening of faults during earthquake slip. *Journal of Geophysical Research: Solid Earth*, 111(B5). <https://doi.org/10.1029/2005JB004006>.

Sassa, K. (1988), Geotechnical model for the motion of landslides, in Proceedings of the 5th International Symposium on Landslides, pp. 37–55, Lausanne, Switzerland.

Sassa, K., Fukuoka, H., Wang, G., Ishikawa, N. (2004). Undrained dynamic-loading ring-shear apparatus and its application to landslide dynamics. *Landslides*, 1(1), 7–19. <https://doi.org/10.1007/s10346-003-0004-y>.

Scaringi, G., Hu, W., Xu, Q., Huang, R. (2018). Shear - rate - dependent behavior of clayey bimaterial interfaces at landslide stress levels. *Geophysical Research Letters*, 45(2), 766–777. <https://doi.org/10.1002/2017GL076214>.

Schofield, A.N., Wroth, C.P. (1968). Critical State Soil Mechanics. McGraw-Hill.

Shreve R.L. (1968a). The Blackhawk Landslide. Geological Society of America. Spec pap108:1–47.

Shreve, R. L. (1968b). Leakage and fluidization in air-layer lubricated avalanches. *The Geological Society of America Bulletin*, 79(5), 653–658. [https://doi.org/10.1130/0016-7606\(1968\)79\[653:lafial\]2.0.co;2](https://doi.org/10.1130/0016-7606(1968)79[653:lafial]2.0.co;2).

Scheidegger A.E. (1973). On the prediction of the reach and velocity of catastrophic landslides. *Rock Mech. Rock Eng.* 5(4), 231–236.

Skempton, A.W., (1985). Residual strength of clays in landslides, folded strata and the laboratory. *Geotechnique*, 35 (1), 3–18.

Spagnuolo, E., Plümer, O., Violay, M., Cavallo, A., Di Toro, G. (2015). Fast-moving dislocations trigger flash weakening in carbonate-bearing faults during earthquakes. *Scientific Reports*, 5(1), 1–11. <https://doi.org/10.1038/srep16112>.

- Strom, A., Abdrakhmatov, K. (2018). Rockslides and rock avalanches of Central Asia: distribution, morphology, and internal structure. Elsevier.
- Suzuki, M., Kobayashi, K., Yamamoto, T., Matsubara, T., Hukuda, J., (2004). Influence of shear rate on residual strength of clay in ring shear test. *Res. Rep. School Eng. Yamaguchi Univ.* 55 (2), 49–62.
- Tika, T.E., (1989). The Effect of Rate of Shear on the Residual Strength of Soil. PhD thesis, University of London.
- Tika, T. E., Vaughan, P. R., & Lemos, L. J. L. (1996). Fast shearing of pre-existing shear zones in soil. *Geotechnique*, 46(2), 197–233. <https://doi.org/10.1680/geot.1996.46.2.197>.
- Tisato, N., Di Toro, G., De Rossi, N., Quaresimin, M., Candela, T. (2012). Experimental investigation of flash weakening in limestone. *Journal of Structural Geology*, 38, 183–199. <https://doi.org/10.1016/j.jsg.2011.11.017>.
- Tsutsumi, A., Shimamoto, T. (1997). High-velocity frictional properties of gabbro. *Geophysical Research Letters*, 24(6), 699–702. <https://doi.org/10.1029/97GL00503>.
- Wang, G., Huang, R., Lourenço, S. D., Kamai, T. (2014). A large landslide triggered by the 2008 Wenchuan (M8.0) earthquake in Donghekou area: Phenomena and mechanisms. *Engineering Geology*, 182, 148–157. <https://doi.org/10.1016/j.enggeo.2014.07.013>.
- Wang, G., Sassa, K. (2002). Post-failure mobility of saturated sands in undrained load-controlled ring shear tests. *Canadian Geotechnical Journal*, 39(4), 821–837. <https://doi.org/10.1139/t02-032>.
- Wang, G., Sassa, K. (2003). Pore-pressure generation and movement of rainfall-induced landslides: Effects of grain size and fine-particle content. *Engineering Geology*, 69(1–2), 109–125. [https://doi.org/10.1016/S0013-7952\(02\)00268-5](https://doi.org/10.1016/S0013-7952(02)00268-5).
- Wang G, Suemine A, Schulz W H. (2010) Shear-rate-dependent strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. *Earth Surface Processes and Landforms*, 35(4): 407–416. <https://doi.org/10.1002/esp.1937>.
- Wang, G., Watanabe, N., Hoshikawa, K., Furuya, G., Cai, F., & Wu, S. (2023). Diverse shear behaviors of clayey materials: Implications for differing landsliding behaviors within the same area in Niigata, Japan. *Engineering Geology*, 312, 106932. <https://doi.org/10.1016/j.enggeo.2022.106932>.
- Wang, Y. F., Dong, J. J., Cheng, Q. G. (2017). Velocity-dependent frictional weakening of large rock avalanche basal facies: Implications for rock avalanche hypermobility? *Journal of Geophysical Research: Solid Earth*, 122(3), 1648–1676. <https://doi.org/10.1002/2016JB013624>.
- Wang, Y. F., Dong, J. J., Cheng, Q. G. (2018). Normal stress-dependent frictional weakening of large rock avalanche basal facies: implications for the rock avalanche volume effect. *Journal of Geophysical Research:*

628 *Solid Earth*, 123,3270–3282. <https://doi.org/10.1002/2018JB015602>.

629 Wibberley, C. A. J., Shimamoto, T. (2005). Earthquake slip weakening and asperities explained by thermal
630 pressurization. *Nature*, 436(7051), 689–692. <https://doi.org/10.1038/nature03901>.

631 Xu, Q., Shang, Y., van Asch, T., Wang, S., Zhang, Z., Dong, X. (2012). Observations from the large, rapid Yigong
632 rock slide–debris avalanche, southeast Tibet. *Canadian Geotechnical Journal*, 49(5), 589-606.
633 <https://doi.org/10.1139/t2012-021>.

634 Zanolari, E. S., S. Danyluk, M. J. McNallan. (1995a), Formation of cylindrical sliding-wear debris on silicon in
635 humid conditions and elevated temperatures, *Tribology Transactions*, 38.3 (1995): 721-727.
636 <https://doi.org/10.1080/10402009508983464>.

637 Zanolari, Elmer, Steven Danyluk, Michael McNallan. (1995b). Effects of length, diameter and population density
638 of tribological rolls on friction between self-mated silicon. *Wear*, 181 (1995): 784-789.
639 [https://doi.org/10.1016/0043-1648\(95\)90196-5](https://doi.org/10.1016/0043-1648(95)90196-5).

640 Zhang, M., Yang, L., Li, W., Wang, Z., Zhang, C., Chen, Q., Wang, B. (2022). Frictional properties of the rupture
641 surface of a carbonate rock avalanche. *International Journal of Rock Mechanics and Mining Sciences*, 153,
642 105088. <https://doi.org/10.1016/j.ijrmms.2022.105088>.

643 Zihms, S.G., Switzer, C., Irvine, J., Karstunen, M. (2013): Effects of high temperature processes on physical
644 properties of silica sand. *Engineering Geology*, 164:139-145.

Captions:

Fig. 1. (a) Pure nano silica sand (SN); (b) TEM image of SN; (c) Pure silica sand No.8 (S8); (d) SEM image of S8; (e) Grain size distribution of S8.

Fig. 2. Results of ring shear tests on SN: (a) Under different normal stresses, by the shear stress-controlled method; (b) Result of high shear-velocity ring shear test under normal stress of 161 kPa, by the shear velocity-controlled method; (c) Average stress ratio of residual state under different shear velocities, by the shear velocity-controlled method.

Fig. 3. Results of ring shear tests on S8: (a) Under different normal stresses, by the shear stress-controlled method; (b) Average stress ratio of residual state under different shear velocities by the shear velocity-controlled method.

Fig. 4. Average stress ratio of residual state of ring shear tests on the mixtures by the shear velocity-controlled method: (a) Under a normal stress of 161 kPa; (b) Under a normal stress of 1030 kPa. M100: pure SN; M0: pure S8. M10, M20, and M50 represent the SN content in the mixture is 10%, 20%, and 50%, respectively.

Fig. 5. Post-test (the largest shear velocity is 10 cm/s) photo and SEM images from a test conducted on SN under the normal stress of 1030 kPa, (a) Shear surface after the test. (b), (c), (d) SEM images obtained by scanning the shear surface. (e) Location for the microstructural observation texture. The red arrow indicates the shear direction and the green arrow indicates the formation of powder rolls. The orange square (2 mm long and 2 mm wide) of the shear surface was taken for SEM testing.

Fig. 6. Post-test (the largest shear velocity is 10 cm/s) SEM images from a test conducted on SN under the normal

stress of 619 kPa. The red arrow indicates the shear direction and the green arrow indicates the formation of powder rolls.

Fig. 7. Post-test (the largest shear velocity is 10 cm/s) SEM image from a test conducted on M50 under the normal stress of 1030 kPa. The red arrow indicates the shear direction.

Fig. 8. Test results of Zanoria et al. (1995b). (a) mean length, (b) diameter, and (c) population density of tribological rolls against temperature. (Modified from Fig. 4 in Zanoria et al., 1995b). The tribological rolls were obtained through the ball-on-flat linear reciprocating sliding of self-mated silicon at different temperatures, humid conditions, and normal loads. P_w : water pressure used in the tests for examining the effects of humidity.

Table 1. Features of ring shear apparatuses of DPRI-5, DPRI-6, and DPRI-7.

Table 2. Test conditions and details results of the ring shear tests

**Title: Mechanical effects of nanomaterials on the residual shear strength of dry sandy mixtures:
implication for the high mobility of rock avalanches**

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Highlight:

- The shear strength of silica nanomaterial (SN) depends on the applied normal stress
- Shear velocity has no significant impact on the shear strength of SN
- The shear strength of the mixtures of sand with SN depends on the SN content
- Powder roll formation regulates the shear strength of mixtures with high SN content

Abstract

Nanoparticles found in rock avalanches and natural faults were inferred to be the reason for the ultra-low shear resistance of the materials along the shear surface. Nevertheless, this inference has not been physically verified yet. To investigate the role of nanoparticles in the shear behavior of granular materials, we conducted a series of ring shear tests on silicon dioxide nanoparticles (SN), silica sand (S8), and mixtures of the S8 with different contents of SN, under varying normal stresses (σ) and shear velocities (V). Our results showed that the shear strength (μ) of SN is high when σ is small (≤ 215 kPa at our test range), even though the maximum shear velocity is about 210 cm/s, but shows a great decrease under higher σ (≥ 619 kPa). The shear strength of mixtures varied with SN content. For S8 (M0) and the mixture of 10% SN (M10), when sheared under small σ , μ first decreased slightly with increasing V when V is smaller than 1 cm/s, after that it increased slightly with further increase of V . Nevertheless, this kind of shear-rate dependent behavior was not observed in the tests under higher σ . When the content of SN in the mixture was less than 20%, μ increased with the increase of SN content. However, with further increase of SN content, μ decreased. Under high normal stress conditions, distinctive powder rolls were observed on the shear surface formed on the tests. When the mixtures with lower SN content ($\leq 50\%$), the powder rolls were not observed. We inferred that powder rolls can be produced under high SN content and high normal stress conditions, and this structure altered the particle movement mode from sliding friction to rolling resistance, resulting in a significant decrease in the shear strength. These findings provide valuable insights into the shear behavior of granular materials with nanoparticles and then provide evidence for a better understanding of the high mobility of rock avalanches.

Keywords: Rock avalanches, High mobility, Nanomaterials, Shear behavior, Powder rolls

1. Introduction

Rock avalanche is a common type of mass movement where the sliding materials are fragmented dry rock or ice at low temperatures prior to or during slope failure (Hungr, 2001). It is normally characterized by its large volume, high velocity, and long sliding displacement (Heim, 1932; Hsü et al., 1978; Legros, 2002; Lucas et al., 2014; Pudasaini and Miller, 2013). These features could be exemplified by some rock avalanche events, in which it has been reported that the displaced materials can move at a very high speed exceeding 200 m/s (Evans, 1989), and extend as far as 43 km (Crandell et al., 1984). Therefore, rock avalanche often results in devastating damage to the local properties and great loss of life (Delaney and Evans, 2015; Mitchell et al., 2020; Xu et al., 2012). To prevent or mitigate this kind of disaster, extensive efforts have been made to better understand the mechanisms behind the high mobility of rock avalanches.

For evaluating the mobility of rock avalanches, Heim (1932) proposed a ratio (hereinafter termed Heim's ratio) between the vertical drop height and the horizontal movement distance of the sliding rock mass. This ratio was later termed an equivalent friction coefficient by Shreve (1968a) and Scheidegger (1973) and was widely used in the evaluation of landslide mobility (Corominas, 1996; Legros, 2002; Lucas et al., 2014; Mitchell et al., 2020). By now, numerous studies have revealed that Heim's ratio has an inverse relationship with the volume of the rock avalanche (i.e., Corominas, 1996; Legros, 2002; Lucas et al., 2014; Mitchell et al., 2020, among others). When the volume is approximately smaller than 10^6 m^3 the Heim's ratio consistently ranges approximately from 0.4 to 0.7. However, as the volume increases beyond 10^9 m^3 , it decreases to a small value, sometimes dipping below 0.1 (Pudasaini and Miller, 2013; Lucas et al., 2014). So far as one of the essential prerequisites for the rapid movements of those rock avalanches, several hypotheses, such as air lubrication (Shreve, 1968b), self-lubrication by transformed rock (Campbell, 1989; Erismann, 1979), lubrication by undrained loading of saturated substrates (Sassa, 1988; Wang et al., 2014), acoustic fluidization (Melosh, 1979, 1996), mechanical fluidization (McSaveney, 1978; Davies, 1982), dynamic rock fragmentation (Davies and McSaveney, 1999), and

normal stress-dependent frictional weakening (Wang et al., 2018) had been proposed from the point of view of lowered shear strength of the displaced materials. Nevertheless, while these assumptions may sound reasonable, none of them has gained widespread acceptance due to a lack of supporting evidence from field investigations or experimental results.

Recent studies revealed that nanoparticles (with particle diameters ranging from 1 to 100 nanometers) exist in rock avalanche deposits or fault rupture surfaces (Chester et al., 2005; Dubovskoi et al., 2008; Fondriest et al., 2013; Green et al., 2015; McSaveney and Hu, 2022; Reznichenko et al., 2012), probably resulting from particle fragmentation (Strom and Abdrakhmatov, 2018; Wang et al., 2017; Hu et al., 2020) or mineral decomposition (De Paola et al., 2011; Han et al., 2007, 2010; Spagnuolo et al., 2015; Zhang et al., 2022). It is also reported that nanoparticles could be generated in laboratory shear tests conducted for simulating the fault slip movements (Han et al., 2007, 2010; Hu et al., 2022; Wang et al., 2017).

Numerous laboratory shear tests on fault gauges or different types of rocks have revealed that the tested materials could present extra-low shear strength under certain conditions (such as high normal stress or high shear rate). As the possible reasons for the presence of extra-low shear strength, in addition to frictional melting (Di Toro et al., 2006; Hirose and Shimamoto, 2005; Tsutsumi and Shimamoto, 1997), thermal pressurization (Han et al., 2007; Rice, 2006; Wibberley and Shimamoto, 2005), flash heating (Goldsby and Tullis, 2011; Rice, 2006; Spagnuolo et al., 2015), and thermal decomposition (Hu et al., 2018; Mitchell et al., 2015), possible lubricant by the presence of nanoparticles (Han et al., 2010, 2011; Reches and Lockner, 2010; Tisato et al., 2012) had also been raised. Therefore, it will be reasonable to infer that the presence of nanomaterials in rock avalanches may also substantially diminish the shear resistance of displaced materials and elevate the mobility of rock avalanches. However, it remains unclear whether the formation of nanomaterials affects the shear behavior of the displaced materials in rock avalanches. Further, considering that the displaced materials of the rock avalanches may have varying thicknesses, sliding velocity, or different nanomaterial contents, clarifying the

effects of these factors, if any, on the shear strength of sliding materials will be important for better understanding the dynamics of rock avalanches.

Therefore, in this study, we conducted a series of ring shear tests on the mixture of silica sand with different contents of silica nanoparticles (SN) under different normal stresses and shear velocities. Considering that in rock avalanches the displaced materials are basically in dry conditions (Hungr et al., 2001), all the samples were sheared under dry conditions. On the other hand, due to the mobility and runout of rock avalanches are mainly controlled by the residual shear strength of the displaced landslide materials, in this study we mainly focus on examining the residual shear strength. We also observed the sliding surfaces formed after tests. Based on the results, we examine the mechanical effects of this nanomaterial on the shear behavior of the sand mixtures and discuss the implications for the enhanced mobility of rock avalanches. This investigation provides valuable insights into the role of nanoparticles in mechanically altering the shear strength of displaced materials and their potential impact on related geophysical phenomena.

2. Materials and methods

2.1 Materials

To investigate whether the nanoparticles can work as lubricants, resulting in a significant reduction in the shear strength of geomaterials, we utilized Silicon dioxide (SiO_2) nanoparticles (SN), fine-silica sand (S8), and the mixtures of S8 with different contents of SN as the test materials. SN (Fig. 1a) consists of nano-scale particles with a spherical microstructure, each having a diameter of approximately 50 nanometers (observed using the TEM image presented in Fig. 1b). S8 is uniform sand produced artificially by crushing natural rocks and sieving, mainly composed of subangular to angular quartz grains (Figs. 1c and 1d) (Wang and Sassa, 2003). The particle size distribution of S8 is presented in Fig. 1e, which was measured following the standard of the Japanese Geotechnical Society (2015). The specific gravities of SN and S8 are measured as 2.20 and 2.63,

respectively. It is noted that we selected SN and S8 for this study because their physical properties are relatively stable when the temperature remains within a certain range (typically below 1200°C) (Zihms et al., 2013; Davenport et al., 2022). In our tests, although the temperature within the samples may increase due to the shear friction, it did not reach such a high degree. This was confirmed because the rubber edge (heat resistant is 300 °C at maximum) as the interface between the lower and upper parts of the shear box did not melt during the shearing. Additionally, we prepared mixtures of S8 with 10%, 20%, and 50% of SN, respectively (hereinafter term these mixtures as M10, M20, and M50, respectively). For consistency, we also term S8 and SN as M0 and M100, respectively.

2.2 Methods

In this research, to shear the samples under different normal stresses at different shear rates, we employed three different types of ring shear apparatuses (DPRI-No.5, DPRI-No.6, and DPRI-No.7) developed at Kyoto University (Sassa et al., 2004; Wang et al., 2010; Wang and Sassa, 2002). Some typical features of these apparatuses are summarized in Table. 1. In all the tests, all the materials were oven-dried at 105 °C for 24 hours to eliminate the possible influence of thermo-pressure (excess pore pressure) on the test results. For the tests on SN, we used a small spoon to load the oven-dried SN into the shear box, ensuring that the samples were uniform in the shear box for each test. For the tests on the mixtures, we mixed the oven-dried samples in small amounts and then filled them into the shear box in batches. The tests were conducted under different normal stresses ($\sigma_n = 107 \text{ kPa}, 161 \text{ kPa}, 215 \text{ kPa}, 619 \text{ kPa}, \text{ and } 1030 \text{ kPa}$, respectively). It is also noted that we encountered difficulty in achieving uniform initial density among samples, as they were consolidated under varying normal stresses, while the procedures for placing the samples into the shear box remained consistent. Nevertheless, considering that differences in the initial densities of the samples are likely to impact only the peak shear strength of the samples (Schofield and Wroth, 1968), while our study primarily focuses on residual shear strength, we did not

allocate additional effort to examining the potential effects of sample initial density.

After consolidation was completed, the samples were sheared either by the shear-stress controlled method (for obtaining more details on the variation of shear strength with progress of shearing) or by the shear-velocity controlled method (for examining the shear rate dependency). In the shear stress-controlled tests, the shear stress was increased at a rate of 1 kPa/s from zero to failure of the sample (peak shear strength) until the sample reached its residual state (residual shear strength). For the shear velocity-controlled method, the samples were initially sheared slowly to reach their residual state (inferred as the pre-shear stage) and then sheared by increasing the velocity to different target values. The shear was stopped after the shear strength was stable at the given shear velocity. In all the tests, the shear velocities were changed in a large range among 0.1 ~ 220 cm/s. It is noted that due to the problem in the sever-control system in DPRI-6, the shear tests with shear velocities exceeding 30 cm/s were conducted by changing the shear rate manually.

After the shear tests were finished, we opened the shear box and observed the sliding surfaces. For those tests with identifiable sliding surfaces, a small part (about 2 mm long and 2 mm wide) containing the sliding surface was sampled and then was further observed by using a scanning electron microscope (SEM) (type: ZEISS Ultra-55) without conductive metal coating. In addition, a transmission electron microscope (TEM) (type: JEM-2200FS) was used to observe the microstructure of SN.

The shear resistances for all the tested samples are presented in terms of the stress ratio (μ), the value of monitored shear strength (τ) divided by the applied normal stress (σ_n). The main conditions and results for the ring shear tests are summarized in Table. 2.

3. Results

3.1 Shear behavior of SN

To investigate the shear behavior of pure nanomaterials, we first conducted shear tests on SN under

different normal stresses of 107, 161, 215, 619, and 1030 kPa, respectively. In all these tests, the shear stress-controlled method was employed, and the final shear velocity in each test was smaller than 0.4 cm/s. The results are depicted in Fig. 2a in the form of the shear stress ratio against the shear displacement. From Fig. 2a, it is seen that the shear displacement before reaching the peak shear strength (occurrence of shear failure) differs for different tests, probably due to the different initial sample densities. The shear stress ratios at peak for all the tests are summarized in Table 2. As expected, samples of different initial densities would have different shear stiffness, which will affect the peak shear strength. At normal stresses of 107, 161, and 215 kPa, the stress ratios at the residual state are greater than 0.53. These values closely align with the shear strength of typical natural soils (Keaton, 2017), suggesting that SN itself possesses high shear strength. However, as shown in Fig. 2a, the stress ratio of SN is also dependent on the normal stress. It decreased to 0.34 and 0.25 approximately under the normal stresses of 619 and 1030 kPa, respectively. It is worth noting that the large oscillation could be observed in the test under the normal stress of 619 kPa. A detailed discussion of this phenomenon will be presented in the following section.

A series of tests were conducted on SN by using ring shear apparatus DPRI-No.6 to examine the possible shear rate effect on the shear resistance of SN in a larger velocity range. As an example, Fig. 2b presents the time series data of stress ratio and shear velocity for one test under normal stress of 161 kPa. In this test, the shear velocity was initially raised to 0.11 m/s and held for approximately 10 seconds. Subsequently, it was gradually raised to 2.1 m/s, and the sample was sheared for 5 approximately seconds at this velocity, and finally, the velocity was lowered gradually to zero. From Fig. 2b, it can be noticed that after the occurrence of shear failure, the stress ratio remains relatively consistent (around 0.52~0.63) and presents no significant variation even under the shear velocity of 210 cm/s. It is worth noting that in this test, the total shear displacement is about 30 m, which is significantly longer than the tests mentioned in Fig. 2a.

Fig. 2c illustrates the change in the residual stress ratio at different shear velocities under normal stresses of

161, 619, and 1030 kPa, respectively. It is noted that these tests were carried out using DPRI-No.5. This apparatus enables the application of high normal stress, but it has a small maximum shear velocity (about 10 cm/s). From Fig. 2c, it is noticed that in the tested range of shear velocities, the stress ratio of SN at residual state presents strong dependence on the normal stress, but at each normal stress level, it does not show significant variation with the shear velocity.

3.2 Shear behavior of mixtures of S8 with SN

The results of a series of shear stress-controlled tests conducted on S8 under various normal stresses are summarized in Fig. 3. From Fig. 3a, it is observed that S8 consistently exhibits a stable shear stress ratio of about 0.67, irrespective of the difference in the applied normal stress. Fig. 3b presents the results of tests on S8 subjected to different shear velocities (V) under normal stress of 161 and 1030 kPa, respectively. It is noted that we employed multistage testing in these shear velocity-controlled tests. Specifically, the sample was sheared until it reached its residual state at a specified shear velocity. Afterward, the shear test was paused while the sample was consolidated under the same normal stress. Subsequently, the sample was re-sheared at a different shear velocity. From Fig. 3b, it can be noticed that S8 exhibits rate dependency, although the shear resistance varies slightly with shear velocity. There is an inflection point in the shear velocity (around 1 cm/s), at which the strength reaches its minimum. Below this velocity, the sample exhibits rate-weakening behavior, while above this velocity the sample shows rate-strengthening. The results shown in Fig. 3b present good consistency with those reported by Jiang et al (2017).

To investigate whether the presence of nanomaterials in the sandy materials can affect the shear behavior, a series of shear tests were conducted on the mixtures of S8 with different SN contents. These tests were performed under the normal stresses of 161 kPa and 1030 kPa, respectively, and at different shear velocities. The stress ratios at the residual states are summarized in Figs. 4a and 4b against the shear velocity for the tests under

the normal stresses of 161 and 1030 kPa, respectively. From Fig. 4a, it is noted that when the stress ratios for M50 and M100 range from 0.52 to 0.61, while those for M0, M10, and M20 from 0.66 to 0.78, indicating that introducing SN to S8 can change the shear behavior of the mixtures. However, the shear strength increases with the increase of SN in the mixture when the content of SN is less than 20%, while a further increase in the content of SN (such as 50% in this study) results in a decrease in the shear resistance. For M10 and M50, the shear strength shows a varying tendency with the shear velocity (V) similar to that of S8. For M20 and M100, the shear strength does not show a significant dependence on V when $V \leq 1$ cm/s; however, when $V \geq 1$ cm/s, the shear strength increases with increasing V . Fig. 4b represents the results for the mixtures under higher normal stress conditions. In this case, it is noticed that in all the mixtures the stress ratio does not show significant change with the variation of the shear velocity. In general, the mixtures with small SN content (M0, M10, M20) present high shear strength, while those with high content of SN exhibit significantly lower values.

3.3. Microphysical features of shear surface

It is noted that in all the tests a shear zone with a sliding surface was formed. To better understand the different shear behaviors of samples under different shear test conditions, after the shear tests were finished we observed the shear surface. We also took sample blocks with sliding surfaces from the shear zone and conducted SEM observation on the sliding surface. The results are presented in Figs. 5-7.

Fig. 5a shows the shear surface obtained after the shear test on SN under normal stress of 1030 kPa, from which the scratches can be seen clearly. Although the surface from this photo seems to be smoothly formed, detailed observations by the SEM shown in Fig. 5b show that there are many aggregates of SN particles on the sliding surface. Further zoomed views shown in Figs. 5c and 5d indicate that some of the SN particles (originally spherically shaped as shown in Fig. 1b) have formed particle aggregates resembling rolls, and the long-axis of these rolls are approximately parallel to each other but perpendicular to the sliding direction, with some broken

rolls being smeared on the slip surfaces.

The SEM images of the sliding surface formed in the shear test on SN under the normal stress of 619 kPa are presented in Fig. 6, from which it can be noticed that aggregates of SN particles were also formed on the sliding surface with their longitudinal axis being approximately perpendicular to the sliding direction, but number of rolls is less than those shown in Figs. 5b-d. Additionally, it is apparent that the shear surface formed (Fig. 6) under lower normal stress exhibits relatively greater roughness compared to that formed under higher normal stress (Fig. 5). This discrepancy likely accounts for the variability in shear behavior observed under normal stress of 619 kPa. Fig. 7 presents the SEM image for the test on M50 under the same normal stress of 1030 kPa. As revealed by Fig. 6, aggregates with different shapes of SN were formed, but the powder rolls were less than those formed in the test on SN (as shown in Figs. 5b-d), suggesting that the sliding surface may be affected by the contents of SN. This was verified by the SEM images shown in Fig. 7, from which no powder rolls could be discovered. These results as shown in Figs. 5-7 indicate that the microstructure of the sliding surface can be affected by the normal stress and also by the content of SN in the mixture. It is noted that we failed to take block samples for SEM observation from the shear zone formed in the tests under the normal stress of 161 kPa, because the shear zone was not densely compacted probably due to the small normal stress. Considering that the nanoparticles are very sensitive to liquid, we also gave up using liquid to bond the shear zone (as normally used in the geological slices).

4. Discussion

4.1. Normal stress-dependent shear behavior of SN

As revealed by Fig. 2a, the residual stress ratios of SN under lower normal stresses (107, 161, 215 kPa) remain relatively high and consistent, while they decrease greatly under higher normal stresses (619 and 1030 kPa). S8 does not show this kind of normal stress-dependent shear behavior (as shown in Fig. 3) although it has

the same mineral ingredients as SN. As shown in Figs. 5, for the test under the normal stress of 1030 kPa, SN particles aggregate to form distinctive powder rolls on the shear surface with the long-axis direction of these rolls being approximately perpendicular to the shear direction. Therefore, we infer that the presence of these powder rolls results in a change in the shear mode from sliding to rolling and then results in a decrease in the shear strength.

It is noted that the powder rolls shown in Fig. 5 present similar features as those debris' rolls reported in the shear tests on different materials for the studies of fault dynamics (Boch et al., 1989; Dong et al., 1991; Zanolari et al., 1995a, b; Hayashi and Tsutsumi, 2010; Nakamura et al., 2012; Chen et al., 2017a, 2017b). In these studies, it is inferred that the rolling of powder rolls facilitates fault slip along the smooth patches of the principal shear zone, contributing to overall weakening and reduced friction. Concerning the formation mechanism of these powder rolls in the shear tests, Chen et al. (2017a, b) present a comprehensive explanation as follows. Namely, the frictional heating resulting from the friction and possible grain-size reduction within the principal slip zone (PSZ) with the progress of shearing may lead to grain compaction, agglomeration, local sintering, and atmospheric water absorption, and then result in the formation of cohesive gouge flakes with smooth, continuous shear surfaces on the top of PSZ. The debris finally agglomerates into powder rolls through the shear-induced torque generated between the opposing slipping surfaces of PSZ, with the axes of the powder rolls being perpendicular to the slip direction. The rolling action of powder contributes to cleaning the surface of the principal shear zone by incorporating encountered particles. However, when these rolls encounter rough or debris-laden areas, they become susceptible to damage, leading to collapse and fracturing. The debris from failed rolls undergoes re-agglomeration, forming new rolls and smooth surfaces until a dynamic balance is achieved between formation and destruction. It has also been addressed that the cohesive behavior of the debris will be key for the formation of powder rolls because they were observed exclusively on cohesive gouge flakes.

The nanoparticles used in this study are no-cohesive. However, flash heating during the shearing may

temporally result in the local melting of nanoparticles near the shear surface and then make these nanoparticles cohesive. Based on Rice (2006), Chen et al (2017a) re-formulated the equation for the temperature rise at a contacting asperity, which writes as:

$$\Delta T = \frac{\tau_a V t}{\rho c \sqrt{\pi a_{th} t}} \quad (1)$$

Here, τ_a : shear stress on the asperity; V : slip velocity; t : time spent at the contact; ρc : the thermal capacity; α_{th} : thermal diffusivity.

Although in this study, we did not make detailed calculations for the possible increase of temperature resulting from the shearing, from equation (1), it will be reasonable to infer that the shear test under higher normal stress would result in greater shear stress on the asperity on the shear surface, and then lead to a higher increase in the temperature. The highly increased temperature would favor the formation of cohesive grains and then enhance the formation of powder rolls under shearing. This may be the reason why the tests under the normal stress of 1030 showed distinguished and much more power rolls on the shear surface (as shown in Fig. 5) with smaller stress ratios, while few formed in the tests under the normal stress of 619 kPa (shown in Fig. 6) with greater stress ratios.

Zanoria et al (1995a, b) produced tribological rolls composed of amorphous silica by the ball-on-flat linear reciprocating sliding of self-mated silicon and examined the effects of length, diameter, and population density (number of rolls per unit area) of tribological rolls on the friction under various loads and environmental conditions. They reported that in all their tests under different loading, humid, and temperature conditions, the coefficients of friction showed identical tendency with the progress of sliding, namely, and were initially relatively high (0.45 ~ 0.65) and then decreased rapidly to a steady value of about 0.13 with the formation and involvement of rolls. They reported that the temperature plays a key role in regulating the length, diameter, and population density of the rolls (as shown in Fig. 8), while the load can only affect the length, and humidity has no significant effect on either of these three items. They further inferred that the balancing influence of changes

in length, diameter, and population density results in a consistent coefficient of friction at the steady state. Although inferring the stress ratio from the length, diameter, and population density of the rolls is not the main purpose of this study, to clarify the effects of rolls on the shear strength of SN in our tests, we also examined the population densities of rolls presented in Figs. 5 and 6. Our results show that the tests under 1030 kPa and 619 kPa produced rolls with their population densities being about $4 \times 10^{11} \text{ m}^{-2}$ and $6 \times 10^{10} \text{ m}^{-2}$, respectively, presenting the same order as those shown in Fig. 8c. Therefore, although we failed to measure the temperature that might result from the shearing, it will be reasonable to infer that the formation of rolls during the shear in our tests made key contribution to the decrease of shear strength.

4.2. Shear-velocity dependent shear behavior

The shear velocity (V) dependency of the shear resistance of geomaterials has been widely recognized and reported. It has been pointed out that the mobilized friction angle of soils during shearing is a consequence of both physical friction and the interlocking of soil grains (Lambe and Whitman, 1969). The friction and interlocking are mainly influenced by the orientation of soil grains and shear modes (including sliding mode, transitional mode, and turbulent mode) (Tika et al., 1996), while the shear modes may change with V , leading to variations in residual shear strength (τ_r) (Kenney, 1977; Lupini et al., 1981; Osipov et al., 1984; Tika, 1989; Tika et al., 1996; Suzuki et al., 2004; Duong et al., 2018; Wang et al., 2023).

By now, based on the shear behavior of clayey soils, three distinct types of $\tau_r \sim V$ behavior have been documented: namely, with an increase in V , τ_r remains unchanged (neutral rate effect), exhibits an increase (positive rate effect), and a decrease (negative rate effect) (i.e., Tika, 1989; Tika et al., 1996; Suzuki et al., 2004, among others). Recently, another type (hereinafter called N-P type) had also been reported, which shows that with an increase of V , τ_r decreases at first, but there is an inflection point of V_c at which τ_r reaches its minimum, after that it increases with a further increase of V (Scaringi et al., 2018; Kang et al., 2022; Wang et al., 2023). As the reasons for these $\tau_r \sim V$ modes, two primary assumptions have been proposed. First, alterations in V may lead

to the accumulation of excess pore water pressure, resulting in a change in residual shear strength (Japanese Geotechnical Society, 1987). Second, variations in V induce changes in shear modes, resulting in a corresponding alteration in the internal friction angle of soils (Skempton, 1985; Tika et al., 1996).

The shear-velocity-dependent shear behavior of sands has not been of great concern by now, probably because the variation of shear strength with shear velocity is not significant. For example, Hungr and Morgenstern (1984) conducted shear tests on different types of coarse sand, mixtures of sand-rock flour, and polystyrene beads under different shear velocities, and concluded that the frictional behavior of these sandy materials was not influenced by either velocity or normal stress over the entire range of shear velocities (0.1~98 cm/s). On the other hand, Duttine et al (2009) conducted a series of direct shear tests on Toyoura sand (a poorly-graded relatively angular quartz-rich sand) under air-dried conditions and found that the residual shear strength decreases with an increase in shear rate (within the tested rate range of 100 mm/min). Kuwano et al (2013) sheared glass beads with a mean diameter of 270 μm under different normal stresses (10 ~ 30 kPa) and shear velocities ($1 \times 10^{-5} \sim 3$ m/s), and found the characteristic shear velocity at which the least friction is realized. Jiang et al. (2017) performed a series of ring shear tests on silica sands (2.0 ~ 2.5 mm) and glass beads of different sizes (0.11 ~ 0.15 mm and 1.0 ~ 1.4 mm, respectively), and reported the presence of N-P type of shear behavior for all these material within the tested velocity range (0.05~ 50 mm/s). Our tests on M0 and M10 under different shear velocities (shown in Fig. 3b and Fig. 4a) showed a type of N-P, similar to Jiang et al. (2017), although the tendency is insignificant. Concerning these inconsistencies in the shear velocity dependency of shear behavior for these sandy materials, it may result from the differences in the tested velocity ranges and normal stress levels. Concerning the presence of the N-P type shear behavior in these tested samples under dry conditions, Kuwano et al (2013) stated that it may result from the competition between frictional healing and anelasticity. On the other hand, as reported by Skempton (1985) and Tika et al. (1996), changes in the shear modes with velocity could also be one of the reasons. Nevertheless, further study on this issue will be needed to make a conclusive

interpretation.

As found in some previous studies (e.g. Han et al., 2007, 2010, 2011; Noda and Shimamoto, 2005; Wang et al., 2017, among others), the residual friction coefficients of some tested samples (such as natural rocks, fault gouges, and nanoparticles) decreased to an extra-low value (less than 0.1) when subjected to rapid shearing (up to 2 m/s approximately). Nevertheless, our results of shear tests on M50 and M100 under the normal stress less than 215 kPa suggest that the shear velocity does not affect the residual shear strength significantly, even when the shear velocity reaches approximately 210 cm/s (as shown in Fig. 2b). On the other hand, our tests showed that the M50 and M100 present smaller shear strength under the normal stresses of 619 and 1030, respectively, possibly due to the formation of rolls on the sliding surface. Therefore, we inferred that for these tests on M100 under the stress ≤ 215 , although the rapid shearing may favorite the generation of high temperature such that more cohesive grains and then more powder rolls could be formed, stronger turbulence during the fast shearing may result in the quick vanish of the powder rolls, if any (Chen et al. 2017b), such that no significant reduction of shear strength could be generated.

4.3. Effect of SN on the shear behavior of the mixtures

Hungr and Morgenstern (1984) conducted a series of ring shear tests on sand-rock flour mixtures and reported that the mixture with 20% of rock flour presented higher shear strength than its host sand, but the shear strength of the mixture did not show significant change with further increase in the flour content. They inferred that the introduction of rock flour to the mixture in a small amount will fill the void spaces in the mixture and then lead to enhanced contact areas between the host sand grains and, consequently, elevate the shear strength. However, the shear behavior of the mixture with higher rock flour will be mainly dominated by the shear behavior of the rock flour.

Our results presented in Fig. 4 show that for the tests on M0, M10, and M20 under the normal stress of 161

kPa, when the shear velocities are the same, the shear strength becomes greater with an increase of SN in the mixture. However, there is no significant difference between M50 and M100. In this sense, our results show good consistency with Hungr and Morgenstern (1984). Namely, the introduction of SN to the mixture below a certain amount will enhance the contact areas of grains and elevate the shear strength; after that, the shear behavior will be mainly controlled by the shear behavior of SN.

For the tests under higher normal stress of 1030 kPa, the shear behavior of M0 ~ M20 will be mainly controlled by the sliding resistance, while those for M50 and M100 will be controlled by the rolling resistance due to the formation of power rolls. Therefore, for the sliding-controlled shearing, the differences among these samples of M0 ~ M20 became smaller, while that between M50 and M100 became greater because more powder rolls would be formed in the tests on M100 (as revealed by Figs. 5 and 6). It will be expected that with the increase of SN on the mixture, the sliding surface will become smoother, with in return will elevate the formation of more powder rolls and their longevity.

In the sliding progress of natural rock avalanches, rock particles could gradually become smaller due to dynamic disintegration and frictional abrasion (Perinotto et al., 2015), resulting in the formation of nanoparticles (Strom and Abdrakhmatov, 2018; Wang et al., 2017; Hu et al., 2020). As revealed by our test results, although nanoparticles may not directly work as the lubricate to lower the shear resistance of the mixtures, powder rolls could be formed by the nanoparticles with the progress of shearing when the normal stress and the content of nanoparticles in the mixtures are high enough. Considering that large volume is a general feature of rock avalanches, it will be reasonable to infer that the normal stress loading on the sliding materials could be great enough (say, greater than the normal stress applied in this study). Concerning the content of nanoparticles in the landsliding materials of rock avalanches, although few records are available, it will be able to expect that with the progress of landsliding, more nanoparticles could be produced and accumulated. When the nanoparticle content reaches a certain threshold, the nanoparticles may play a significant role in affecting the structure of the

sliding surface with the formation of powder rolls, resulting in the significant reduction of the shear strength and then elevating the mobility of rock avalanches. We further infer that the threshold of nanoparticle content may depend on the applied normal stress and also on the types of nanoparticles. Nevertheless, concerning this inference, further study (including field investigation and laboratory tests under higher normal stress) will be needed for a conclusive remark.

5. Conclusions

To clarify the role of nanoparticles in shear behavior and investigate their potential as lubricants to weaken shear strength during high-velocity shearing, we conducted a series of ring shear tests on SN, S8, and mixtures of the two, under varying normal stresses and shear velocities. The following conclusions can be drawn from our study:

1. The shear resistance of pure nanomaterial SN is high and stable at lower normal stress levels, even though the maximum shear velocity is approximately 210 cm/s. However, with the increase of applied normal stress (619 and 1030 kPa in this study), the shear resistance decreases significantly.
2. The shear strength of the mixtures of S8 depends on the SN content. When the SN content is less than 20%, the shear strength of the mixture increases with SN content. However, a further increase of SN in the mixture will result in a significant reduction in the shear strength. These results indicate the different roles of SN in the shear behavior of the mixture, namely, the SN with less content will reduce the void space, resulting in the increase in the contacting areas of grains, while further increase of SN in the mixture will result in the fact that the main shear behavior will be mainly controlled by the nanoparticles.
3. The SEM observation on the shear surfaces formed in the tests on SN and mixtures of S8 with high content of SN under higher normal stress (619 and 1030 kPa) revealed the formation of powder rolls

laying above the sliding surface and being perpendicular to the sliding direction. When the applied normal stress or the content of SN in the mixtures is higher, the presence of powder rolls becomes denser. Therefore, it is inferred that the significantly lowered shear strength of SN or mixtures with higher content of SN under higher normal stress results from the formation of these powder rolls, which enable the particle movement mode from sliding to rolling.

Finally, it is noted that although our test results showed that the shear resistance of the mixtures can suffer from significant reduction when the applied normal stress or the content of nanoparticles is high enough, the application of our test results to natural rock avalanches needs further scrutiny. In most cases the rock avalanches featured by large scale enable the displaced materials to be loaded by high normal stress during the transportation due to the great thickness, however, the content of nanoparticles in the sliding mass (or along the sliding zone) will be a key issue in affecting whether the weakening mechanism as shown in Fig. 5 can occur or not. Nevertheless, our results provide insight into understanding the possible roles of nanoparticles in the hypermobility of rock avalanches, because the threshold of nanoparticle content in the mixture could be different under differing normal stress, and the content of nanoparticles may increase due to the continuous pulverization of rocks with the progress of movement. The threshold of nanoparticle content may also be differing for different types of nanoparticles. Concerning this, further study by using different types of nanoparticles will be necessary and are undergoing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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References

- Boch, P., Platon, F., Kapelski, G. (1989). Tribological and interfacial phenomena in Al₂O₃/SiC and SiC/SiC couples at high temperature. *Journal of the European Ceramic Society*, 5(4), 223-228.
- Campbell, C. S. (1989). Self-lubrication for long runout landslides. *The Journal of Geology*, 97(6), 653-665. <https://doi.org/10.1086/629350>.
- Chen, Xiaofeng, Andrew S. Elwood Madden, Ze'ev Reches. (2017a). Friction evolution of granitic faults: heating controlled transition from powder lubrication to frictional melt. *Journal of Geophysical Research: Solid Earth*, 122.11: 9275-9289. <https://doi.org/10.1002/2017JB014462>.
- Chen, Xiaofeng, Andrew S. Elwood Madden, Ze'ev Reches. (2017b). Powder rolling as a mechanism of dynamic fault weakening. *Fault zone dynamic processes: Evolution of fault properties during seismic rupture*: 133-150. <https://doi.org/10.1002/9781119156895.ch7>.
- Chester, J. S., Chester, F. M., Kronenberg, A. K. (2005). Fracture surface energy of the Punchbowl fault, San Andreas system. *Nature*, 437(7055), 133-136. <https://doi.org/10.1038/nature03942>.
- Corominas, J. (1996). The angle of reach as a mobility index for small and large landslides. *Canadian Geotechnical Journal*, 33(2), 260–271. <https://doi.org/10.1139/t96-005>.
- Crandell, D. R., Miller, C. D., Glicken, H. X., Christiansen, R. L., Newhall, C. G. (1984). Catastrophic debris avalanche from ancestral Mount Shasta volcano, California. *Geology*, 12(3), 143-146. [https://doi.org/10.1130/0091-7613\(1984\)12<143:CDAFAM>2.0.CO;2](https://doi.org/10.1130/0091-7613(1984)12<143:CDAFAM>2.0.CO;2).
- Davenport, P., Ma, Z.W., Nation, W., Schirck, J., Morris, A., Lambert, M. (2022): Thermal Stability of Silica for Application in Thermal Energy Storage. *AIP Conference Proceedings* 2445(1), 160003. <https://doi.org/10.1063/5.0085641>.
- Davies, T.R.H. (1982). The spreading of rock avalanche debris by mechanical fluidization. *Rock Mechanics*, 15: 9–24. <https://doi.org/10.1007/BF01239474>.
- Davies, T. R., McSaveney, M. J. (1999). Runout of dry granular avalanches. *Canadian Geotechnical Journal*, 36(2), 313–320. <https://doi.org/10.1139/t98-108>.
- Delaney, K. B., Evans, S. G. (2015). The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: Review, remote sensing analysis, and process modelling. *Geomorphology*, 246, 377-393. <https://doi.org/10.1016/j.geomorph.2015.06.020>.
- De Paola, N., Holdsworth, R.E., Viti, C., Collettini, C., Bullock, R. (2015), Can grain size sensitive flow lubricate faults during the initial stages of earthquake propagation? *Earth and Planetary Science Letters*, 431, 48–58. <https://doi.org/10.1016/j.epsl.2015.09.002>.

- Di Toro, G., Hirose, T., Nielsen, S., Pennacchioni, G., Shimamoto, T. (2006). Natural and experimental evidence of melt lubrication of faults during earthquakes. *Science*, 311(5761), 647–649. <https://doi.org/10.1126/science.1121012>.
- Dong, X., Jahanmir, S., Hsu, S. M. (1991). Tribological characteristics of α -Alumina at elevated temperatures. *Journal of the American Ceramic Society*, 74(5), 1036–1044.
- Dubovskoi, A. N., Pernik, L. M., Strom, A. L. (2008). Experimental simulation of rockslide fragmentation. *Journal of Mining Science*, 44(2), 123–130. <https://doi.org/10.1007/s10913-008-0025-y>.
- Duttine, A., & Tatsuoka, F. (2009). Viscous properties of granular materials having different particle shapes in direct shear. *Soils and foundations*, 49(5), 777–796. <https://doi.org/10.3208/sandf.49.777>.
- Duong, N.T., Suzuki, M., Hai, N.V., 2018. Rate and acceleration effects on residual strength of kaolin and kaolin–bentonite mixtures in ring shearing. *Soils Found.* 58 (5), 1153–1172.
- Erismann, T. H. (1979). Mechanisms of large landslides. *Rock Mechanics*, 12(1), 15–46. Mechanisms of large landslides. *Rock Mechanics* 12(1), 15–46. <https://doi.org/10.1007/BF01241087>.
- Evans, S. G. (1989). Rock avalanche run-up record. *Nature (London)*, 340(6231). <https://doi.org/10.1038/340271a0>.
- Fondriest, M., Smith, S. A., Candela, T., Nielsen, S. B., Mair, K., Di Toro, G. (2013). Mirror-like faults and power dissipation during earthquakes. *Geology*, 41(11), 1175–1178. <https://doi.org/10.1130/G34641.1>.
- Goldsby, D. L., Tullis, T. E. (2011). Flash heating leads to low frictional strength of crustal rocks at earthquake slip rates. *Science*, 334(6053), 216–218. <https://doi.org/10.1126/science.1207902>.
- Green II, H. W., Shi, F., Bozhilov, K., Xia, G., Reches, A. Z. (2015). Phase transformation and nanometric flow cause extreme weakening during fault slip. *Nature Geoscience*, 8(6), 484–489. <https://doi.org/10.1038/ngeo2436>.
- Han, R., Hirose, T., Shimamoto, T. (2010). Strong velocity weakening and powder lubrication of simulated carbonate faults at seismic slip rates. *Journal of Geophysical Research: Solid Earth*, 115(B3). <https://doi.org/10.1029/2008JB006136>.
- Han, R., Hirose, T., Shimamoto, T., Lee, Y., Ando, J. I. (2011). Granular nanoparticles lubricate faults during seismic slip. *Geology*, 39(6), 599–602. <https://doi.org/10.1130/G31842.1>.
- Han, R., Shimamoto, T., Hirose, T., Ree, J. H., Ando, J. I. (2007). Ultralow friction of carbonate faults caused by thermal decomposition. *Science*, 316(5826), 878–881. <https://doi.org/10.1126/science.1139763>.
- Hayashi, N., & Tsutsumi, A. (2010). Deformation textures and mechanical behavior of a hydrated amorphous silica formed along an experimentally produced fault in chert. *Geophysical Research Letters*, 37(12).

<https://doi.org/10.1029/2010GL042943>.

Heim, A., (1932) Bergsturz und Menschleben. Fretz and Wasmuth, Zurich. 218 pp.

Hirose, T., Shimamoto, T. (2005). Growth of molten zone as a mechanism of slip weakening of simulated faults in gabbro during frictional melting. *Journal of Geophysical Research: Solid Earth*, 110(B5). <https://doi.org/10.1029/2004JB003207>.

Hsü, K. J., Voight, B. (1978). Albert Heim: observations on landslides and relevance to modern interpretations. *Natural Phenomena*, 1, 70-93.

Hu, W., Chang, C. S., McSaveney, M., Huang, R., Xu, Q., Zheng, Y., Yu, J. (2020). A Weakening Rheology of Dry Granular Flows With Extensive Brittle Grain Damage in High-Speed Rotary Shear Experiments. *Geophysical Research Letters*, 47(11), 1–10. <https://doi.org/10.1029/2020GL087763>.

Hu, W., Huang, R., McSaveney, M., Zhang, X. hui, Yao, L., Shimamoto, T. (2018). Mineral changes quantify frictional heating during a large low-friction landslide. *Geology*, 46(3), 223–226. <https://doi.org/10.1130/G39662.1>.

Hu, W., Xu, Q., Mcsaveney, M., Huang, R., Wang, Y., Chang, C. S., Gou, H., Zheng, Y. (2022). The intrinsic mobility of very dense grain flows. *Earth and Planetary Science Letters*, 580, 117389. <https://doi.org/10.1016/j.epsl.2022.117389>.

Hungr, O., Morgenstern, N. R. (1984). High velocity ring shear tests on sand. *Geotechnique*, 34(3), 415-421. <https://doi.org/10.1680/geot.1984.34.3.415>.

Hungr, O., Evans, S. G., Bovis, M., Hutchinson, J.N. (2001) Review of the classification of landslides of the flow type. *Environ Engineering Geoscience* VII:221–238

Japanese Geotechnical Society, 2015. Japanese Geotechnical Society Standard (JGS 0051–2009): Method of Classification of Geomaterials for Engineering Purposes, vol. 1. The Japanese Geotechnical Society Standards: Laboratory Testing Standards of Geomaterial.

Jiang, Y., Wang, G., & Kamai, T. (2017). Fast shear behavior of granular materials in ring-shear tests and implications for rapid landslides. *Acta Geotechnica*, 12, 645-655. <https://doi.10.1007/s11440-016-0508-y>.

Kang, X., Wang, S., Wu, W., & Xu, G. (2022). Residual state rate effects of shear-zone soil regulating slow-to-fast transition of catastrophic landslides. *Engineering Geology*, 304, 106692. <https://doi.org/10.1016/j.enggeo.2022.106692>.

Keaton, J.R. (2017). Angle of Internal Friction. In: Bobrowsky, P., Marker, B. (eds) *Encyclopedia of Engineering Geology*. Encyclopedia of Earth Sciences Series. Springer, Cham. https://doi-org.kyoto-u.idm.oclc.org/10.1007/978-3-319-12127-7_16-1.

- Kenney, T.C., (1977). Residual strength of mineral mixtures. In: Proc. of the 9th ICSMFE, pp. 155–160.
- Kuwano, O., Ando, R., & Hatano, T. (2013). Crossover from negative to positive shear rate dependence in granular friction. *Geophysical research letters*, 40(7), 1295-1299. <https://doi.org/10.1002/grl.50311>.
- Lambe, T. W., and Whitman, R. V. (1969). Soil mechanics. John Wiley and Sons, Inc., New York, N.Y.
- Legros, F. (2002). The mobility of long-runout landslides. *Engineering Geology*, 63(3–4), 301–331. [https://doi.org/10.1016/S0013-7952\(01\)00090-4](https://doi.org/10.1016/S0013-7952(01)00090-4).
- Lucas, A., Mangeney, A., Ampuero, J. P. (2014). Frictional velocity-weakening in landslides on Earth and on other planetary bodies. *Nature Communications*, 5(1), 1-9. <https://doi.org/10.1038/ncomms4417>.
- Lupini, J.F., Skinner, A.E., Vaughan, P.R., (1981). The drained residual strength of cohesive soils. *Geotechnique*, 31 (2), 181–213. <https://doi.org/10.1680/geot.1981.31.2.181>.
- McSaveney, M. J. (1978). "Sherman glacier rock avalanche, Alaska, USA." *Developments in Geotechnical Engineering*. Vol. 14, pp. 197-258.
- McSaveney, M., Hu, W. (2022). Nanoparticles in the 2008 Yangjiagou rock avalanche. Short Papers and Extended Abstracts, Geological Society of America Penrose Conference Penrose Conference: Progressive Failure of Brittle Rocks. PRF2022. Flat Rock, N.C., 20-24 June, 2022. <https://doi.org/10.1130/abs/2022PR-376041>.
- Melosh, H. J. (1979). Acoustic fluidization: a new geologic process? *Journal of Geophysical Research*, 84(B13), 7513–7520. <https://doi.org/10.1029/JB084iB13p07513>.
- Melosh, H. J. (1996). Dynamical weakening of faults by acoustic fluidization. *Nature*, 379(6566), 601–606. <https://doi.org/10.1038/379601a0>.
- Mitchell, A., McDougall, S., Aaron, J., Brideau, M. A. (2020). Rock avalanche-generated sediment mass flows: Definitions and hazard. *Frontiers in Earth Science*, 8, 543937. <https://doi.org/10.3389/feart.2020.543937>.
- Mitchell, T. M., Smith, S. A. F., Anders, M. H., Di Toro, G., Nielsen, S., Cavallo, A., Beard, A. D. (2015). Catastrophic emplacement of giant landslides aided by thermal decomposition: Heart Mountain, Wyoming. *Earth and Planetary Science Letters*, 411, 199–207. <https://doi.org/10.1016/j.epsl.2014.10.051>.
- Nakamura, Y., Muto, J., Nagahama, H., Shimizu, I., Miura, T., and Arakawa, I. (2012). Amorphization of quartz by friction: Implication to silica-gel lubrication of fault surfaces. *Geophysical Research Letters*, 39(21). <https://doi.org/10.1029/2012GL053228>.
- Noda, H., & Shimamoto, T. (2005). Thermal pressurization and slip-weakening distance of a fault: an example of the Hanaore fault, southwest Japan. *Bulletin of the Seismological Society of America*, 95(4), 1224–1233. <https://doi.org/10.1785/0120040089>.

577 Osipov, V.I., Nikolaeva, S.K., Sokolov, V.N., 1984. Microstructural changes associated with thixotropic
578 phenomena in clay soils. *Geotechnique*, 34 (2), 293–303.

579 Perinotto, H., Schneider, J. L., Bachèlery, P., Le Bourdonnec, F. X., Famin, V., & Michon, L. (2015). The
580 extreme mobility of debris avalanches: A new model of transport mechanism. *Journal of Geophysical*
581 *Research: Solid Earth*, 120(12), 8110–8119. <https://doi.org/10.1002/2015JB011994>.

582 Pudasaini, S. P., Miller, S. A. (2013). The hypermobility of huge landslides and avalanches. *Engineering*
583 *Geology*, 157, 124–132. <https://doi.org/10.1016/j.enggeo.2013.01.012>.

584 Reches, Z., Lockner, D. A. (2010). Fault weakening and earthquake instability by powder lubrication. *Nature*,
585 467(7314), 452–455. <https://doi.org/10.1038/nature09348>.

586 Reznichenko, N. V., Davies, T. R. H., Shulmeister, J., Larsen, S. H. (2012). A new technique for identifying rock
587 avalanche-sourced sediment in moraines and some paleoclimatic implications. *Geology*, 40(4), 319–322.
588 <https://doi.org/10.1130/G32684.1>.

589 Rice, J. R. (2006). Heating and weakening of faults during earthquake slip. *Journal of Geophysical Research:*
590 *Solid Earth*, 111(B5). <https://doi.org/10.1029/2005JB004006>.

591 Sassa, K. (1988), Geotechnical model for the motion of landslides, in Proceedings of the 5th International
592 Symposium on Landslides, pp. 37–55, Lausanne, Switzerland.

593 Sassa, K., Fukuoka, H., Wang, G., Ishikawa, N. (2004). Undrained dynamic-loading ring-shear apparatus and its
594 application to landslide dynamics. *Landslides*, 1(1), 7–19. <https://doi.org/10.1007/s10346-003-0004-y>.

595 Scaringi, G., Hu, W., Xu, Q., Huang, R. (2018). Shear - rate - dependent behavior of clayey bimaterial interfaces
596 at landslide stress levels. *Geophysical Research Letters*, 45(2), 766–777.
597 <https://doi.org/10.1002/2017GL076214>.

598 Schofield, A.N., Wroth, C.P. (1968). *Critical State Soil Mechanics*. McGraw-Hill.

599 Shreve R.L. (1968a). The Blackhawk Landslide. Geological Society of America. Spec pap108:1–47.

600 Shreve, R. L. (1968b). Leakage and fluidization in air-layer lubricated avalanches. *The Geological Society of*
601 *America Bulletin*, 79(5), 653–658. [https://doi.org/10.1130/0016-7606\(1968\)79\[653:lafial\]2.0.co;2](https://doi.org/10.1130/0016-7606(1968)79[653:lafial]2.0.co;2).

602 Scheidegger A.E. (1973). On the prediction of the reach and velocity of catastrophic landslides. *Rock Mech.*
603 *Rock Eng.* 5(4), 231–236.

604 Skempton, A.W., (1985). Residual strength of clays in landslides, folded strata and the laboratory. *Geotechnique*,
605 35 (1), 3–18.

606 Spagnuolo, E., Plümper, O., Violay, M., Cavallo, A., Di Toro, G. (2015). Fast-moving dislocations trigger flash
607 weakening in carbonate-bearing faults during earthquakes. *Scientific Reports*, 5(1), 1–11.

<https://doi.org/10.1038/srep16112>.

- Strom, A., Abdrakhmatov, K. (2018). Rockslides and rock avalanches of Central Asia: distribution, morphology, and internal structure. Elsevier.
- Suzuki, M., Kobayashi, K., Yamamoto, T., Matsubara, T., Hukuda, J., (2004). Influence of shear rate on residual strength of clay in ring shear test. *Res. Rep. School Eng. Yamaguchi Univ.* 55 (2), 49–62.
- Tika, T.E., (1989). The Effect of Rate of Shear on the Residual Strength of Soil. PhD thesis, University of London.
- Tika, T. E., Vaughan, P. R., & Lemos, L. J. L. (1996). Fast shearing of pre-existing shear zones in soil. *Geotechnique*, 46(2), 197–233. <https://doi.org/10.1680/geot.1996.46.2.197>.
- Tisato, N., Di Toro, G., De Rossi, N., Quaresimin, M., Candela, T. (2012). Experimental investigation of flash weakening in limestone. *Journal of Structural Geology*, 38, 183–199. <https://doi.org/10.1016/j.jsg.2011.11.017>.
- Tsutsumi, A., Shimamoto, T. (1997). High-velocity frictional properties of gabbro. *Geophysical Research Letters*, 24(6), 699–702. <https://doi.org/10.1029/97GL00503>.
- Wang, G., Huang, R., Lourenço, S. D., Kamai, T. (2014). A large landslide triggered by the 2008 Wenchuan (M8.0) earthquake in Donghekou area: Phenomena and mechanisms. *Engineering Geology*, 182, 148–157. <https://doi.org/10.1016/j.enggeo.2014.07.013>.
- Wang, G., Sassa, K. (2002). Post-failure mobility of saturated sands in undrained load-controlled ring shear tests. *Canadian Geotechnical Journal*, 39(4), 821–837. <https://doi.org/10.1139/t02-032>.
- Wang, G., Sassa, K. (2003). Pore-pressure generation and movement of rainfall-induced landslides: Effects of grain size and fine-particle content. *Engineering Geology*, 69(1–2), 109–125. [https://doi.org/10.1016/S0013-7952\(02\)00268-5](https://doi.org/10.1016/S0013-7952(02)00268-5).
- Wang G, Suemine A, Schulz W H. (2010) Shear-rate-dependent strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. *Earth Surface Processes and Landforms*, 35(4): 407–416. <https://doi.org/10.1002/esp.1937>.
- Wang, G., Watanabe, N., Hoshikawa, K., Furuya, G., Cai, F., & Wu, S. (2023). Diverse shear behaviors of clayey materials: Implications for differing landsliding behaviors within the same area in Niigata, Japan. *Engineering Geology*, 312, 106932. <https://doi.org/10.1016/j.enggeo.2022.106932>.
- Wang, Y. F., Dong, J. J., Cheng, Q. G. (2017). Velocity-dependent frictional weakening of large rock avalanche basal facies: Implications for rock avalanche hypermobility? *Journal of Geophysical Research: Solid Earth*, 122(3), 1648–1676. <https://doi.org/10.1002/2016JB013624>.

- Wang, Y. F., Dong, J. J., Cheng, Q. G. (2018). Normal stress-dependent frictional weakening of large rock avalanche basal facies: implications for the rock avalanche volume effect. *Journal of Geophysical Research: Solid Earth*, 123,3270–3282. <https://doi.org/10.1002/2018JB015602>.
- Wibberley, C. A. J., Shimamoto, T. (2005). Earthquake slip weakening and asperities explained by thermal pressurization. *Nature*, 436(7051), 689–692. <https://doi.org/10.1038/nature03901>.
- Xu, Q., Shang, Y., van Asch, T., Wang, S., Zhang, Z., Dong, X. (2012). Observations from the large, rapid Yigong rock slide–debris avalanche, southeast Tibet. *Canadian Geotechnical Journal*, 49(5), 589-606. <https://doi.org/10.1139/t2012-021>.
- Zanoria, E. S., S. Danyluk, M. J. McNallan. (1995a), Formation of cylindrical sliding-wear debris on silicon in humid conditions and elevated temperatures, *Tribology Transactions*, 38.3 (1995): 721-727. <https://doi.org/10.1080/10402009508983464>.
- Zanoria, Elmer, Steven Danyluk, Michael McNallan. (1995b). Effects of length, diameter and population density of tribological rolls on friction between self-mated silicon. *Wear*, 181 (1995): 784-789. [https://doi.org/10.1016/0043-1648\(95\)90196-5](https://doi.org/10.1016/0043-1648(95)90196-5).
- Zhang, M., Yang, L., Li, W., Wang, Z., Zhang, C., Chen, Q., Wang, B. (2022). Frictional properties of the rupture surface of a carbonate rock avalanche. *International Journal of Rock Mechanics and Mining Sciences*, 153, 105088. <https://doi.org/10.1016/j.ijrmms.2022.105088>.
- Zihms, S.G., Switzer, C., Irvine, J., Karstunen, M. (2013): Effects of high temperature processes on physical properties of silica sand. *Engineering Geology*, 164:139-145.

Captions:

Fig. 1. (a) Pure nano silica sand (SN); (b) TEM image of SN; (c) Pure silica sand No.8 (S8); (d) SEM image of S8; (e) Grain size distribution of S8.

Fig. 2. Results of ring shear tests on SN: (a) Under different normal stresses, by the shear stress-controlled method; (b) Result of high shear-velocity ring shear test under normal stress of 161 kPa, by the shear velocity-controlled method; (c) Average stress ratio of residual state under different shear velocities, by the shear velocity-controlled method.

Fig. 3. Results of ring shear tests on S8: (a) Under different normal stresses, by the shear stress-controlled method; (b) Average stress ratio of residual state under different shear velocities by the shear velocity-controlled method.

Fig. 4. Average stress ratio of residual state of ring shear tests on the mixtures by the shear velocity-controlled method: (a) Under a normal stress of 161 kPa; (b) Under a normal stress of 1030 kPa. M100: pure SN; M0: pure S8. M10, M20, and M50 represent the SN content in the mixture is 10%, 20%, and 50%, respectively.

Fig. 5. Post-test (the largest shear velocity is 10 cm/s) photo and SEM images from a test conducted on SN under the normal stress of 1030 kPa, (a) Shear surface after the test. (b), (c), (d) SEM images obtained by scanning the shear surface. (e) Location for the microstructural observation texture. The red arrow indicates the shear direction and the green arrow indicates the formation of powder rolls. The orange square (2 mm long and 2 mm wide) of the shear surface was taken for SEM testing.

Fig. 6. Post-test (the largest shear velocity is 10 cm/s) SEM images from a test conducted on SN under the normal stress of 619 kPa. The red arrow indicates the shear direction and the green arrow indicates the formation of powder rolls.

Fig. 7. Post-test (the largest shear velocity is 10 cm/s) SEM image from a test conducted on M50 under the normal stress of 1030 kPa. The red arrow indicates the shear direction.

Fig. 8. Test results of Zanoria et al. (1995b). (a) mean length, (b) diameter, and (c) population density of tribological rolls against temperature. (Modified from Fig. 4 in Zanoria et al., 1995b). The tribological rolls were obtained through the ball-on-flat linear reciprocating sliding of self-mated silicon at different temperatures, humid conditions, and normal loads. P_w : water pressure used in the tests for examining the effects of humidity.

Table 1. Features of ring shear apparatuses of DPRI-5, DPRI-6, and DPRI-7.

Table 2. Test conditions and details results of the ring shear tests

Figures

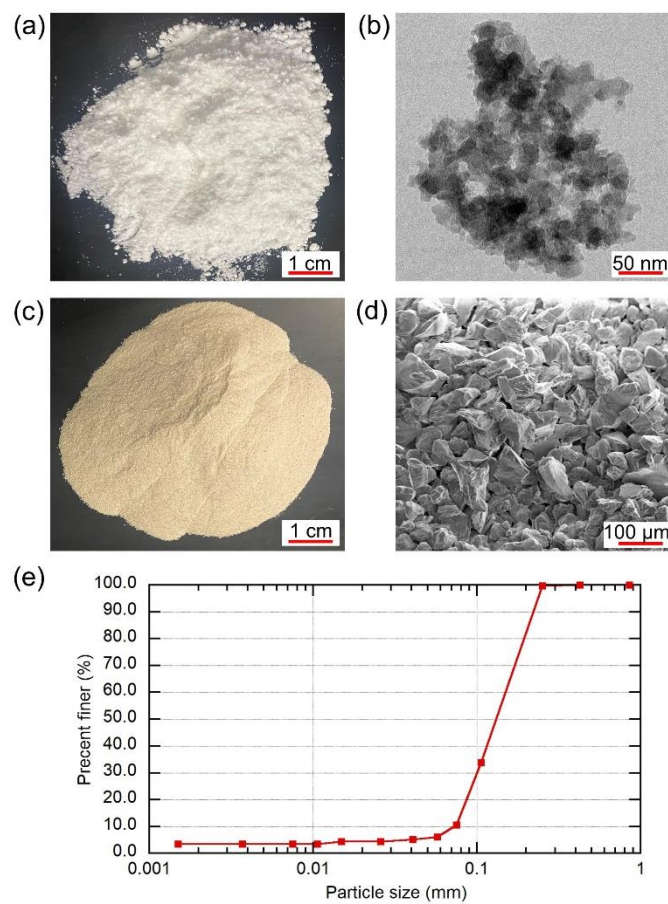


Fig. 1. (a) Pure nano silica sand (SN); (b) TEM image of SN; (c) Pure silica sand No.8 (S8); (d) SEM image of S8; (e) Grain size distribution of S8.

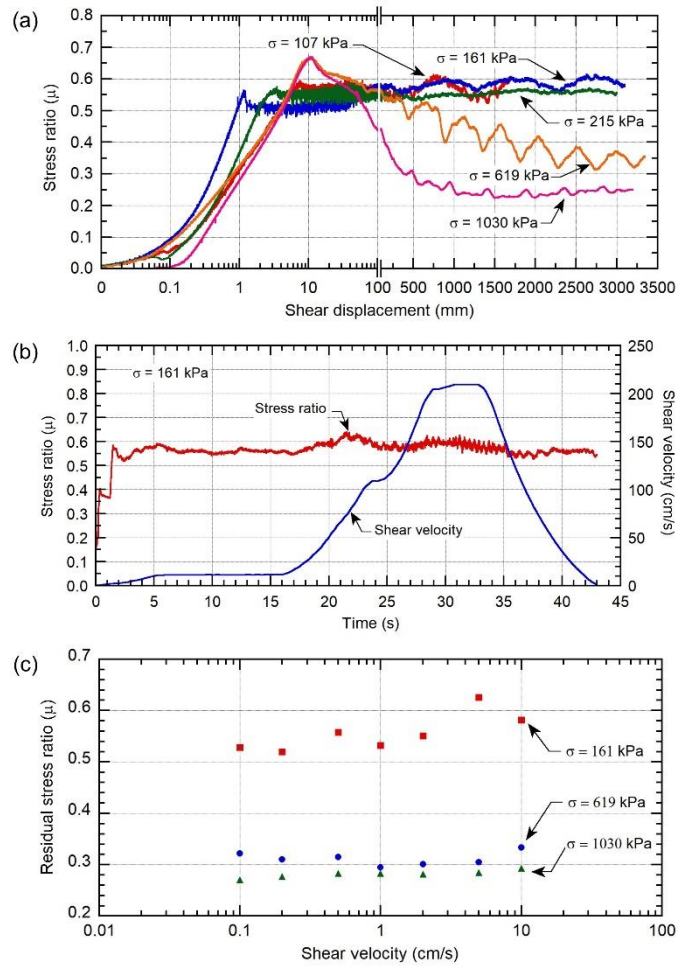


Fig. 2. Results of ring shear tests on SN: (a) Under different normal stresses, by the shear stress-controlled method; (b) Result of high shear-velocity ring shear test under normal stress of 161 kPa, by the shear velocity-controlled method; (c) Average stress ratio of residual state under different shear velocities, by the shear velocity-controlled method.

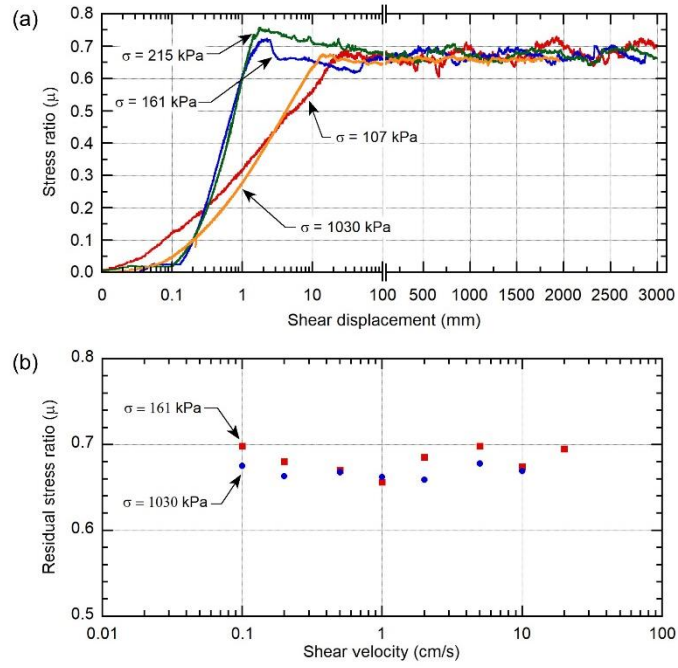


Fig. 3. Results of ring shear tests on S8: (a) Under different normal stresses, by the shear stress-controlled method; (b) Average stress ratio of residual state under different shear velocities by the shear velocity-controlled method.

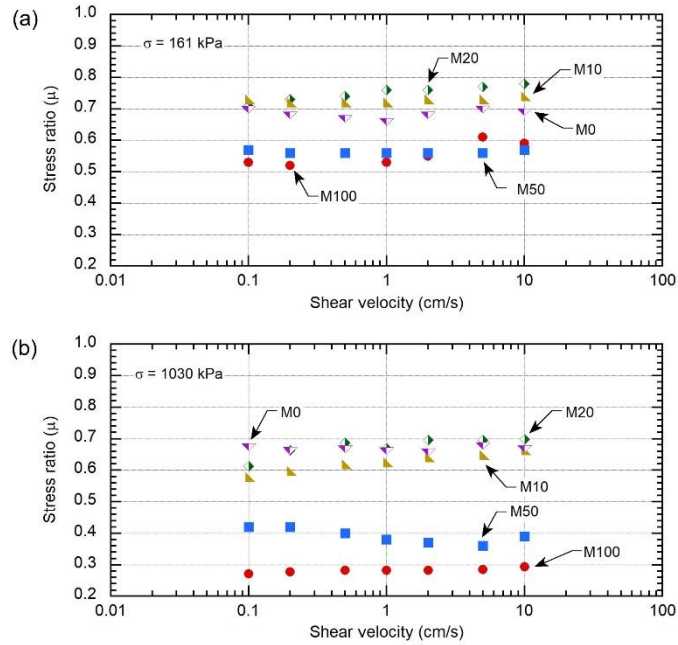


Fig. 4. Average stress ratio of residual state of ring shear tests on the mixtures by the shear velocity-controlled method: (a) Under a normal stress of 161 kPa; (b) Under a normal stress of 1030 kPa. M100: pure SN; M0: pure S8. M10, M20, and M50 represent the SN content in the mixture is 10%, 20%, and 50%, respectively.

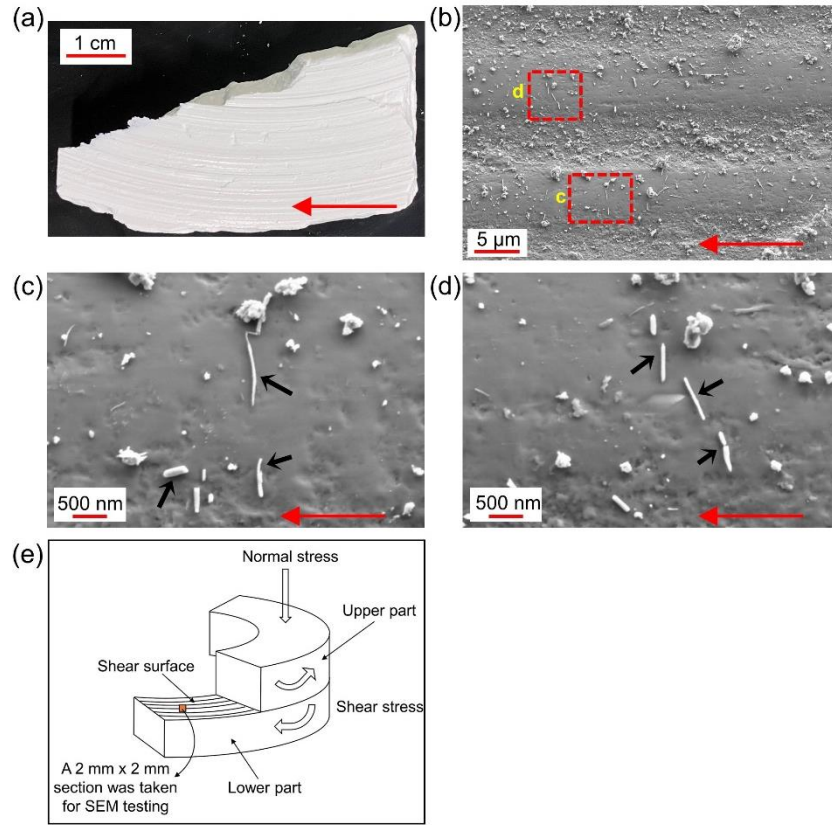


Fig. 5. Post-test (the largest shear velocity is 10 cm/s) photo and SEM images from a test conducted on SN under the normal stress of 1030 kPa, (a) Shear surface after the test. (b), (c), (d) SEM images obtained by scanning the shear surface. (e) Location for the microstructural observation texture. The red arrow indicates the shear direction and the black arrow indicates the formation of powder rolls. The orange square (2 mm long and 2 mm wide) of the shear surface was taken for SEM testing.

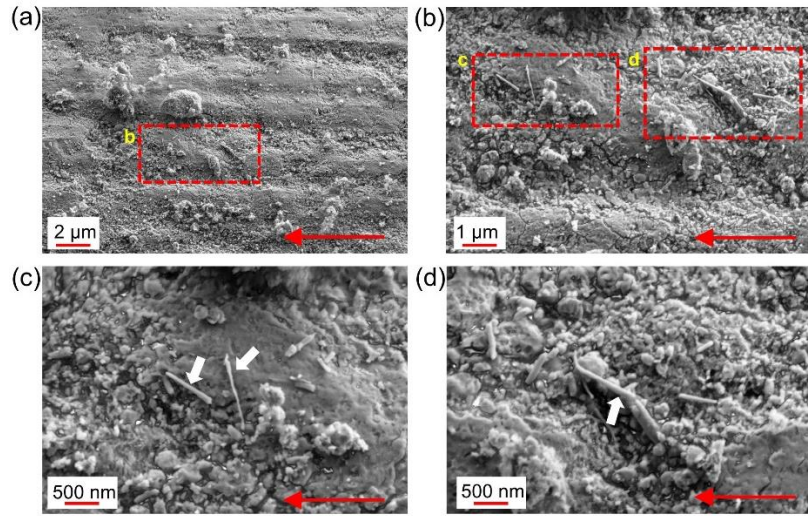


Fig. 6. Post-test (the largest shear velocity is 10 cm/s) SEM images from a test conducted on SN under the normal stress of 619 kPa. The red arrow indicates the shear direction and the white arrow indicates the formation of powder rolls.

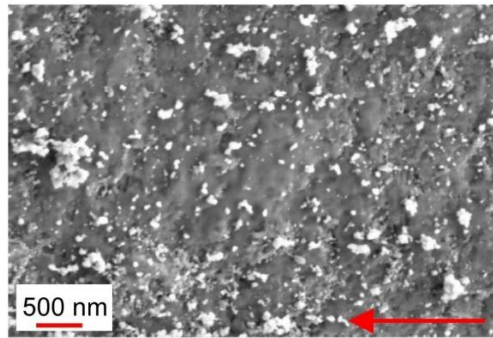


Fig. 7. Post-test (the largest shear velocity is 10 cm/s) SEM image from a test conducted on M50 under the normal stress of 1030 kPa. The red arrow indicates the shear direction.

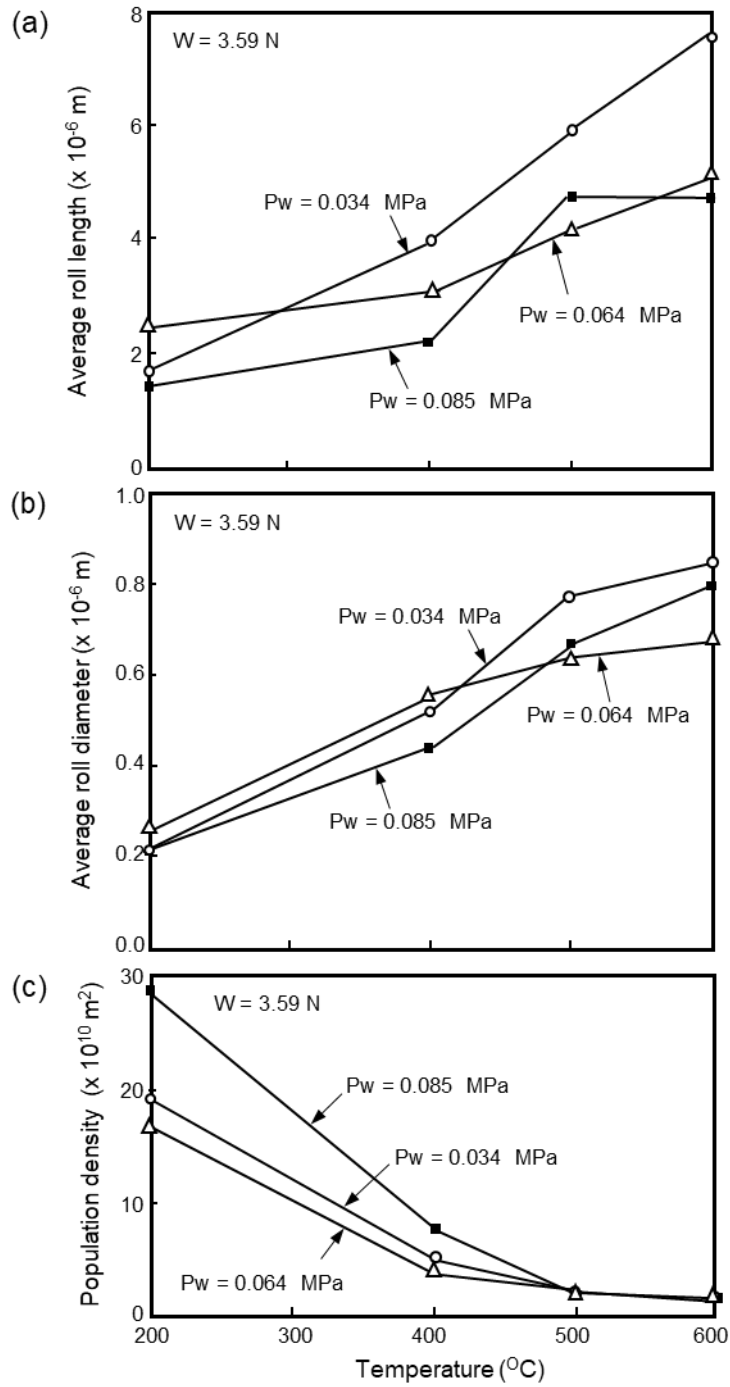


Fig. 8. Test results of Zanoria et al. (1995). (a) mean length, (b) diameter, and (c) population density of tribological rolls against temperature. (Modified from Fig. 4 in Zanoria et al., 1995). The tribological rolls were obtained through the ball-on-flat linear reciprocating sliding of self-mated silicon at different temperatures, humid conditions, and normal loads. P_w : water pressure used in the tests for examining the effects of humidity.

Tables

Table 1. Features of ring shear apparatuses of DPRI-5, DPRI-6 and DPRI-7

Ring shear apparatus	DPRI-5	DPRI-6	DPRI-7
Inner diameter (cm)	12.0	25.0	27.0
Outer diameter (cm)	18.0	35.0	35.0
Maximum height of sample (cm)	11.5	15.0	11.5
Shear area (cm ²)	141.37	471.24	389.56
Maximum normal stress (kPa)	2000	3000	500
Maximum shear speed (cm/s)	10.0	224.0	300.0

Table 2. Test conditions and details results of the ring shear tests

Samples	No.	σ_n (kPa)	The density of the sample after consolidation (g/cm ³)	Peak stress ratio (by Shear stress- controlled method)	Residual stress ratio (μ)											Ring shear apparatus
					Shear stress- controlled method	Shear velocity-controlled method										
						Shear velocities (cm/s)										
						0.1	0.2	0.5	1	2	5	10	20	30	220	
SN (M100)	1	107	0.300	0.59	0.56											DPRI-6
	2	161	0.313	0.56	0.60	0.53	0.52	0.56	0.53	0.55	0.61	0.59	0.58	0.60	0.59	DPRI-6
	3	215	0.310	0.57	0.56											DPRI-6
	4	619	0.405	0.66	0.34	0.32	0.31	0.32	0.30	0.30	0.31	0.33				DPRI-5
	5	1030	0.420	0.67	0.25	0.27	0.28	0.28	0.28	0.28	0.29	0.29				DPRI-5
S8 (M0)	6	107	1.204	0.69	0.71											DPRI-6
	7	161	1.241	0.72	0.63	0.70	0.68	0.67	0.66	0.68	0.70	0.69				DPRI-6
	8	215	1.272	0.76	0.68											DPRI-6
	9	1030	1.270	0.68	0.66	0.68	0.63	0.67	0.66	0.66	0.68	0.67				DPRI-5
M50	11	161	0.532	0.66		0.57	0.56	0.56	0.56	0.56	0.56	0.57				DPRI-6
	12	1030	0.724	0.63	0.41	0.42	0.42	0.40	0.38	0.37	0.36	0.39				DPRI-5
M20	13	161	0.831	0.78		0.71	0.73	0.74	0.76	0.73	0.77	0.78				DPRI-6
	14	1030	1.052	0.64	0.58	0.61	0.66	0.69	0.67	0.70	0.70	0.70				DPRI-5
M10	15	161	-	0.76		0.73	0.72	0.72	0.72	0.73	0.73	0.74				DPRI-7
	16	1030	1.215	0.64	0.58	0.58	0.60	0.62	0.63	0.64	0.65	0.66				DPRI-5

-: not available due to the loss of test memory.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: