

Original article

Non-uniformly distributed proppant crushing in hydraulic fractures: An experimental and numerical investigation

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Abstract:

Proppant crushing reduces hydraulic-fracture conductivity; however, its spatial heterogeneity is masked by the overall breakage ratio. Understanding this heterogeneity is important for identifying localized damage within the proppant pack and assessing its influence on conductive pathways and the prediction of fracture conductivity in hydraulically fractured oil and gas reservoirs. In this work, *in-situ* micro-computed tomography and discrete element simulations were combined to reveal the evolution and controlling mechanisms of spatially heterogeneous proppant crushing under closure stresses. A cluster-based model was built to represent breakable particles with reconstructed geometries, which was calibrated against single-particle compression tests. Crushing localized near the loading boundary because force-chain development and stress shadowing limited load transfer to distal layers. Under the same closure stress, higher sphericity reduced overall breakage but increased the spatial contrast of crushing. In a separate material comparison at matched overall breakage ratios and comparable sphericity, the upper-to-lower ratio was higher for quartz sand than that for ceramic proppant. Wider fractures promoted spatial contrast and concentrated breakage close to upper boundaries, whereas narrower fractures produced through-going force chains and more uniform damage. At the examined overall breakage ratio, accounting for layered crushing increased the predicted equivalent permeability relative to the uniform-crushing assumption. Spatial breakage distributions should therefore be considered in fracture-conductivity prediction rather than relying solely on overall breakage ratios.

1. Introduction

Proppants, which are typically high-strength ceramic or sand grains, are placed in hydraulic fractures to resist *in-situ* closure stress as well as maintain conductive flow paths (Katende et al., 2023; Ramazanov et al., 2025). During and after stimulation, high and often cyclic reservoir loads can crush and rearrange these grains (Bandara et al., 2021; Wang et al., 2026). Particle breakage changes the strength, deformation and permeability of granular materials that in turn affect their long-term stability (Shen et al., 2019; Tahmasebi, 2023; Liu

et al., 2025). In propped fractures, conductivity is degraded by the associated loss of fracture width and pack porosity (Zheng et al., 2018; Yu et al., 2022). Reservoir fines can cause further long-term conductivity impairment (Moghadasi et al., 2019; Qi et al., 2023). Since proppant transport, placement and selection jointly influence fracture performance (Ding et al., 2025), quantifying the spatial distribution of crushing is important for proppant selection and completion design.

Experimental evidence on proppant breakage spans single-particle compression, image-based fracture analysis, and ass-

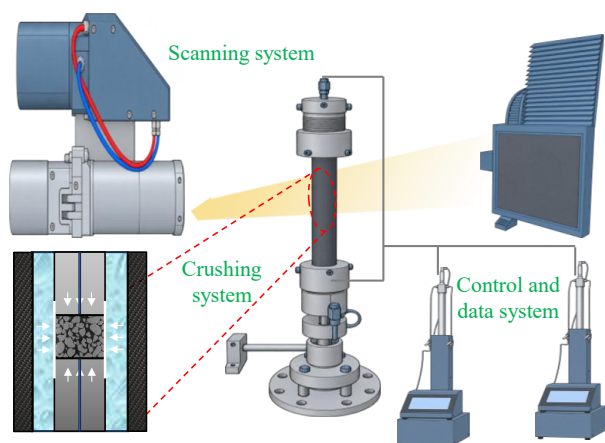


Fig. 1. Experimental setup for in-situ micro-CT imaging during triaxial loading of the proppant pack.

assembly-scale conductivity testing. Single-particle compression tests characterize grain strength and failure processes (McDowell and Bolton, 1998), while impact tests quantify fragmentation under dynamic loads (Salman et al., 2002). High-speed microscopy and three-dimensional imaging resolve crack development, fragment morphology, as well as post-crushing size distributions (Wang and Coop, 2016; Seo et al., 2021; Liu et al., 2025). In addition, conductivity tests have linked crushing, compaction and proppant embedment to flow-capacity loss (Zheng et al., 2018; Xu et al., 2021; Sun et al., 2022; Yu et al., 2022). A breakage ratio of 5% has been proved to reduce proppant-pack permeability by as much as 60% (Hari et al., 2021). Measurements and semi-analytical modeling have related fracture flow capacity to closure stress, particle size and pack porosity (Pusztai et al., 2023). An overall breakage ratio, however, provides only a pack-averaged description of damage, which cannot resolve spatial variations in crushing, the influence of particle shape, or the internal load paths responsible for localized damage. Because fracture conductivity is also an explicit variable in reservoir-scale optimization (Chen et al., 2021), this unresolved heterogeneity limits both mechanism interpretation and conductivity prediction.

Particle-scale load transfer provides a good mechanistic basis for spatially heterogeneous crushing. Breakage begins when local stress exceeds grain strength (McDowell and Bolton, 1998), and force chains determine where load is carried and stress concentrations develop within a granular assembly (Tkachenko and Witten, 1999; Majmudar and Behringer, 2005). Variations in interparticle friction, size and morphology make these force networks heterogeneous (Zhang et al., 2022; Carrasco et al., 2025). Subsequently, preferred load paths can form arching structures within the pack. By redirecting stress toward supports near the loading boundary, these structures suppress further failure in adjacent regions (Wang et al., 2013; Zhou et al., 2014; Fang et al., 2020; Wang et al., 2025). To this end, the discrete element method (DEM) can examine force-chain evolution (Nie et al., 2022) and the dependence of crushing on particle-scale failure criteria (de Bono and McDowell, 2016).

Recent hydraulic-fracturing studies have combined experi-

ments with numerical methods across multiple scales (Huang et al., 2024; Cai et al., 2026). Coupled computational fluid dynamics-discrete element method models and lattice Boltzmann method-discrete element method models have resolved proppant transport, migration and agglomeration in confined fractures and channels (Zhu et al., 2025). As for mechanical breakage, DEM represents granular materials as discrete bodies whose motion follows contact constitutive laws (Cundall and Strack, 1979; Zhu et al., 2022). Bonded-particle models represent fracture through the progressive rupture of internal bonds (Potyondy, 2015), while grain-scale experiments provide failure-load and fracture-pattern data for calibration (Seo et al., 2024). At the assembly scale, DEM can track stress-strain behavior and particle-size-distribution evolution during compression (Ueda et al., 2013; Zhao et al., 2024), while X-ray tomography provides experimental evidence of grain fracture under triaxial loading (Zhang et al., 2023). Nevertheless, many assembly-scale models idealize grains as spheres, and this simplification omits shape descriptors that influence yielding and compressive deformation (Buscarnera and Einav, 2021), as well as particle interlocking and frictional response (Li et al., 2021). Realistic particle geometry is therefore required to link force transmission with the spatial distribution of crushing.

To investigate the evolution mechanisms of spatially heterogeneous proppant crushing under closure stresses, this study combined *in-situ* micro-computed tomography (micro-CT) experiments and DEM simulations of shape-reconstructed breakable particles. The experimental outcomes characterized the spatial distribution characteristics of particle crushing under loads, while DEM simulations could further explain force-chain evolutions and stress redistributions associated with non-uniform breakage. Based on the validated DEM model, effects of particle sphericity, material properties, and fracture width on crushing behaviors were examined. Furthermore, to evaluate influences on fracture-conductivity prediction, spatially varying breakage characteristics were incorporated into permeability calculations.

2. *In-situ* visualization of proppant-pack crushing

2.1 Materials and experimental setup

Commercial quartz-sand proppant was selected due to its wide application in field operations. It consisted primarily of silica (SiO_2 , > 98% by mass), had a bulk density of 1.65 g/cm^3 , and exhibited irregular particle morphology. A randomly selected fraction of 8-16 mesh particles was utilized for characterization and testing.

The *in-situ* crushing apparatus combined a micro-CT scanning system with a triaxial loading system (Fig. 1). The NanoVoxel5000 micro-CT system comprised an X-ray source, an imaging detector, a precision sample stage, an image-acquisition unit, and a three-dimensional reconstruction module. The voxel size of this module is approximately $20 \text{ }\mu\text{m}$, and a complete scan requires about 2.5 h. The system captures three-dimensional particle geometry at successive loading stages after pack stabilization, with the target axial stress and

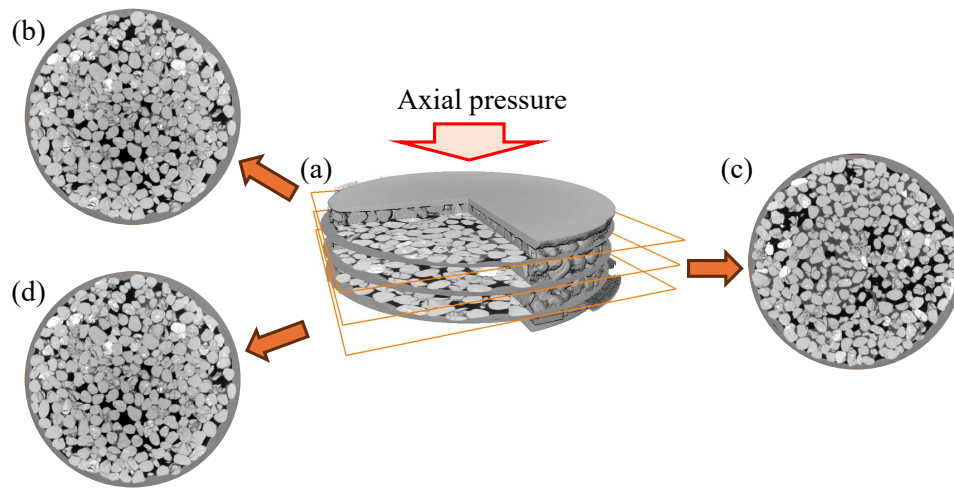


Fig. 2. Non-uniform spatial distribution of crushed particles in the proppant pack: (a) Overall distribution, (b) upper layer, (c) middle layer, and (d) lower layer.

the confining pressure of 10 MPa maintained throughout each scan. No obvious motion artifacts or blurring were observed in the reconstructed images, supporting structural stability during image acquisition.

The loading assembly reproduced the mechanical response of a granular pack under true triaxial stress. A carbon-fiber outer tube minimized imaging artifacts from metallic components while maintaining structural rigidity. The specimen and loading platens were sealed in a polyethylene heat-shrink tube. Fluid pressure in the annulus between the two tubes controlled confinement to an accuracy of 0.01 MPa, while a servo-controlled mechanism was used to apply the axial load. In-situ micro-CT imaging was utilized to track crack initiation and propagation, together with pore evolution, under triaxial loading.

2.2 Experimental procedure

The experiments were conducted in three stages: mechanical loading, *in-situ* image acquisition, and volumetric image processing.

- 1) Sieved proppant particles were placed in a 25-mm-diameter triaxial cell to form an approximately 5-mm thick initial layer. After the cell seal was verified, a fluid pressure of 5 MPa was applied, and the axial and confining stresses were simultaneously increased to 10 MPa to establish the initial confined loading condition. Subsequently, the confining pressure was maintained at 10 MPa, while the axial stress was increased stepwise to 25 MPa and 40 MPa at a loading rate of 0.01 MPa/s to simulate the increasing compressive load experienced by the proppant pack during fracture closure. To constrain the lateral deformation of the proppant pack, the core holder maintained the confining pressure through a hydrostatic loading medium. After each target stress level was reached, the specimen was held under constant stress for 60 min before micro-CT scanning.
- 2) *In-situ* X-ray micro-CT scans were acquired at each stress

level to capture changes in particle arrangement and fracture development. The raw projections were reconstructed in Voxel Studio Recon using beam-hardening correction and detector-angle compensation.

- 3) The reconstructed volumes were imported into Avizo for voxel calibration and grayscale normalization. To extract three-dimensional particle geometries and separate contacting or partially overlapped particles, threshold segmentation combined with watershed separation was applied. During segmentation, the grayscale distribution and spatial morphology of particle regions were used to identify particle boundaries, and watershed markers were generated from the internal regions of individual particles to avoid artificial merging caused by particle contact. After segmentation, each particle and fragment was independently labeled and its three-dimensional volume was extracted to calculate the equivalent diameter. Particle-size distribution was obtained based on the segmented particle volumes. Fragments smaller than 20 μm were excluded as they could not be segmented reliably.

The coordination number (CN) was calculated based on the segmented particle network. A contact relationship was identified when the minimum surface-to-surface distance between two independently labeled particles was smaller than the contact threshold. The CN of each particle was determined as the number of neighboring particles satisfying this contact criterion.

To ensure the reproducibility of the statistical analysis, the same image processing workflow, including voxel calibration, grayscale normalization, segmentation parameters, fragment exclusion criterion, and contact threshold, was applied to all stress levels.

2.3 Experimental results and discussion

For spatial comparison, the reconstructed specimen was divided into three sections perpendicular to the principal loading direction. Fig. 2 presents the three-dimensional distribution of

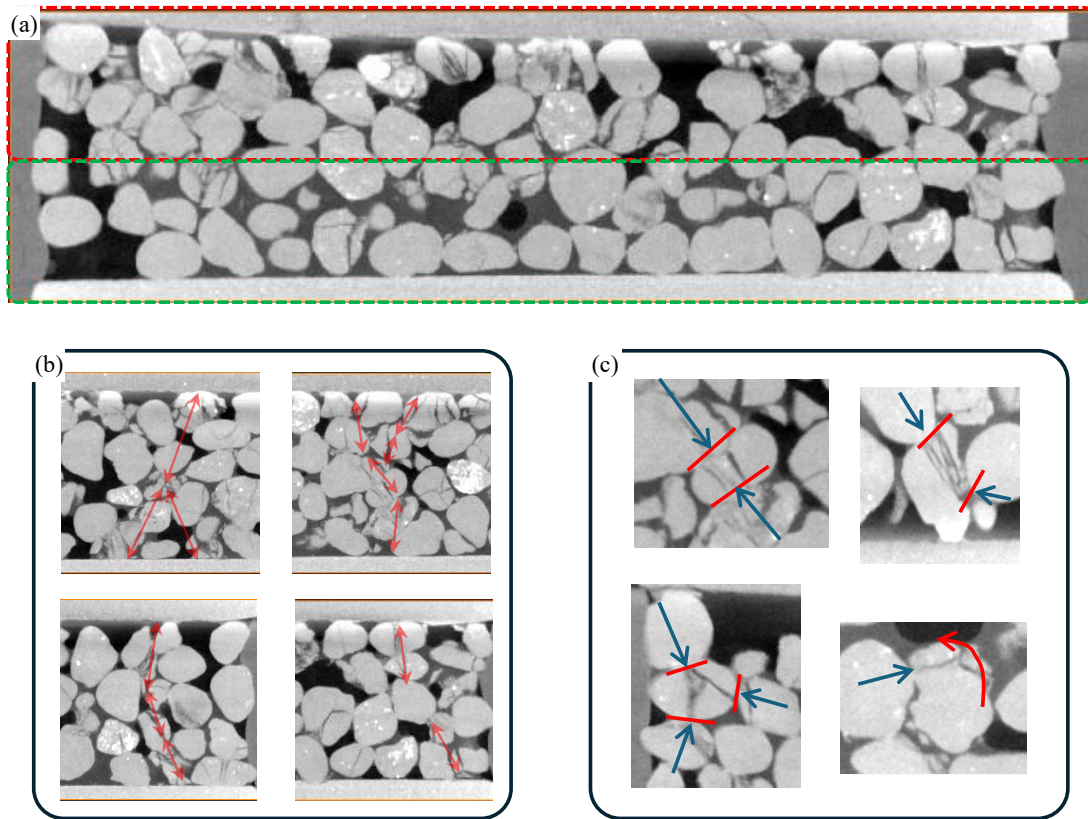


Fig. 3. Heterogeneous crushing of the proppant pack under triaxial loading: (a) Spatial variation in particle breakage, (b) chain-like evolution of local particle failure, and (c) breakage modes associated with particle geometry.

crushed particles with increasing closure stress. Crushing was most extensive in the upper section adjacent to the loading platen and least extensive in the lower section (Figs. 2(b)-2(d)). This gradient is consistent with greater local stress near the loading interface. In addition, the resulting fines could obstruct pore throats and compact the pack, linking the observed damage pattern to permeability loss.

To assess how damage varied with distance from the loading boundary, the local breakage pattern was examined. Fig. 3(a) resolves the local failure pattern near the loading boundary. It can be seen that damage is concentrated in a zone adjacent to the platen and becomes less extensive with increasing distance from the loaded surface, and the resulting layered damage indicates preferential failure under boundary-induced stress concentration, a pattern hereafter termed as the stratified breakage mode. The chained particle failures in Fig. 3(b) provide morphological evidence for the development of the stratified pattern. Platen roughness and nonspherical grain geometry promote bridging and interlocking, which concentrate stress at boundary contacts and between neighboring particles. Once a particle fractures, compaction reorganizes the local contact network and transfers load to nearby grains, so that failure can then propagate through weak contacts along the redistributed load path. Because the concentrated load paths dissipate and stress attenuates with depth, many of these chains terminate before reaching the lower part of the pack, and damage remains concentrated near the loading boundary.

To interpret the different failure modes within the pack, particle geometry and loading position were examined. Fig. 3(c) illustrates that fragment number and fracture morphology depend on particle geometry and loading position. Regular, high-sphericity particles survive more frequently because their intra-particle contact stresses are distributed more evenly. By contrast, elongated grains commonly split along their major axis, and polygonal grains are fragmented at point-to-face contacts. Sliding and interlocking among irregular particles also produce local shear failure and chipping. These mechanisms generate single, bifurcated and interrupted failure chains within the pack.

From the particle-scale failure modes, the top-down damage pattern and the post-crushing size distributions were collectively produced, as shown in Fig. 4. The particle-size distributions after crushing correspond to the final axial stress stage of 40 MPa. Particle breakage was characterized using the particle-size distribution obtained from micro-CT segmentation. The equivalent diameter of each particle was calculated from its segmented three-dimensional volume, and the volume-based particle-size distribution was used to describe the size evolution of particles after crushing (Nakata et al., 1999; Zhao et al., 2024). Relative to the initial pack, all post-failure distributions shifted toward smaller sizes and lower distribution peaks, indicating the loss of large grains and the generation of fines. Particles smaller than 200 μm were more abundant in the upper section, consistent with intensive comminution.

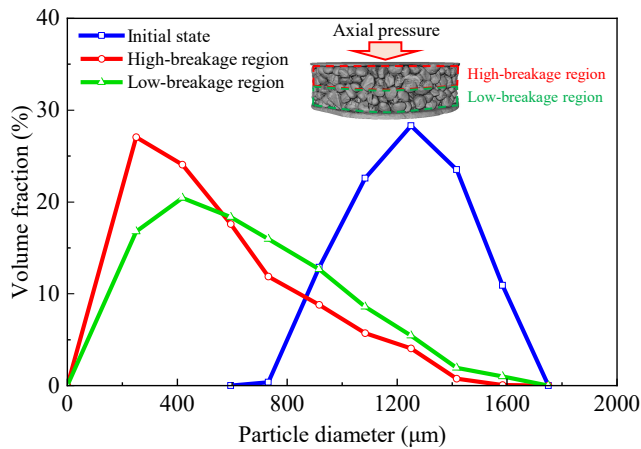


Fig. 4. Particle-size distributions of the proppant pack before and after crushing.

inution near the platen. The lower section exhibited less breakage and was dominated by splitting into two or three fragments; its size distribution peaked at 200-700 μm , or roughly one-third to one-half of the initial peak size. The median particle size, D_{50} , decreased from 1,391.5 μm initially to 701.4 μm in the high-breakage region and 841.6 μm in the low-breakage region.

CN denotes the number of distinct particles in direct contact with a given grain. In a polydisperse pack, larger grains generally have higher CN values and contribute more strongly to the load-bearing skeleton. Fig. 5 relates closure pressure to the evolution of CN and particle breakage. The initial unbroken pack had an average CN of approximately 6, providing a reference for the transition from loose packing to a stable contact network.

As compaction proceeded, particles with low initial CN and limited load-bearing capacity failed preferentially. Their fragments filled voids, restricted particle motion, and created additional contacts, thereby increasing the average CN and homogenizing the force-chain network. Between 25 and 40 MPa, CN approached a plateau and little additional breakage occurred. Large particles with high CN remained comparatively stable because their loads were distributed among more contacts. The pack therefore transitioned from breakage-dominated deformation to a compaction-stabilized state, after which higher closure pressure produced little change in the established spatial damage pattern.

3. DEM simulation of non-uniform crushing in the proppant pack

The *in-situ* experiments documented spatial damage at successive loading stages, whereas they could not independently control all geometric variables or directly resolve internal force transmission. A grain-scale DEM model was therefore used to isolate the effects of particle sphericity, strength and fracture width, and to relate the observed damage to contact-scale mechanics.

3.1 Modeling methodology

3.1.1 Bonded-contact formulation and local failure rule

The grain scale refers to individual proppant particles and is characterized by particle diameter, while the assembly scale refers to the confined particle pack and is characterized by pack thickness (fracture width) and lateral extent. Each nonspherical grain was represented as a breakable cluster of bonded constituent spheres. Prior to damage, the bonds transmitted load and maintained grain integrity. Local bond rupture allowed cracks to emerge through successive failures in the internal network rather than along a prescribed plane. This demonstrates that the model treats crack initiation and growth as consequences of evolving contact forces.

Interactions among constituent spheres followed a linear parallel-bond law (Ueda et al., 2013; Potyondy, 2015). Each bonded contact transmitted normal and tangential forces together with moments, thereby restricting relative rotation. This formulation reproduces the combined compression, shear and bending generated by eccentric load paths. In angular grains, surface irregularities and uneven bearing areas concentrate load locally, making this formulation particularly relevant.

Two contact classes separated intragranular cohesion from external friction. Parallel bonds connected constituent spheres within each grain, whereas particle-platen interfaces followed an unbonded linear-frictional law (Zhao et al., 2024). Intact clusters could therefore sustain cohesive resistance, while external contacts remained free to slide, roll and mobilize Coulomb friction.

DEM breakage criteria may use principal stress, particle-averaged stress, or a characteristic stress calculated from contact force (de Bono and McDowell, 2016). The model evaluates failure at each bonded contact by comparing local bond stresses with the corresponding calibrated strengths. When a bond stress exceeds the applicable strength threshold, the bond is removed and recorded as a microcrack. Both stresses and strengths are expressed in MPa. Continued loading allowed these local failures to accumulate and coalesce into a macroscopic fracture. The contact-level criterion was selected because protrusions, sharp edges and small bearing areas generate stress concentrations in irregular grains that particle-averaged quantities may obscure (Wu et al., 2025). In the DEM analysis, the breakage ratio was calculated as the ratio of broken bonded contacts to the initial bonded contacts, providing a quantitative measure of bond breakage evolution during compression (Potyondy and Cundall, 2004).

Once sufficient internal bonds had ruptured, a cluster separated into individual fragments. These fragments remained active DEM bodies and could rearrange, form new contacts, slide, and undergo further damage. The calculation continued after the first rupture to follow the subsequent mechanical response of the fragments.

3.1.2 Shape reconstruction and breakable-cluster generation

Particle shape and breakability were represented in two stages. The external boundary of each grain was reconstructed from its target nonspherical geometry. Constituent spheres then filled the enclosed volume, and parallel bonds connected

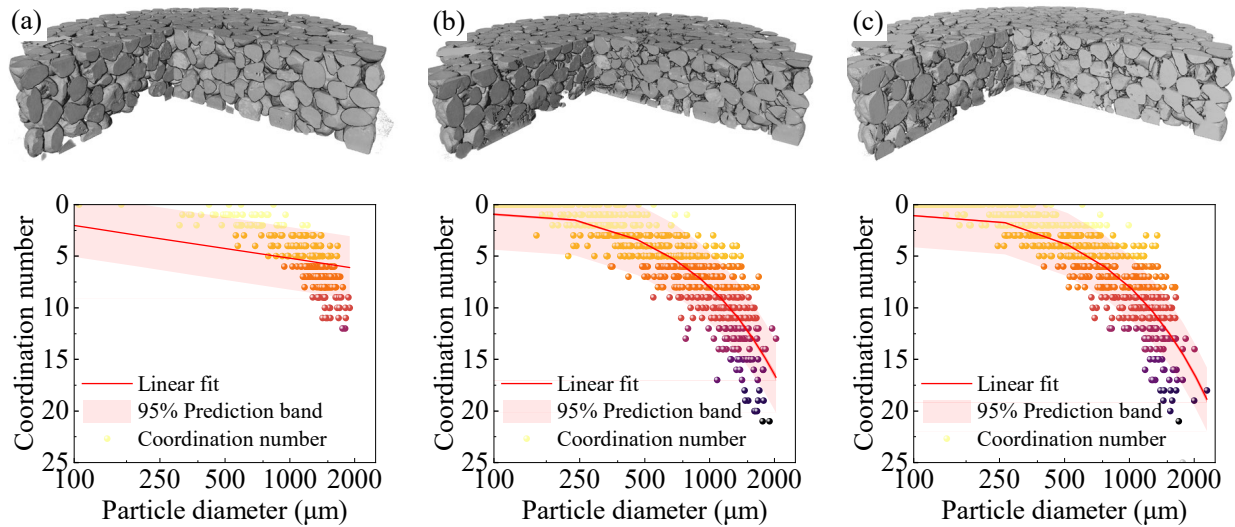


Fig. 5. Evolution of proppant-pack crushing and relationship between particle diameter and CN at different pressures: (a) Loose packing, (b) axial stress of 25 MPa, and (c) axial stress of 40 MPa.

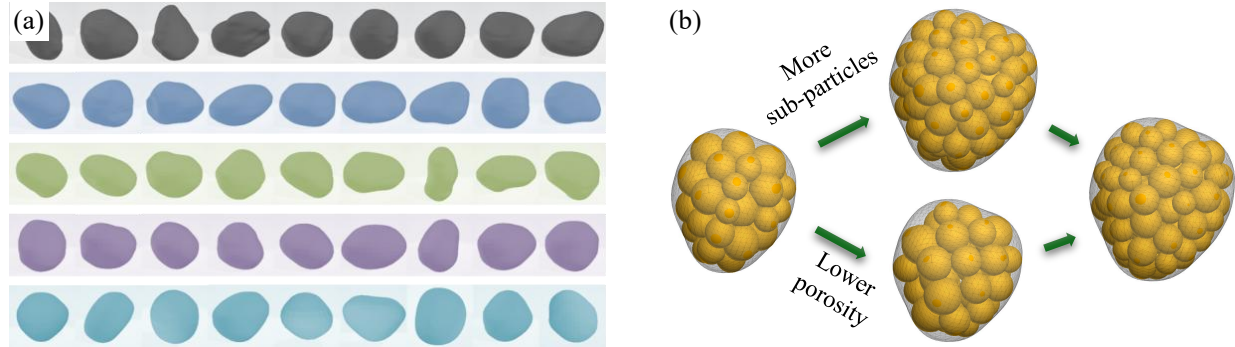


Fig. 6. The numerical particle-model workflow: (a) Reconstructed shape library and (b) replacement with breakable bonded clusters.

neighboring spheres. This procedure preserved the irregular external shape while providing an internal network capable of progressive fragmentation.

A scaled surface in stereolithography format (STL) preserves grain shape but does not reproduce the size dependence of particle strength (Fig. 6(a)). Here, micro-CT-derived STL models were utilized to define the external geometries, while the internal cluster architecture was used to account for size-dependent breakability. Because larger grains generally contain more flaws (Qian et al., 2019), the number and size distribution of constituent spheres and the cluster porosity were varied with grain size. This approach introduced size-dependent breakability without relying on geometric scaling alone.

Conventional bubble-pack representations of irregular grains can place nearly coincident constituent spheres and multiple bonds within a small region, and such overlaps obscure crack paths and bias particle-replacement behavior. The revised cluster particle method addresses this limitation in three steps. First, each micro-CT-derived STL boundary is imported as a set of rigid walls and filled with spheres at the prescribed porosity. Second, the internal assembly is

mechanically equilibrated to remove near-coincident overlaps while preserving porosity and shape fidelity. Third, the equilibrated assembly is stored as a reusable template (Fig. 6(b)). For each size class, the internal architecture and contact parameters were calibrated against single-particle compression. The resulting templates retained a realistic grain geometry and allowed progressive breakage in assembly-scale simulations.

3.1.3 Boundary control for quasi-static compression

The specimen boundaries were controlled by force feedback. Rigid walls were installed to enclose the particle pack, and the force at each controlled wall was compared with its prescribed value. The particle-wall friction coefficient was set to 0 to minimize additional tangential resistance from the lateral boundary. Wall deformation was neglected, and the wall-particle interaction was governed by the assigned contact parameters. At every control step, the wall velocity was updated from this force difference to maintain the required confinement as the pack deformed.

The DEM model dimensions and particle number were determined according to the experimental specimen geometry. The particle-size distribution was assigned based on the equ-

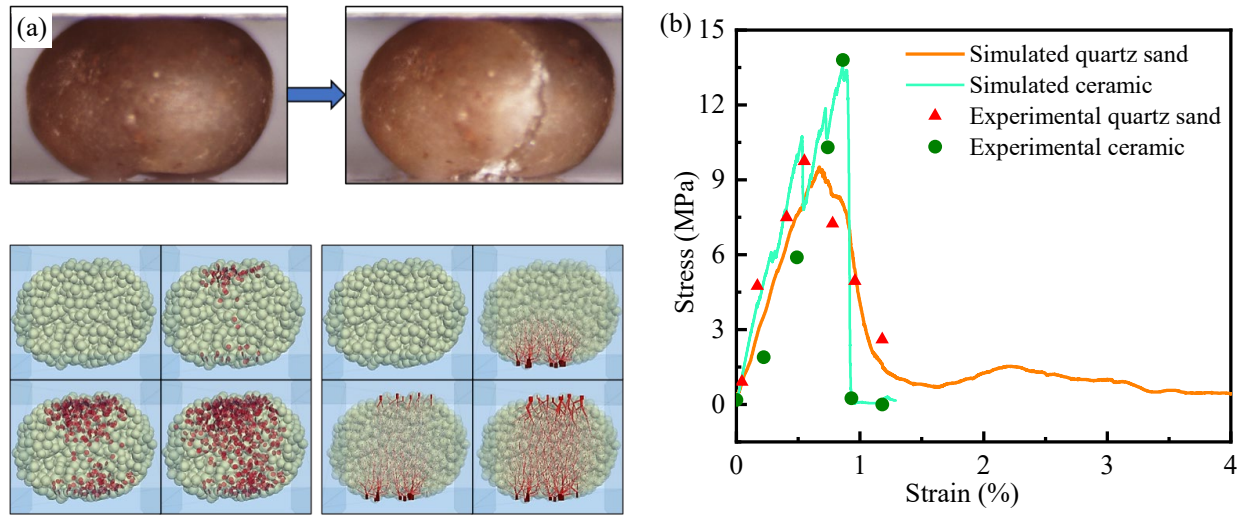


Fig. 7. Calibration of the single-particle DEM model: (a) Experimental crack development during uniaxial compression (top), simulated damage evolution (lower left) and force-chain evolution (lower right) and (b) experimental and simulated stress-strain curves.

Table 1. Calibrated micromechanical parameters of the DEM model.

Parameter	Quartz sand	Ceramic
Stiffness ratio (-)	2	2
Friction coefficient (-)	0.4	0.38
Internal friction angle (°)	36	34
Contact normal strength (MPa)	20	28
Contact shear strength (MPa)	13	18
Contact elastic modulus (GPa)	1	1.25
Bond elastic modulus (GPa)	1.50	1.9
Bond normal strength (MPa)	40	58
Bond shear strength (MPa)	8	11.5

ivalent particle-size distribution obtained from micro-CT segmentation.

Axial compression was applied using a stress servo-controlled scheme, in which the loading platen velocity was automatically adjusted according to the difference between the measured and prescribed stresses. The quasi-static condition was evaluated using the ratio of the mean unbalanced force to the mean contact force. A force ratio in the order of 1×10^{-4} has been widely adopted as an indicator of quasi-static equilibrium in DEM simulations (Ai et al., 2014), and this range was maintained throughout compression. Boundary stress and strain, bond-break events, and fragment evolution were recorded for subsequent analysis.

3.2 Calibration

The micromechanical parameters were calibrated against single-particle compression tests performed under the same vertical loading condition as the simulations. These tests im-

plemented the same proppant material as the pack experiments. Three-dimensional particle geometries reconstructed from the tested grains enabled direct comparison between the simulated and observed failure. At the macroscopic level, calibration matched the experimental stress-strain response; at the particle level, the observed crack path was compared with the spatial distribution of simulated bond failures, while the force-chain field was used to interpret internal load transfer. The final micromechanical parameters for quartz sand and ceramic are listed in Table 1.

The experimental fracture process was used to assess whether the DEM model reproduced particle damage and the associated load-transfer behavior. Fig. 7(a) compares the experimental fracture process with the corresponding DEM damage and force-chain fields. The upper images show the particle before loading and after the formation of the principal crack. In the lower-left panel, simulated bond-break events accumulate and coalesce into a through-going crack as compression proceeds. The lower-right panel shows that strong load-bearing paths become increasingly concentrated as failure approaches. The agreement between the experimental crack location and the simulated damage zone supports the predicted failure mode, while the simulated force chains provide an interpretation of load transfer before rupture.

The experimental record covered loading and immediate post-peak failure, whereas the simulation extended to larger strains and captured the residual load-bearing stage. Fig. 7(b) compares the experimental and simulated stress-strain responses of quartz sand and ceramic proppants during single-particle compression. The simulation reproduces the rapid pre-peak stress increase, peak strength, and sharp post-peak drop associated with brittle fracture; the agreement found in peak response and crack pattern supports the calibrated parameters used in the subsequent proppant-pack simulations.

3.3 Simulation results and discussion

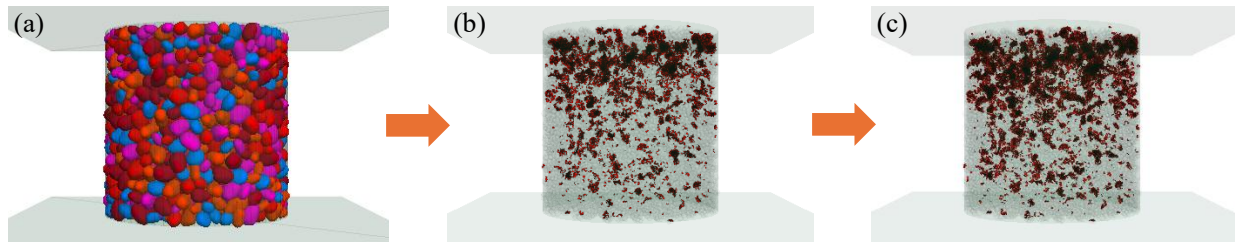


Fig. 8. Crack evolution within the proppant pack: (a) Initial state; (b) microcrack distribution at a breakage ratio of 5% and (c) microcrack distribution at a breakage ratio of 10%.

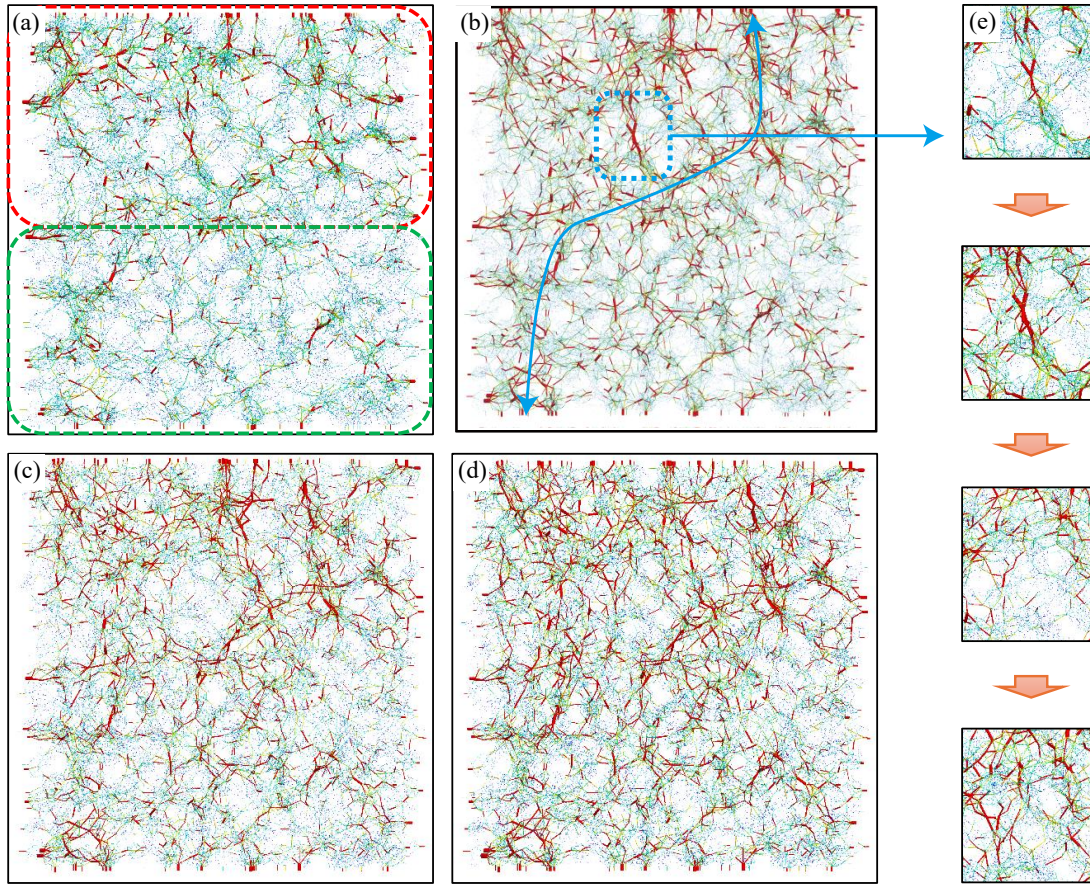


Fig. 9. Force-chain distribution within the proppant pack at different breakage ratios: (a) 5%, (b) 10%, (c) 15%, (d) 20% and (e) local force-chain evolution.

3.3.1 Crack propagation and force-chain evolution

To quantify spatial differences in crushing, the regional breakage ratio was defined as the number of cracks divided by the initial number of contacts. Fig. 8 presents crack evolution during the compression of the proppant pack. The simulation reproduces the experimental pattern of damage initiating at the top, propagating downward, and stabilizing over a limited depth. The spatial pattern is similar at overall breakage ratios of 5% and 10%, while the 10% state contained denser cracking and a deeper highly damaged region.

The spatial correspondence between strong force chains and cracking links local stress concentration to the layered damage pattern. Fig. 9 presents the force-chain network at four

breakage ratios, with the chain color and diameter indicating contact-force magnitude. At 5% breakage, strong chains are concentrated in the upper pack (Fig. 9(a)), coinciding with the region of downward crack propagation. As breakage increases, the force network becomes more evenly distributed, indicating progressive re-equilibration of the pack.

It can be seen that local force redistribution sustained damage in the upper zone (Fig. 9(e)). Initial differences in grain geometry and size caused some particles to carry greater loads than their neighbors. With the strain increasing, these strong chains thickened and extended (Fig. 9(b)). Particle failure then redirected the released load preferentially into neighboring strong paths, reinforcing established chains while weaker paths developed more slowly. In the upper pack, inter-

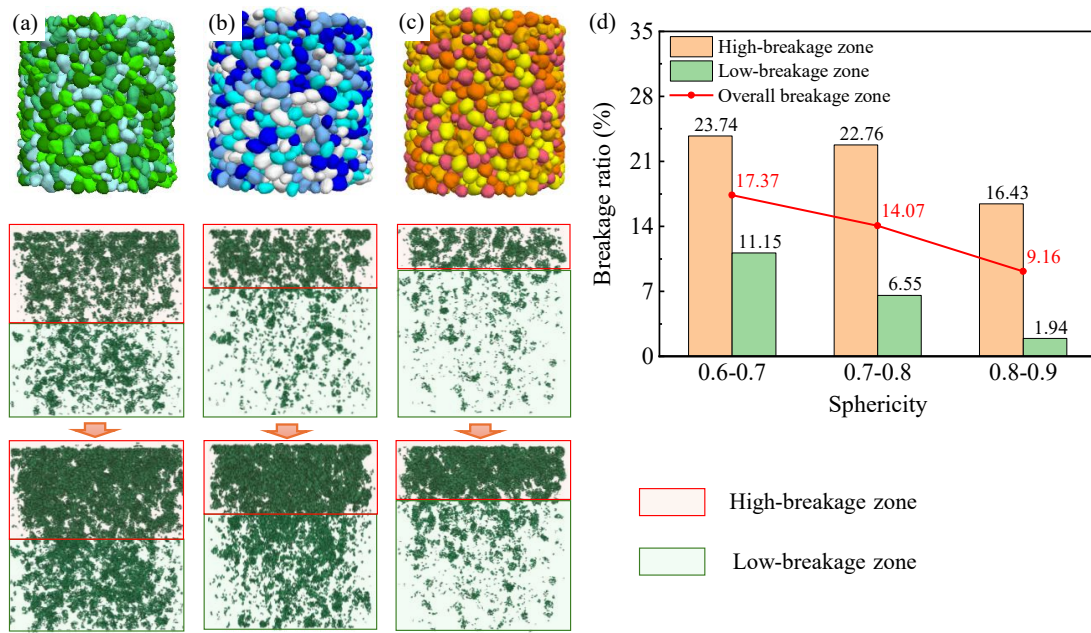


Fig. 10. Effect of proppant sphericity on microcrack distribution at different breakage stages: (a) Sphericity of 0.6-0.7, (b) sphericity of 0.7-0.8, (c) sphericity of 0.8-0.9 and (d) comparison of breakage ratios between two regions.

connected chains formed arch-like structures that transferred load laterally and reduced transmission to the lower region. Repeated redistribution therefore confined crack growth and produced the continuous chain-like damage zone marked by the double solid line.

3.3.2 Effect of particle sphericity on breakage distribution

To isolate the effect of particle shape, three DEM packs were generated from the experimentally derived geometry library. Particle morphology was quantified using the three-dimensional Wadell sphericity, defined as the ratio of the surface area of a volume-equivalent sphere to the actual particle surface area. Three morphology groups with sphericity ranges of 0.6-0.7, 0.7-0.8, and 0.8-0.9 were constructed for comparison.

For different sphericity models, the particle-size distribution, contact parameters, friction parameters, bonding parameters, loading conditions, and boundary conditions were kept identical, and only particle geometry was varied. All models followed the same packing procedure and underwent the same settling and mechanical equilibration process, ensuring consistent model generation conditions across different sphericity cases. Comparing these packs quantified how sphericity affected both overall resistance to crushing and the spatial distribution of breakage.

At the same closure stress, overall breakage decreased with sphericity, while damage became more localized (Fig. 10). For sphericity ranges of 0.6-0.7, 0.7-0.8 and 0.8-0.9, the overall breakage ratios were 17.37%, 14.07% and 9.16%, respectively (Fig. 10(d)). The corresponding upper-to-lower breakage ratios increased from 2.13 to 3.47 and 8.47. In the low-sphericity pack, the upper and lower regions had breakage ratios of 23.74% and 11.15%, respectively, indicating a relatively less

localized damage pattern. In the high-sphericity pack, these values decreased to 16.43% and 1.94%, maintaining a pronounced damage concentration near the loading platen.

The spatial damage patterns in Fig. 10 are well explained by the force-chain networks in Fig. 11. In the low-sphericity pack (Fig. 11(a)), the relatively distributed breakage is consistent with dispersed load transfer through multiple local paths. The irregular particle geometry generates heterogeneous contacts and promotes the development of short and discontinuous force chains, causing local stress concentrations at multiple positions rather than a single dominant loading path. Consequently, the vertical stress gradient is reduced, resulting in a smaller upper-to-lower breakage contrast. This interpretation concerns the assembly-scale load network rather than the intrinsic strength of individual grains.

With increasing sphericity, the breakage ratios in both regions decreased, whereas the upper-to-lower breakage ratio increased from 2.13 to 3.47 and 8.47 (Fig. 10(d)). The increased breakage contrast indicates that failure becomes more concentrated near the loading boundary in high-sphericity packs. The force-chain networks in Figs. 11(b)-11(c) are consistent with more continuous load-transfer paths, which facilitate the formation of dominant load-bearing chains in the upper region. These continuous load-transfer chains preferentially sustain the applied load, while the lower region receives less stress transfer and remains relatively intact. This assembly-scale trend does not establish a universal relation between sphericity and single-particle strength. To further examine the influence of packing randomness, additional simulations with different random seeds were conducted. Although different realizations showed minor variations in quantitative values, the trend of enhanced breakage localization with increasing sphericity remained consistent.

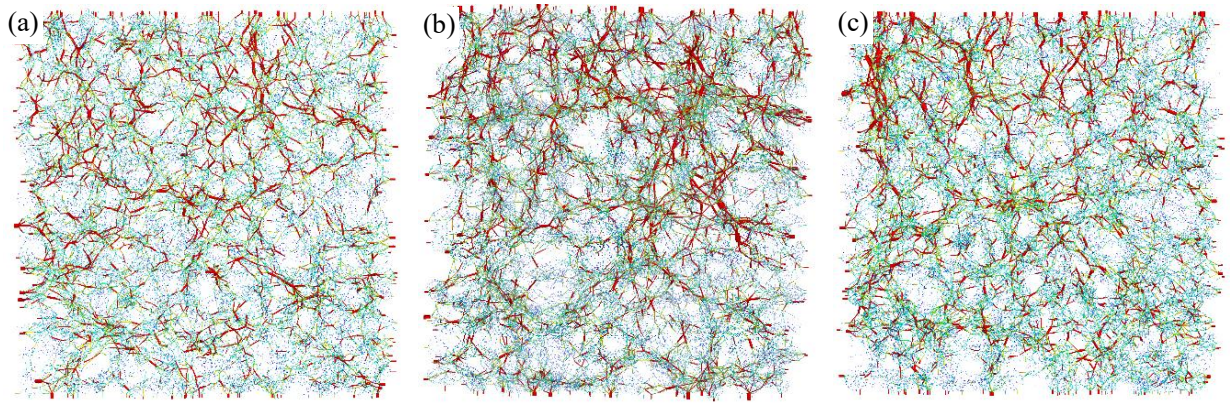


Fig. 11. Force-chain distribution within proppant packs of different particle sphericities: (a) 0.6-0.7, (b) 0.7-0.8 and (c) 0.8-0.9.

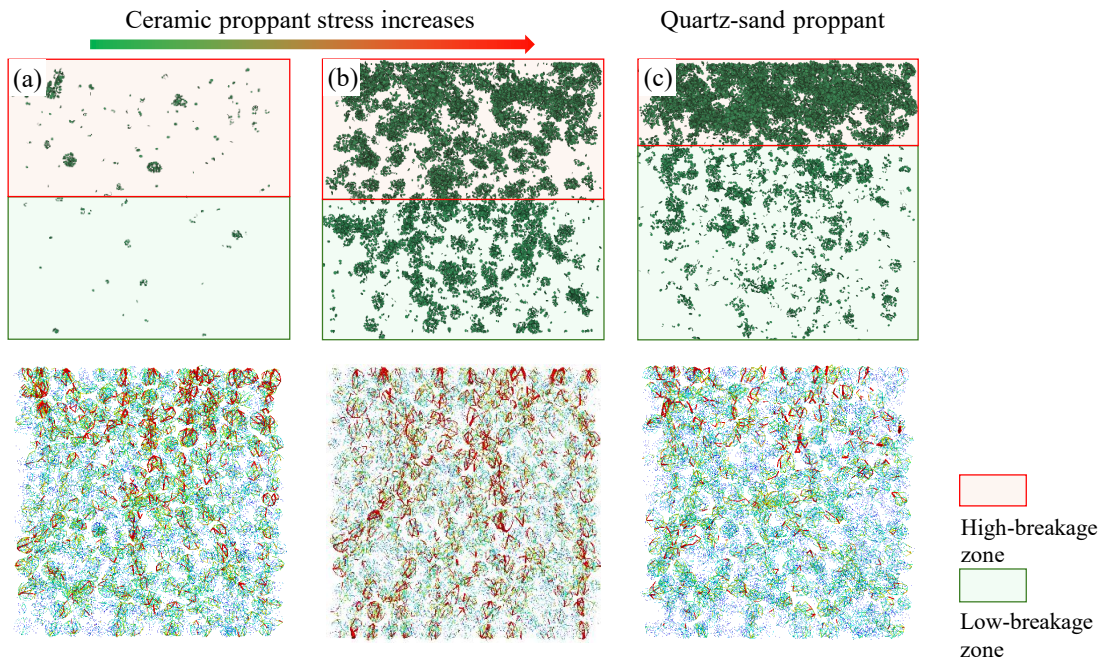


Fig. 12. (a)-(c) Microcrack distributions and (d)-(f) force chains in ceramic (a, b, d, e), and (c), (f) quartz-sand proppant packs: Comparisons at the same closure stress ((a) and (c); (d) and (f)) and the same overall breakage ratio ((b) and (c); (e) and (f)).

3.3.3 Comparison of breakage behavior between proppant types

Ceramic proppant is used when high crush resistance is required. Reported fines contents range from about 5% at 52 MPa for ceramic proppant to 12% at 35 MPa for quartz sand (Zhou et al., 2013). Although these values were obtained under different test conditions, they indicate the higher strength of ceramic grains. To isolate the effect of strength on spatial breakage, ceramic and quartz-sand packs were compared at similar overall breakage ratios. The quartz-sand pack was constructed from high-sphericity grains to reduce the confounding effect of particle shape. At the closure stress at which quartz sand reached an overall breakage ratio of approximately 6.5%, ceramic proppants exhibited negligible breakage (Figs. 12(a) and 12(c)).

At similar overall breakage ratios near 6.5%, the two proppant types exhibited different spatial distributions of damage.

The upper-to-lower breakage ratio was 8.47 for quartz sand but 1.71 for ceramic proppant. Ceramic breakage was therefore distributed more uniformly through the pack, whereas quartz-sand damage remained concentrated near the loading boundary (Fig. 12). This comparison used matched overall breakage ratios, rather than the identical closure stress used in the sphericity comparison.

The loading response comprised initial compaction, quasi-linear elastic deformation, and particle breakage. During the pre-failure stages, external work was stored mainly as bond and strain energy, and the stress response was approximately linear during elastic deformation. Breakage began when local bond stresses exceeded the corresponding calibrated strengths, followed by bond rupture and energy release. The stronger ceramic grains sustained greater loads and remained in the pre-failure stages longer than the quartz grains. At the same overall breakage ratio, the smaller simulated height of the ceramic

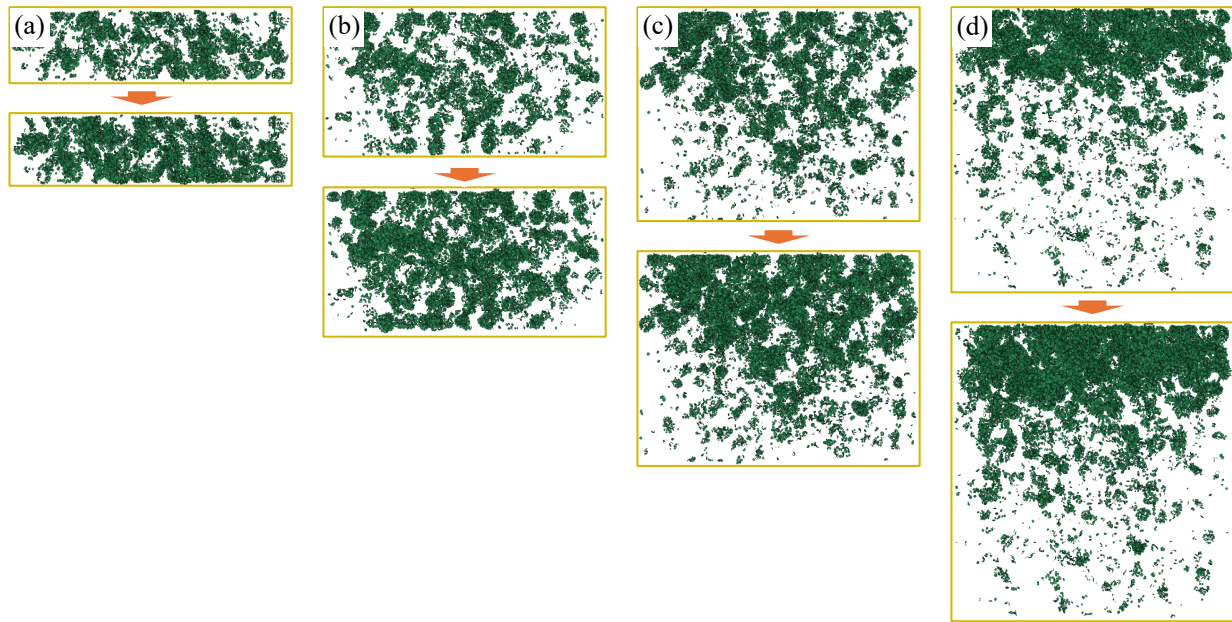


Fig. 13. Effect of fracture width on microcrack evolution in the proppant pack: (a) 2 mm, (b) 4 mm, (c) 6 mm and (d) 8 mm.

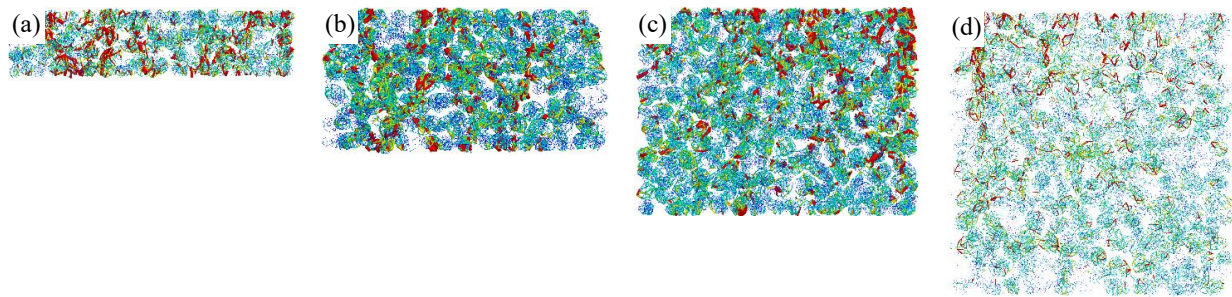


Fig. 14. Force-chain distributions in proppant packs at different fracture widths: (a) 2 mm, (b) 4 mm, (c) 6 mm and (d) 8 mm.

pack (Fig. 12(b)) was consistent with greater deformation before widespread failure.

Stress shadowing controlled spatial crack propagation after breakage began. Before widespread failure, numerous strong force chains spanned the ceramic pack (Fig. 12(e)), transferring load from the upper platen to lower particles and limiting stress concentration in the top layer (Fig. 12(b)). In quartz sand, dominant chains failed earlier (Fig. 12(f)). The subsequent redistribution concentrated load and breakage in the upper layer, producing the stratified pattern in Fig. 12(c).

The extended pre-failure stage of the stronger ceramic proppant kept multiple through-going load paths stable and reduced breakage localization. The lower breakage threshold of quartz sand caused earlier chain collapse and greater spatial heterogeneity at the same overall breakage ratio.

3.3.4 Effect of fracture width on the spatial distribution of breakage

With varying local stress, fracture width varies between primary and secondary hydraulic fractures and along individual fractures. This geometric variation controls the number of proppant layers and the distance over which force chains must transfer load. Therefore, simulations at different widths were

used to determine how aperture governs the spatial distribution of breakage.

Microcrack distributions and force-chain networks were examined to assess how fracture width affected breakage localization and load transfer. Figs. 13 and 14 compare microcracks and force chains at fracture widths of 2–8 mm. In the 2-mm model, the small number of particle layers allowed dominant chains to span the upper and lower walls. Consequently, breakage around these through-going paths was distributed through the pack. At 4 mm, some chains still crossed the aperture, but longer transmission paths and local stress concentrations produced lateral branching. Damage changed from a columnar to a network pattern, although the difference between upper- and lower-region breakage remained small.

At widths of 6 and 8 mm (Figs. 14(c) and 14(d)), dominant chains no longer spanned the fracture. Reduced through-thickness load transfer allowed upper-region chains to absorb load from surrounding weak paths and form a stable bridging network. Stress shadowing then restricted chain development and particle failure in the lower region. Therefore, breakage became increasingly concentrated in the upper layers as fracture width increased.

Increasing fracture width changed the force network from

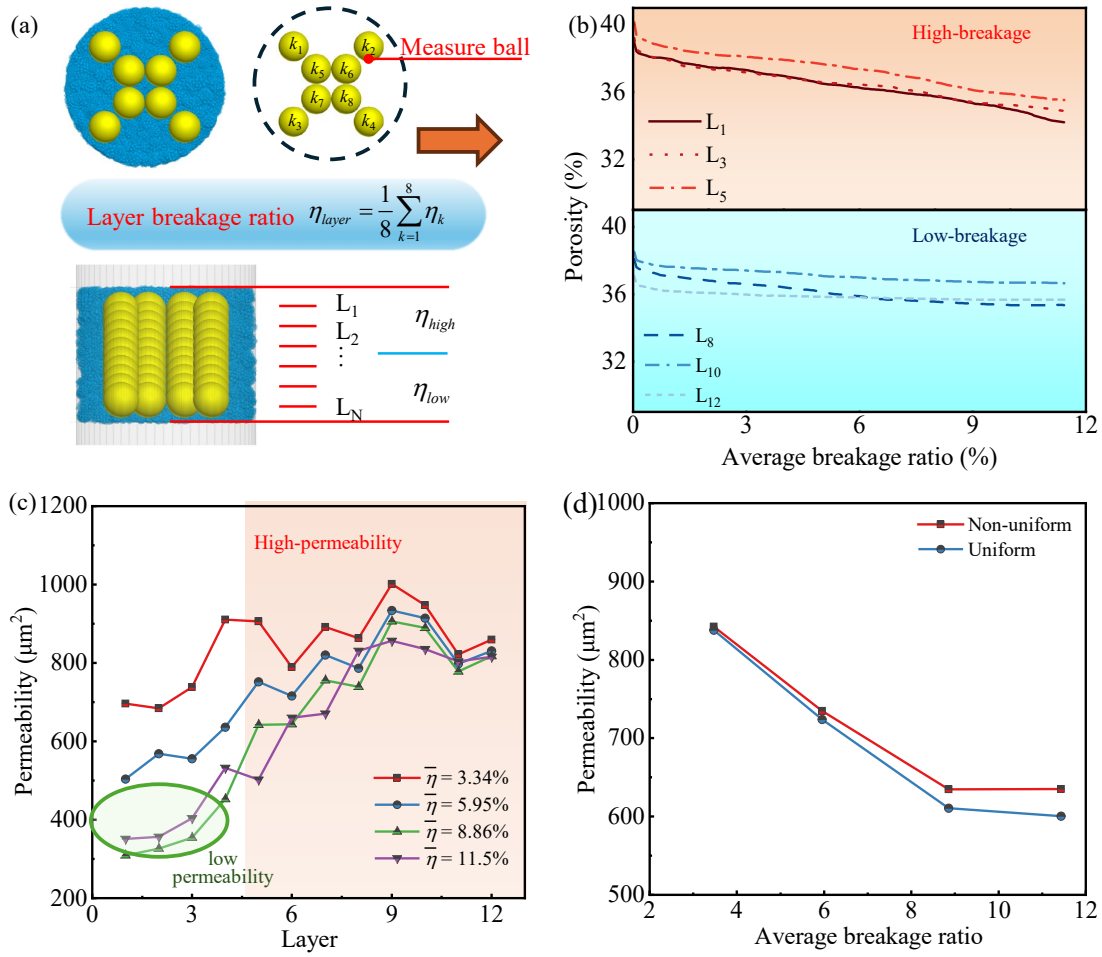


Fig. 15. Porosity and permeability evolution under layered crushing: (a) Schematic of layer breakage-ratio measurement, (b) porosity in different layers, (c) permeability in different layers and (d) equivalent permeability under non-uniform and uniform crushing.

through-going load paths to localized bridges. This transition reduced load transfer between the fracture walls and explains the stronger top-to-bottom breakage gradient in wider fractures.

3.3.5 Prediction of fracture conductivity under non-uniform crushing

Spatially variable crushing produces permeability contrasts that cannot be represented by an overall breakage ratio. Non-uniform proppant placement can alter residual aperture and fracture conductivity during closure (Wang and Elsworth, 2018). Herein, a layered conductivity model was used to isolate the effect of spatially variable crushing at a fixed fracture width. At the reservoir scale, finite fracture conductivity affects could predict well performance and interact with other parameters during conductivity inversion.

Propped-fracture conductivity equals fracture width multiplied by proppant-pack permeability. To isolate the effect of breakage distribution at a given stress, fracture width was held constant and only spatial variation in pack permeability was considered.

Proppant-pack permeability was estimated using the

Kozeny-Carman equation (Wang and Elsworth, 2018), which relates porous-medium permeability to porosity and particle size:

$$k = \frac{r^2 \phi^3}{45(1 - \phi)^2} = \frac{\bar{d}^2 \phi^3}{180(1 - \phi)^2} \quad (1)$$

where k denotes the proppant-pack permeability, μm^2 ; ϕ represents the pack porosity; r denotes the particle radius, μm ; and $\bar{d}$ is the mean particle diameter, μm . The propped fracture was divided into N layers of equal thickness along its height. Layer i was characterized by porosity ϕ_i and breakage ratio B_i , %; as shown in Figs. 15(a) and 15(b). To obtain the layer-specific mean diameter, μm , the relationship between breakage ratio and mean particle diameter was fitted:

$$\bar{d}_i = 1150.5 - 17.81B_i, R^2 = 0.976 \quad (2)$$

where $\bar{d}_i$ represents the mean particle diameter in layer i , μm ; and R^2 is the coefficient of determination of the fit. Because layers of equal thickness conduct flow in parallel under the same pressure gradient, the equivalent permeability of the non-uniformly crushed pack was calculated as follows:

$$k_{\text{layer}} = \frac{1}{N} \sum_{i=1}^N k_i \quad (3)$$

where k_{layer} denotes the equivalent permeability of the layered pack, μm^2 ; k_i denotes the permeability of layer i , μm^2 ; N denotes the total number of equal-thickness layers; and i is the layer index. The uniform-crushing case treated the pack as a homogeneous porous medium and used its overall mean porosity and particle diameter. For the layered case, measurement spheres in the DEM model were used to determine the porosity of equal-thickness layers. Crushing statistics supplied the corresponding breakage ratio of each layer, from which the layer-specific mean particle diameter was calculated.

Porosity was examined to assess how compaction and crushing altered the pore structure of the pack. Fig. 15(b) shows that porosity decreases in every layer as the average breakage ratio increases. Porosity remains lower in the high-breakage region because fragmentation, rearrangement, and fines migration cause greater local pore-structure deterioration, consistent with experimental evidence on fines-induced impairment of hydraulic-fracturing performance. The initially rapid decrease becomes more gradual at higher breakage ratios. Therefore, porosity evolution comprises an early compaction stage followed by a stage governed by crushing and pore filling.

For a fracture of fixed width, localized damage reduces the flow contribution of heavily crushed layers while leaving less damaged layers conductive. Fig. 15(c) shows that permeability contrasts increase as the average breakage ratio rises from about 3% to 12%. The interlayer permeability range expands from 317.60 to 504.75 μm^2 , corresponding to a 1.6-fold increase. Therefore, a uniform permeability reduction cannot represent the hydraulic effect of crushing.

The uniform assumption distributes flow-capacity loss across all layers, whereas the layered model retains preferential paths in less damaged regions. Fig. 15(d) compares the equivalent permeability predicted by the layered model with the conventional uniform-crushing estimate. Both estimates decrease with increasing breakage, but the layered estimate remains slightly higher, with the difference widening as damage increased. At an overall breakage ratio of 11.43%, the difference relative to the uniform estimate reaches about 5.7%, compared with 0.53% at low breakage. These paths carry part of the total flow and partially offset local blockage in heavily crushed layers.

4. Conclusions

This study examined how force transmission governs spatially heterogeneous proppant crushing using *in-situ* micro-CT experiments and DEM simulations of breakable particles with reconstructed geometries. Given the conditions considered in this study, the main conclusions are as follows:

- 1) Proppant crushing develops from the loading boundary toward the lower pack. Concentrated strong force chains and boundary stress produce preferential failure in the upper region and a stratified damage pattern.
- 2) The pack transitions from breakage-dominated deformation

to a compaction-stabilized state. Fragments fill voids and increased CN, strengthening the contact network; between 25 and 40 MPa, CN approaches a plateau and little additional breakage occurs.

- 3) DEM simulations showed that, under the modeled conditions, increasing particle sphericity reduces overall breakage but increases damage localization. Across the sphericity ranges of 0.6-0.7, 0.7-0.8, and 0.8-0.9, overall breakage decreases from 17.37% to 14.07% and 9.16%. The upper-to-lower breakage ratio increases from 2.13 to 3.47 and 8.47, indicating a more localized failure pattern at higher sphericity.
- 4) Particle strength controls the persistence of through-going force chains. At overall breakage ratios near 6.5%, the upper-to-lower breakage ratio is 1.71 for ceramic proppant and 8.47 for quartz sand, indicating substantially more uniform damage in the stronger ceramic pack.
- 5) Fracture width governs whether force chains span the proppant pack. The 2-mm model maintains through-going paths and distributes breakage, whereas widths of 6-8 mm promote localized bridging, weak load transfer to the lower region, and damage concentrated near the upper boundary.
- 6) The layered model predicts higher equivalent permeability than the uniform-crushing model. At an overall breakage ratio of 11.43%, the layered estimate is about 5.7% higher because less damaged layers retained preferential flow paths.

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Conflicts of interest

The authors declare no competing interest.

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References

- Ai, J., Langston, P. A., Yu, H. Discrete element modelling of material non-coaxiality in simple shear flows. *International Journal for Numerical and Analytical Methods in Geomechanics*, 2014, 38(6): 615-635.
- Bandara, K. M. A. S., Ranjith, P. G., Rathnaweera, T. D., et al. Crushing and embedment of proppant packs under cyclic loading: An insight to enhanced unconventional oil/gas recovery. *Geoscience Frontiers*, 2021, 12(6): 100970.
- Buscarnera, G., Einav, I. The mechanics of brittle granular materials with coevolving grain size and shape. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2021, 477(2249): 20201005.
- Cai, J., Xia, X., Elsworth, D., et al. Evolution of multiscale pore structure and microscopic flow behavior in shales

- subject to fluid-rock interaction. *Engineering Geology*, 2026, 373: 109052.
- Carrasco, S., Cantor, D., Ovalle, C., et al. Particle shape distribution effects on the critical strength of granular materials. *Computers and Geotechnics*, 2025, 177: 106896.
- Chen, J., Wang, L., Wang, C., et al. Automatic fracture optimization for shale gas reservoirs based on gradient descent method and reservoir simulation. *Advances in Geo-Energy Research*, 2021, 5(2): 191-201.
- Cundall, P. A., Strack, O. D. L. A discrete numerical model for granular assemblies. *Géotechnique*, 1979, 29(1): 47-65.
- de Bono, J. P., McDowell, G. R. Particle breakage criteria in discrete-element modelling. *Géotechnique*, 2016, 66(12): 1014-1027.
- Ding, F., Dai, C., You, Q., et al. Aminated nano-silica reinforced slickwater fracturing fluids with enhanced drag reduction, proppant transport and thermal stability. *Advances in Geo-Energy Research*, 2025, 18(2): 153-164.
- Fang, Y., Guo, L., Hou, M. Arching effect analysis of granular media based on force chain visualization. *Powder Technology*, 2020, 363: 621-628.
- Hari, S., Krishna, S., Gurralla, L. N., et al. Impact of reservoir, fracturing fluid and proppant characteristics on proppant crushing and embedment in sandstone formations. *Journal of Natural Gas Science and Engineering*, 2021, 95: 104187.
- Huang, L., Liao, X., Fan, M., et al. Experimental and numerical simulation technique for hydraulic fracturing of shale formations. *Advances in Geo-Energy Research*, 2024, 13(2): 83-88.
- Katende, A., Allen, C., Rutqvist, J., et al. Experimental and numerical investigation of proppant embedment and conductivity reduction within a fracture in the Caney Shale, Southern Oklahoma, USA. *Fuel*, 2023, 341: 127571.
- Li, J., Huang, Y., Pu, H., et al. Influence of block shape on macroscopic deformation response and meso-fabric evolution of crushed gangue under the triaxial compression. *Powder Technology*, 2021, 384: 112-124.
- Liu, B., Cen, W., Yan, G., et al. Particle shape effects on breakage behaviors in granular materials: a multiscale geotechnical perspective. *Computers and Geotechnics*, 2025, 187: 107504.
- Majmudar, T. S., Behringer, R. P. Contact force measurements and stress-induced anisotropy in granular materials. *Nature*, 2005, 435(7045): 1079-1082.
- McDowell, G. R., Bolton, M. D. On the micromechanics of crushable aggregates. *Géotechnique*, 1998, 48(5): 667-679.
- Moghadas, R., Rostami, A., Hemmati-Sarapardeh, A. Application of nanofluids for treating fines migration during hydraulic fracturing: Experimental study and mechanistic understanding. *Advances in Geo-Energy Research*, 2019, 3(2): 198-206.
- Nakata, Y., Hyde, A. F. L., Hyodo, M., et al. A probabilistic approach to sand particle crushing in the triaxial test. *Géotechnique*, 1999, 49(5): 567-583.
- Nie, Z., Qi, Q., Wang, X., et al. DEM investigation of strain behaviour and force chain evolution of gravel-sand mixtures subjected to cyclic loading. *Particuology*, 2022, 68: 13-28.
- Potyondy, D. O., Cundall, P. A. A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 2004, 41(8): 1329-1364.
- Potyondy, D. O. The bonded-particle model as a tool for rock mechanics research and application: Current trends and future directions. *Geosystem Engineering*, 2015, 18(1): 1-28.
- Pusztai, P., Koroncz, P. J., Kuncz, M., et al. Semi-analytical approach to the determination of fracture permeability. *GEM - International Journal on Geomathematics*, 2023, 14(1): 16.
- Qi, M., Li, Y., Ghanbar Moghanloo, R., et al. Applying deep bed filtration theory to study long-term impairment of fracture conductivity caused by reservoir fines. *Geoenergy Science and Engineering*, 2023, 231: 212253.
- Qian, G., Lei, W.-S., Yu, Z., et al. Statistical size scaling of breakage strength of irregularly-shaped particles. *Theoretical and Applied Fracture Mechanics*, 2019, 102: 51-58.
- Ramazanov, V., Matovu, S., Al Shafloot, T., et al. Enhancing Fracturing Proppant Performance: Methods and Assessment. *Arabian Journal for Science and Engineering*, 2025, 50(7): 4477-4503.
- Salman, A. D., Biggs, C. A., Fu, J., et al. An experimental investigation of particle fragmentation using single particle impact studies. *Powder Technology*, 2002, 128(1): 36-46.
- Seo, D., Sohn, C., Cil, M. B., et al. Evolution of particle morphology and mode of fracture during the oedometric compression of sand. *Géotechnique*, 2021, 71(10): 853-865.
- Seo, D., Tengattini, A., Viggiani, G., et al. Experimental and analytical assessment of fracture criteria for non-spherical sand grains. *Granular Matter*, 2024, 26(1): 1.
- Shen, C., Liu, S., Wang, L., et al. Micromechanical modeling of particle breakage of granular materials in the framework of thermomechanics. *Acta Geotechnica*, 2019, 14(4): 939-954.
- Sun, H., He, B., Xu, H., et al. Experimental Investigation on the Fracture Conductivity Behavior of Quartz Sand and Ceramic Mixed Proppants. *ACS Omega*, 2022, 7(12): 10243-10254.
- Tahmasebi, P. A state-of-the-art review of experimental and computational studies of granular materials: Properties, advances, challenges, and future directions. *Progress in Materials Science*, 2023, 138: 101157.
- Tkachenko, A. V., Witten, T. A. Stress propagation through frictionless granular material. *Physical Review E*, 1999, 60(1): 687-696.
- Ueda, T., Matsushima, T., Yamada, Y. DEM simulation on the one-dimensional compression behavior of various shaped crushable granular materials. *Granular Matter*, 2013, 15(5): 675-684.
- Wang, J., Elsworth, D. Role of proppant distribution on the evolution of hydraulic fracture conductivity. *Journal of Petroleum Science and Engineering*, 2018, 166: 249-262.

- Wang, W., Coop, M. R. An investigation of breakage behaviour of single sand particles using a high-speed microscope camera. *Géotechnique*, 2016, 66(12): 984-998.
- Wang, W., Zhong, Z., Zhang, M., et al. Stress redistribution and regional behavior of arching effect: Insights from 2D FDM-DEM trapdoor tests. *Transportation Geotechnics*, 2025, 54: 101622.
- Wang, X., Yang, D., Liu, C., et al. Experimental and theoretical quantification of *in-situ* crushing characteristics of irregularly-shaped particles under multi-axis pressure with X-ray micro-computed tomography (μ CT) and discrete element method (DEM). *Powder Technology*, 2026, 469: 121733.
- Wang, X., Zhu, H. P., Luding, S., et al. Regime transitions of granular flow in a shear cell: A micromechanical study. *Physical Review E*, 2013, 88(3): 032203.
- Wu, Y., Dai, B., Xu, K., et al. Particle-morphology-based characterization of the breakage behavior of particle assemblies under one-dimensional compression. *Acta Geotechnica*, 2025, 20(4): 1813-1830.
- Xu, J., Ding, Y., Yang, L., et al. Conductivity analysis of tortuous fractures filled with non-spherical proppants. *Journal of Petroleum Science and Engineering*, 2021, 198: 108235.
- Yu, J., Wang, J., Wang, S., et al. Conductivity evolution in propped fractures during reservoir drawdown. *Rock Mechanics and Rock Engineering*, 2022, 55(6): 3583-3597.
- Zhang, T., Zhang, C., Luo, T. Effect of stress anisotropy on deformation and particle breakage of silica sand at high-pressure compression tests. *Construction and Building Materials*, 2022, 316: 125835.
- Zhang, T., Zhang, C., Song, F., et al. Breakage behavior of silica sands during high-pressure triaxial loading using X-ray microtomography. *Acta Geotechnica*, 2023, 18(10): 5195-5211.
- Zhao, X., Wu, Y., Jia, Y., et al. Impact of particle shape on crushing behaviour of rock particles using X-ray micro-CT testing and DEM modelling. *Rock Mechanics and Rock Engineering*, 2024, 57(10): 7813-7834.
- Zheng, W., Silva, S. C., Tannant, D. D. Crushing characteristics of four different proppants and implications for fracture conductivity. *Journal of Natural Gas Science and Engineering*, 2018, 53: 125-138.
- Zhou, S., Tian, Y., Chen, Z., et al. Current Research Situation and New Progress of Ceramic Fracturing Proppants. *Bulletin of the Chinese Ceramic Society*, 2013, 32(6): 1097-1102. (in Chinese)
- Zhou, L., Chu, X., Xu, Y.. Evolution of Anisotropy in Granular Materials: Effect of Particle Rolling and Particle Crushing. *Strength of Materials*, 2014, 46(2): 214-220.
- Zhu, X., Liu, W., Wei, Y., et al. Prediction of proppant accumulation morphology in coal reservoir fractures using numerical simulation and response surface approach methodology. *Advances in Geo-Energy Research*, 2025, 18(3): 218-230.
- Zhu, Z., Wang, J., Wu, M. DEM simulation of particle crushing in a triaxial test considering the influence of particle morphology and coordination number. *Computers and Geotechnics*, 2022, 148: 104769.