

Research on the Hysteresis Performance of Powder Dampers Based on Media Property Tests and PFC Simulation

Bocheng Teng*, Yutong Zhang, Mengdie Zhang

*Key Laboratory of Engineering Seismic Protection and Structural, Diagnosis and Treatment,
Beijing University of Technology, Beijing, 100124, China*

**Corresponding Author*

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Abstract: This study investigates the influence of the mechanical properties of powder-damper filling media on the hysteretic response of powder dampers by combining material property tests with PFC-based discrete element simulations. Density, angle of repose, internal friction angle, particle gradation, and equivalent elastic modulus tests were carried out on five powder materials, namely silty soil, sand, magnetite, iron powder, and talc powder. Based on the test results, a PFC2D model of the powder damper was established, and the hysteretic curves under different filling media conditions were analyzed. The results show that all five powder materials can form closed hysteresis loops, although significant differences are observed in reaction force level, loop area, and stability. Materials with high density and high stiffness are more favorable for improving load-carrying capacity, whereas materials with high friction characteristics are more conducive to enhancing energy dissipation capacity. A parameter sensitivity analysis using iron powder as the reference material indicates that density, equivalent elastic modulus, friction coefficient, and particle gradation have significant effects on the hysteretic performance of the damper.

1. Introduction

1.1 Research Background

With the growing demand for vibration reduction and control in engineering structures, dampers-important energy-dissipating components-have garnered widespread attention in civil engineering, mechanical engineering, and equipment engineering. By dissipating external input energy, dampers reduce structural vibration responses and enhance structural safety and stability. Compared to traditional dampers, powder dampers have increasingly attracted researchers' interest due to their relatively simple structure, strong adaptability, and unique energy-dissipation mechanisms [1].

Powder dampers typically utilize granular or powdered materials as the internal filling medium. Under external loads or cyclic displacements, complex interactions such as collisions, friction, compression, and rearrangement occur between the particles and between the particles and the wall surface, thereby dissipating vibration energy. Thus, the physical and mechanical properties of the

filling medium are critical factors determining the performance of powder dampers. Different media exhibit significant variations in particle size, density, fluidity, compressibility, and friction characteristics; these differences further influence the hysteresis curve shape, energy dissipation capacity, and mechanical response behavior of the dampers. Consequently, conducting material property studies on powder media and analyzing their impact on damper hysteresis performance holds substantial engineering relevance and theoretical value.

Powder media, however, are typical bulk materials whose macroscopic mechanical responses originate from complex contact interactions between microscopic particles [2]. While conventional experimental methods can obtain macroscopic performance parameters, they struggle to elucidate internal processes such as particle motion, contact evolution, and energy dissipation formation within dampers. The discrete element method, particularly Particle Flow Code (PFC), enables simulation of particle system interactions-including contact, slip, collision, and reorganization-at the mesoscale, providing an effective approach for studying the mechanism of powder media in dampers [3]. Integrating material property tests with PFC simulations allows mesoscopic parameter calibration based on macroscopic performance evaluations, while further analyzing variation patterns of damper hysteresis characteristics under different medium parameters [3-5].

Building on this foundation, this study focuses on the selection of filling media for powder dampers. We first conduct material property tests using various materials to obtain fundamental mechanical parameters of the powder medium. Based on these findings, we establish a PFC (Particle-Filled Composite) model for powder dampers. By adjusting mesoscopic parameters of the powder, we investigate the evolution characteristics of the damper's hysteresis curve, aiming to provide references for medium selection and performance optimization in powder damping systems.

1.2 Current Research Status of Powder Dampers and Their Media

Compared to traditional types such as viscous dampers and metal yield dampers, powder dampers exhibit distinct particle-based medium characteristics during energy dissipation, demonstrating significant application potential in complex vibration environments. Huang Yunwen et al. conducted theoretical analysis, numerical simulations, and experimental studies on the energy dissipation mechanisms and performance of particle dampers [6], demonstrating their energy dissipation capability and advantages in structural applications. As particles with smaller diameters, powders still possess outstanding energy dissipation properties. However, existing research on powder media primarily focuses on macroscopic characteristics such as bulk density, angle of repose, compression, and shear properties, reflecting fundamental material behavior under static or quasi-static conditions, while providing insufficient support for understanding the dynamic energy dissipation processes of powder dampers under cyclic loads. Notably, a clear correlation between powder medium parameters and the hysteresis performance of dampers remains elusive, and parameter selections in numerical analyses often lack experimental validation. Therefore, it is essential to integrate material property tests with PFC (Particulate Fluid Dynamics) models to further investigate how powder medium characteristics influence the hysteresis performance of powder dampers.

1.3 Research Content of This Paper

To investigate the influence of filling medium parameters on the hysteresis performance of powder dampers, this study employs a combined approach of experimental investigation and discrete element numerical simulation.

The main research topics of this paper are as follows:

- 1) Conduct mechanical parameter tests on the powder damper filling medium to obtain fundamental parameters such as density, internal friction angle, angle of repose, particle size

distribution, and equivalent elastic modulus;

2) Based on experimental results, establish the PFC model for powder media and powder dampers, and complete the mesoscopic parameter calibration;

3) Analyze the variation characteristics of hysteresis curves for powder dampers under different powder medium parameter conditions, and conduct sensitivity analysis on mechanical parameters of the same powder type, to reveal the influence patterns of medium parameters on damping energy dissipation performance.

2. Powder Media Material Property Test

2.1 Test Materials and Test Protocol

To investigate the influence of mechanical parameters of the filling medium in powder dampers on their hysteresis behavior, this study selected five representative powder materials-silt, sand, iron oxide (Fe_2O_3), iron powder, and talc powder-as research subjects, as shown in Figure 1. These materials form a comparative system ranging from low to medium to high density, with varying fluidities and particle morphologies, effectively demonstrating how different medium characteristics affect the energy dissipation performance of powder dampers [7–11]. Among them, silt is widely available and cost-effective, with well-established parameter measurement methods, making it suitable as a reference material; sand, iron oxide, iron powder, and talc represent powder media with distinct densities, particle sizes, and morphologies, enabling comparative analysis of how medium properties impact damper performance. Both iron oxide and iron powder were prepared as fine powders of approximately 200 mesh, while talc was used as industrial-grade powder of about 1200 mesh.



Figure 1: Five Powder Samples

Given that the energy dissipation in powder dampers primarily originates from collisions, friction, compression, and reorganization processes between particles and between particles and the wall surface, the macroscopic physical and mechanical parameters of the powder medium directly influence the damper's output performance, hysteresis behavior, and energy dissipation capacity. This study focuses on medium parameter calibration and PFC modeling requirements, selecting density, internal friction angle, angle of repose, particle size distribution, and equivalent elastic modulus as key testing indicators. Specifically, density reflects the mass characteristics and inertial effects of the

particle material; the angle of repose characterizes the powder's natural stacking and flowability; the internal friction angle indicates the shear strength and frictional energy dissipation potential of the particle system; particle size distribution determines the contact configurations and pore structure; while the equivalent elastic modulus characterizes the overall deformation stiffness of the loose powder bed under compressive conditions [12–14]. These parameters serve as critical criteria for material selection and form the foundation for subsequent mesoscopic parameter selection and calibration in PFC modeling.

In terms of testing methods, the density parameters were obtained through powder density and bulk density measurements to evaluate the material's compactness in its natural piled state; the angle of repose was determined via free-piling tests to analyze flowability differences among various powders; the internal friction angle was measured using direct shear tests to characterize shear and friction resistance between powder particles; particle size distribution was determined by screening tests combined with microscopic observation of particle morphology; the equivalent elastic modulus was derived from static triaxial tests on loose powder beds, reflecting the material's overall stress-deformation behavior under confining pressure. These tests collectively form a parameter system encompassing both fundamental physical properties and macroscopic mechanical responses of powder materials, providing critical input for subsequent development of the powder damper (PFC) model and analysis of hysteresis behavior.

Based on the aforementioned experimental materials and testing methods, this paper establishes a medium parameter system for analyzing powder dampers. Through comparative tests conducted under unified conditions on five types of powder media, the study systematically elucidates the potential influences of varying densities, fluidity, friction characteristics, and deformation stiffness on the hysteresis behavior of powder dampers, thereby laying the foundation for material parameter calibration and cyclic loading analysis in subsequent PFC models.

2.2 Test Results of Mechanical Properties of Powder Media

2.2.1 Analysis of Density and Particle Size Distribution Results

The experimental results demonstrate significant differences among the various powder materials in terms of density and particle size distribution. The densities of each powder are listed in Table 1.

Table 1: Dry density and Natural Density of Powder

material	Silt	sand	Ferric oxide	ferrous powder	Talcum powder
Dry density (g/cm ³)	2.60	2.45	6.17	7.18	2.75
Specific density (g/cm ³)	1.30	1.50	2.70	2.2	0.45

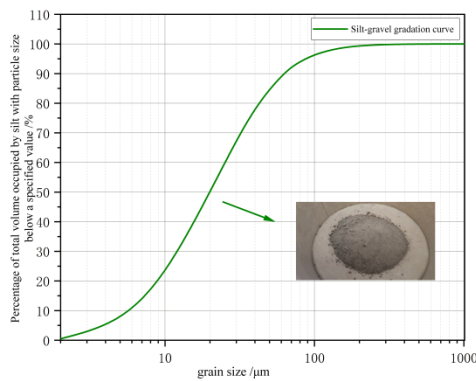
Overall, ferrous trioxide and iron powder are high-density powders, with iron powder exhibiting the highest density, indicating greater mass and inertial effects under the same volume conditions; talcum powder has the lowest bulk density, suggesting a higher porosity and a relatively loose structure in its natural accumulation state. For powder dampers, higher material density enhances the inertial response and contact strength of the particle system under cyclic loads, thereby improving the damper's load-bearing capacity and energy dissipation potential.

The particle size distribution test results further reveal the particle size characteristics of different materials. Using the screening method, we measured the particle size distributions of various powder materials and plotted their particle size distribution curves; Figure 2 shows the distribution curves for five powders. As indicated in Table 2, sand exhibits the largest average particle size (0.81 mm) with a distribution range of 0.50–1.20 mm, classifying it as a coarse-grained material; talc powder has the smallest average particle size (0.010 mm) with a range of 0.0022–0.042 mm, representing a typical fine powder; iron oxide and iron powder have average particle sizes of 0.099 mm and 0.087 mm

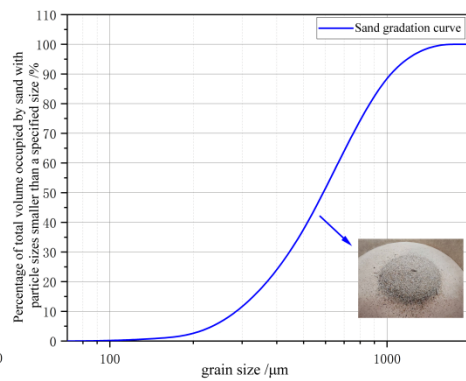
respectively, falling between sand and fine powders; clay powder has an average particle size of 0.046 mm. Particle size distribution directly influences a powder's fluidity, Stacking behavior, and particle contact patterns: coarse-grained materials tend to exhibit pronounced collision effects, while fine-grained materials demonstrate stronger compaction and reorganization characteristics. From a particle size distribution perspective, sand is more conducive to energy dissipation dominated by particle collisions, whereas talc powder typically exhibits response mechanisms characterized by fine particle sliding and localized reorganization.

Table 2: Summary Table of Particle Size Distribution

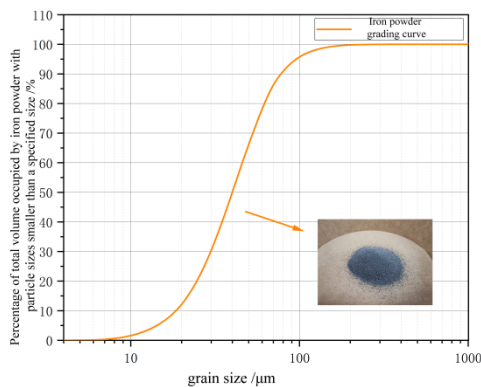
dusty materials	Maximum particle size (mm)	Minimum particle size (mm)	Average particle size (mm)	Particle size distribution range
soil	0.070	0.002	0.046	0.002–0.070
Sand (silicon dioxide)	1.20	0.50	0.81	0.50-1.20
Ferric oxide	0.32	< 0.045	0.099	< 0.045-0.32
ferrous powder	0.212	< 0.045	0.087	< 0.045-0.212
Talcum powder	0.042	0.0022	0.010	0.0022–0.042



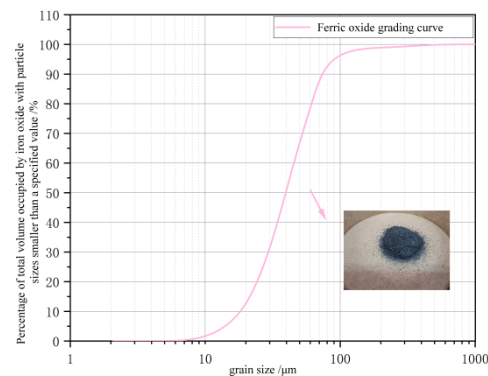
a) Loam gradation curve



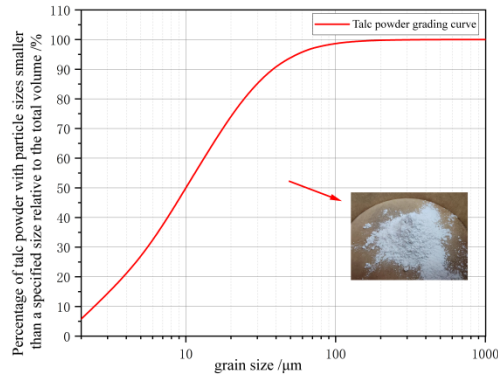
b) Sand gradation curve



c) Iron powder particle size distribution curve



d) Iron oxide (Fe₂O₃) grading curve



e) Talc powder grading curve

Figure 2: Particle Size Distribution Curves of Five Powder Samples

2.2.2 Analysis of the Results for the Frenetic Angle and Internal Friction Angle

The results of the static angle test are presented in Table 3, showing significant differences in fluidity among the five powder materials under natural loose-piling storage conditions. The angles of repose for silty soil, sand, iron powder, ferrous oxide, and talc powder were 35 °, 31 °, 36 °, 38 ° and 47 °, respectively. Sand exhibited the smallest angle of repose, indicating superior fluidity and weaker particle interlocking effects. Talc powder demonstrated the highest angle of repose, suggesting poorest fluidity and increased tendency for particle agglomeration. Silty soil, iron powder, and ferrous oxide exhibited intermediate values. For powder dampers, media with a smaller angle of repose are more prone to flow and structural reorganization during filling, whereas media with a larger angle of repose can more effectively maintain localized stacking structures, thereby exhibiting enhanced stacking stability.

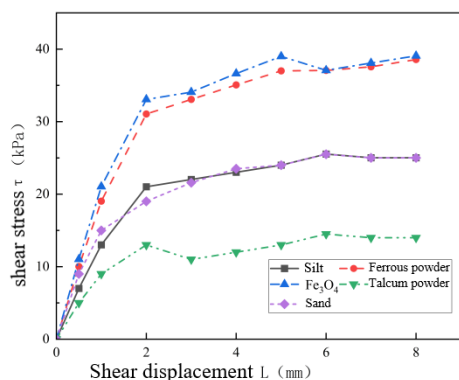
Table 3: Results of angle of repose measurement

material	Silt	sand	ferrous powder	Ferric oxide	Talcum powder
angle of repose (°)	35	31	36	38	47
Static friction angle (°)	30	27	26	28	32
friction factor	0.58	0.51	0.49	0.53	0.62

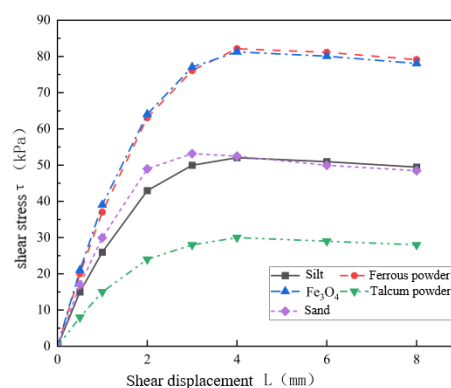
The direct shear test results indicate that the differences in shear strength among materials primarily manifest in their internal friction angles. Figure 3 illustrates the relationships between powder shear stress and shear displacement under varying normal pressures, as well as the relationship between shear strength and vertical pressure. Based on the Mohr-Coulomb strength theory criterion, the internal friction angle φ and cohesion μ were determined. The internal friction angles and cohesion values for each powder are presented in Table 4. Overall, iron powder and ferric oxide exhibited the highest internal friction angles, reflecting stronger interparticle interlocking and frictional effects that reduce relative slip during shear processes, thereby demonstrating higher frictional energy dissipation potential. Silty soil and sand exhibited moderate internal friction angles, while talc powder showed the lowest value, indicating weaker interparticle shear resistance. The results of the contact angle measurements indicate that although talc powder exhibits strong stacking stability, its effective interparticle frictional load-bearing capacity is relatively low. In contrast, iron powder and ferric oxide possess both high density and a large internal friction angle, which facilitates the formation of stable force chains and frictional energy dissipation pathways within the damper.

Table 4: Table of Shear Strength Parameters for Powder Materials

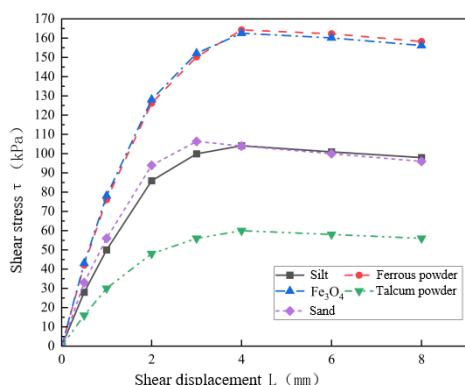
material	internal friction angle ϕ (°)	Cohesion c (kPa)
soil	27.5	1.32
Silica (sand)	28.0	0.232
Ferric oxide	39.1	0.11
ferrous powder	39.4	0.164
Talcum powder	16.7	0



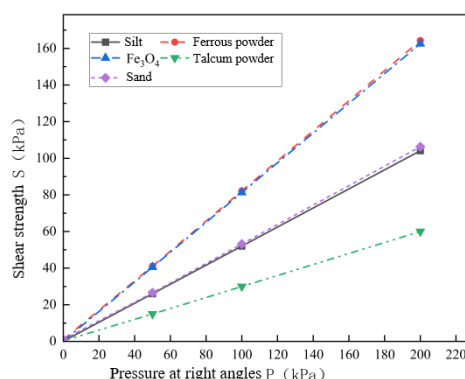
a) The relationship between shear stress and shear displacement at 50 kPa



b) The relationship between shear stress and shear displacement at 100 kPa



c) Relationship between shear stress and shear displacement at 100 kPa



d) Relationship between shear strength and vertical pressure

Figure 3: Relationships between shear stress and shear displacement, and between shear strength and normal stress under different σ_n

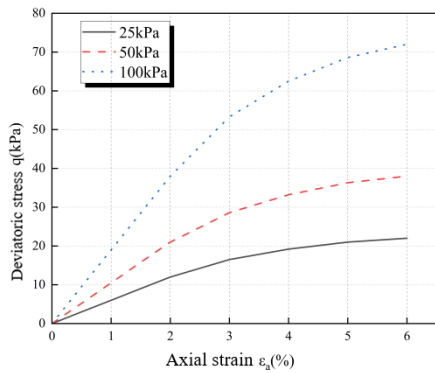
2.2.3 Analysis of Equivalent Elastic Modulus Results

Figure 4 shows the static triaxial tests conducted on a loose powder bed. The equivalent elastic modulus of all materials increased with rising confining pressure, indicating that confining pressure significantly enhances the overall stiffness of the powder bed. Under the $q = a\varepsilon_a + b$ three confining pressure conditions of 25 kPa, 50 kPa, and 100 kPa, the equivalent elastic modulus of all five materials exhibited an increasing trend. By performing linear fitting on the partial stress–axial strain data points and the data points within the 0.2%–2.0% axial strain range using the specified formula, the equivalent elastic moduli of silt, sand, iron oxide (Fe_2O_3), iron powder, and talc powder were obtained, as shown in Table 5. These results demonstrate that iron powder and iron oxide exhibit

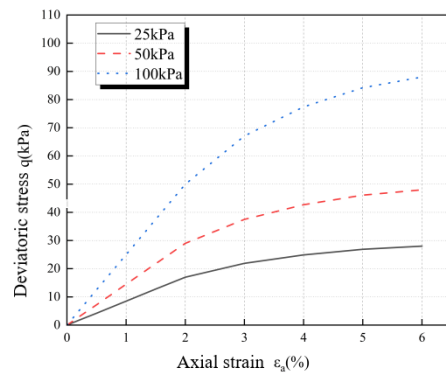
the highest overall compressive stiffness, while talc has the lowest, with silt and sand falling in the intermediate range.

Table 5: Calculated results of the equivalent elastic modulus of each material under different confining pressures

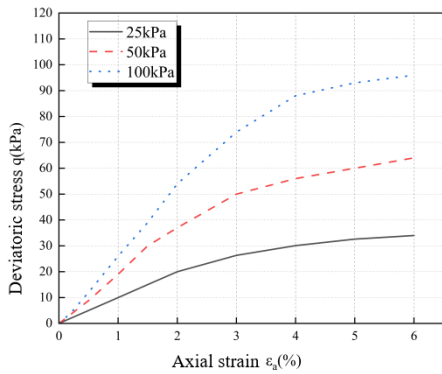
material	Silt (MPa)	sand (MPa)	Ferric oxide (MPa)	ferrous powder (MPa)	Talcum powder (MPa)
25kPa	0.60	0.85	1.00	1.10	0.35
50kPa	1.05	1.45	1.75	1.90	0.60
100kPa	1.85	2.50	3.00	3.20	1.10



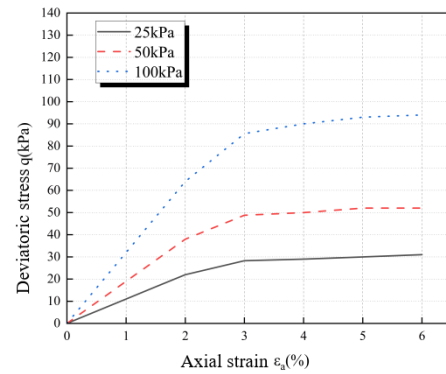
a) Relationship curve between soil powder bias stress and axial strain



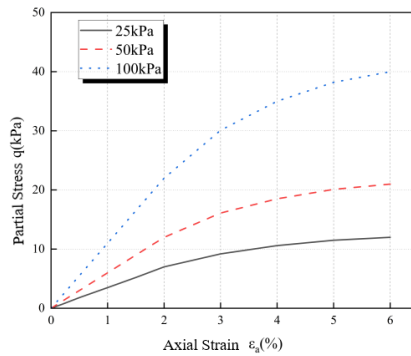
b) Sand shear stress-axial strain relationship curve



c) Partial stress-axial strain relationship curve for ferric trioxide



d) Relationship curve between iron powder shear stress and axial strain



e) Relationship curve between talc powder bias stress and axial strain

Figure 4: Deviatoric stress-axial strain relationships of five powder samples

3. Establishment of the PFC Model and Parameter Calibration

3.1 Establishment of the Powder Filler Coefficient (PFC) Particle Model

To analyze the influence of mesoscopic parameters of powder media on damper hysteresis performance, this study employs the discrete element software PFC2D to establish a numerical model of powder media. The model is based on experimentally obtained macroscopic parameters including density, angle of repose, internal friction angle, particle size distribution, and equivalent elastic modulus, while selecting mesoscopic parameters such as particle density, particle size distribution, contact stiffness, and friction parameters. The Hertz–Mindlin contact model is adopted to describe interactions between particles and between particles and boundaries [15]. Particle systems are generated according to particle size distribution results, and after density assignment, numerical cycling, and damping treatment, a stable stacking state is formed as the initial operating condition for subsequent analysis. Considering the irregularity of actual particle shapes, equivalent spherical particles are used in the model with rolling friction parameters introduced for approximate characterization [16]. Given the non-strict one-to-one correspondence between macroscopic and mesoscopic parameters, this study adopts a method combining experimental data constraints and numerical response verification for parameter calibration, providing a foundation for subsequent analysis of damper hysteresis performance.

3.2 Parameter Selection and Loading Conditions

This study employs iron powder as the filling medium for a powder damper. Model parameters were determined based on experimental results from previous research, with the equivalent elastic modulus under 50 kPa confining pressure serving as the reference value for medium compression stiffness. A two-dimensional numerical model was established featuring an outer cylinder with an equivalent inner diameter of 70 mm, a powder working chamber effective length of 240 mm, a damping head diameter of 50 mm, and a displacement amplitude of ± 20 mm. The model was subjected to cyclic displacement loading at 0.2 Hz, with fixed boundary conditions applied to the sidewalls and base, while the damping head served as a moving boundary for excitation. By extracting displacement data and resultant contact forces from the damping head, a force-displacement hysteresis curve was obtained. The output power and energy dissipation performance were analyzed, with component dimensions and initial model positions detailed in Table 6.

Table 6: Component Dimensions and Initial Position

Parameter Name	symbol	Number/Range	unit
Equivalent inner diameter of the outer cylinder (cavity height)	H	70	mm
working length of outer cylinder section	L	320	mm
guiding guide length (per end)	L_{guide}	40	mm
Effective length of the powder working chamber	L_{active}	240	mm
Diameter of the damping head	D_h	50	mm
Initial position of the damping head	x_0, y_0	$x_0=90, y_0=35$	mm
Amplitude of damping head displacement	A	± 20	mm

3.3 Setting of iron powder contact parameters

To compare the effects of different powder materials as filling media on the hysteresis performance of dampers, this study calibrated the parameters of the powder damper PFC model based on experimental data-including density, angle of repose, internal friction angle, particle size distribution,

and equivalent elastic modulus-for silt, sand, iron oxide (Fe_2O_3), iron powder, and talc powder.

Regarding contact parameter settings, this study employs iron powder as the sole filling medium and establishes a unified contact parameter system for particles themselves and their interactions with the wall surface. Considering that the contact between the damper wall and iron powder particles primarily involves normal compression, tangential sliding, and rolling resistance [17], the model uniformly defines these contact parameters to ensure numerical consistency between boundary contact behavior and particle contact behavior. The Poisson's ratio is uniformly adopted as an auxiliary contact parameter, while recovery characteristics, sliding friction characteristics, and rolling friction characteristics are determined based on iron powder material properties and model calibration requirements [18]. Through these approaches, the contact, sliding, rolling, and energy dissipation behaviors of the iron powder particle system under cyclic loading can be accurately characterized while maintaining model simplicity and computational stability. The parameter settings for powder particle generation and related physical properties are presented in Table 7.

Table 7: Generation of iron powder particles and assignment of physical properties

Parameter Name	symbol	Number/Range	unit
granular materials	/	ferrous powder	/
particle shape	/	Equivalent circular particles	/
Particle radius range	r	75-150	μm
particle density	ρ	7.18	g/cm^3
angle of repose	θ	36	$^\circ$
Particle Restoration Coefficient	e	0.64	/
Elastic modulus (confined pressure 50 kPa)	E	1.90	MPa
internal friction angle	φ	26	$^\circ$
cohesive strength	c	0.164	kPa
coefficient of sliding friction	μ	0.49	/
coefficient of rolling friction	μ_r	0.50	/
Poisson's ratio	v	0.25	/

4. Effect of Powder Media Parameters on the Hysteresis Performance of the Damper

4.1 Comparison of Hysteresis Curves for Different Powder Materials

Under identical structural dimensions, loading conditions, and cyclic loading scenarios, the force-displacement hysteresis curves during the stable cyclic phase of the damper were obtained when using silt, sand, ferric oxide, iron powder, and talc powder as filling media, and compared and analyzed as shown in Figure 5.

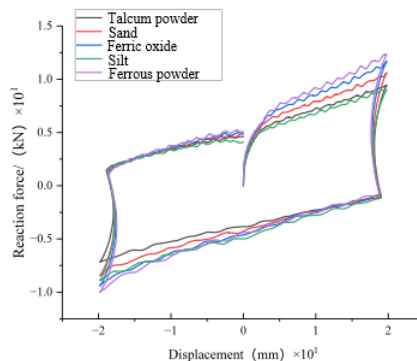


Figure 5: Comparison of the hysteresis curves of five powders

The results demonstrate that all curve sets formed relatively complete closed loops, exhibiting a full rounded closure profile, indicating that the dampers possess significant hysteresis energy dissipation capability under different powder material conditions. Additionally, the curves corresponding to different materials show variations in the main hysteresis segment's reaction force magnitude, loop area, and local fluctuation characteristics, highlighting the substantial influence of powder material parameters on particle contact, force transmission, and frictional energy dissipation processes.

As shown in the figure, the hysteresis curves of iron powder and ferric oxide are positioned on the outer side overall, with higher reaction force levels in their primary hysteresis segments—most pronounced for iron powder followed by ferric oxide. This indicates that high-density metal powders are more effective in enhancing the damper's reaction force output and overall load-bearing capacity. The hysteresis curve of sand lies centrally, demonstrating a balance between load-bearing capacity and energy dissipation. The curves for talc powder and clay are more inward-sloping with relatively lower reaction forces, reflecting weaker load-bearing capabilities. Additionally, all curves exhibit subtle serrated fluctuations during both the stable phase and cyclic region, attributable to local resistance and contact state adjustments during cyclic loading. In summary, while different powder materials do not alter the fundamental type of the damper's hysteresis curve, they influence its specific morphology and mechanical response: iron powder and ferric oxide exhibit higher reaction forces and more pronounced hysteresis characteristics, sand falls in the middle, while talc powder and clay perform relatively poorly.

4.2 Determination of the Reference Filling Medium

The comparison of hysteresis curves for different powder materials in Section 4.1 reveals significant differences in how the five powder media affect the damper's hysteresis performance. Specifically, the curves for iron powder and ferric oxide generally lie further outward, exhibiting higher reaction forces and demonstrating strong load-bearing capacity; sand shows a moderate hysteresis response with both load-bearing and energy-dissipating characteristics; while the curves for talc powder and silt are more inward-sloping, exhibiting relatively lower reaction forces. These results indicate that although different powder materials do not alter the fundamental type of the damper's hysteresis curve, they significantly influence its specific morphology, reaction force output, and energy dissipation characteristics.

Given that the subsequent research in this paper focuses on analyzing how changes in mechanical properties of powder materials affect the hysteresis performance of dampers, it is essential to select a representative material with a comprehensive parameter system as the analytical benchmark. Iron powder, as a typical metallic powder, exhibits high density, significant particle contact stiffness, and well-established parameter characteristics. These attributes not only accurately reflect the load-bearing behavior of high-density powder media within dampers [19] but also facilitate single-factor parameter adjustment analysis under unified modeling conditions. Therefore, iron powder is chosen as the reference filling medium for subsequent parameter sensitivity analysis in this study.

4.3 Parameter Sensitivity Analysis of Powder Media

Based on the aforementioned material comparisons, this study selects iron powder as the reference filling medium. While maintaining constant damper geometric dimensions, loading conditions, and loading parameters, single-factor adjustments are made to its key mechanical performance parameters to analyze how varying parameters affect the hysteresis curve of the powder damper. Specifically, using the measured parameters of iron powder as baseline and referencing the variation ranges of corresponding parameters for silt, sand, ferric oxide, and talc powder, adjustments are applied to

density, equivalent elastic modulus, particle size distribution, friction coefficient, and cohesion force. This enables an examination of the trends in hysteresis curve morphology, peak reaction force, and loop area. The methodology allows for the identification of how sensitive different mechanical parameters are to the damper's response without altering the material composition itself, as shown in Table 8.

Table 8: The Sensitivity of Different Mechanical Parameters to the Dämpfer Response

Parameter Name	Adjustment Method	adjustment range
density ρ	magnify	+5%
friction factor μ	magnify	+10%
cohesion c	magnify	+10%
Equivalent elastic modulus E_{eq}	magnify	+10%
grain composition	optimize	continuous grading

As shown in Figure 6, when using the iron powder's reference parameters as a benchmark, the impact and affected regions of various mechanical parameter adjustments on the powder damper's hysteresis curve exhibit significant variations, generally demonstrating a more sensitive response in the central region and relatively stable responses at the edges.

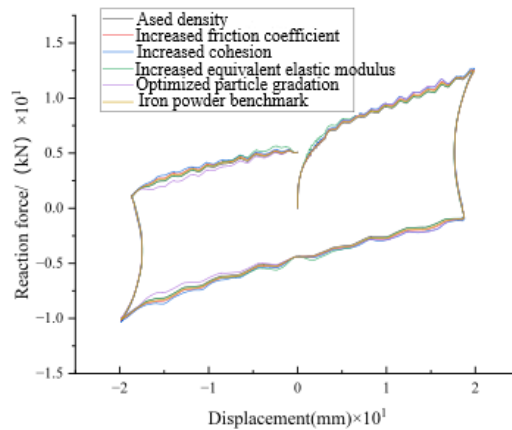


Figure 6: Comparative plot of powder parameter sensitivity analysis

Specifically, upon increasing density, the hysteresis curve exhibits only a slight outward expansion in the central annular section, with minimal changes in the peripheral edge regions. This indicates that density increase primarily enhances contact interactions within the particle system during the main stress-bearing phase, resulting in a modest rise in mid-section reaction forces. As the friction coefficient increases, the annular area of the primary energy-dissipating zone expands significantly, while the peripheral section remains largely unchanged, demonstrating that the elevated friction coefficient primarily enhances frictional slip energy dissipation between particles—thereby directly improving single-cycle energy dissipation efficiency. When cohesion increases, curve variations concentrate mainly near the origin and the central transition zone, with minimal overall contour changes, suggesting limited impact on peak reaction forces; its effect primarily manifests in improved particle contact continuity and localized deformation constraints. With an increased equivalent elastic modulus, the slope of the mid-hysteresis curve rises markedly, indicating enhanced overall compressive stiffness of the particle system and improved damper load-bearing capacity, though the improvement in annular area remains relatively limited. Post-grading optimization yields a more robust and smoother hysteresis curve, demonstrating that optimized particle gradation enhances stacking compactness and coordinated force transmission, thereby strengthening hysteresis response stability.

In summary, different parameters exhibit distinct roles in influencing the hysteresis curve: density and equivalent elastic modulus primarily affect the damper's load-bearing capacity and stiffness response; the friction coefficient mainly controls the hysteresis loop area and energy dissipation level; cohesive force regulates local response and stability; while particle size distribution optimization enhances overall coordination and stability. Therefore, if the goal is to improve energy dissipation capability, priority should be given to the friction coefficient and particle size distribution; if the objective is to enhance load-bearing capacity and stiffness response, adjustments to density and equivalent elastic modulus should be emphasized.

5. Conclusion

This paper investigates the material properties testing of powder damper filling media and PFC hysteresis analysis, with the main conclusions summarized as follows.

(1) By conducting comprehensive parameter tests on five powdered materials-including silty soil, sand, iron(III) oxide, iron powder, and talc powder-covering density measurements, angle of repose, particle size distribution, shear strength, and equivalent elastic modulus, a fundamental physical-mechanical parameter system for powdered media was established. The study reveals significant variations among different powder materials in terms of density, fluidity, friction characteristics, and overall stiffness. These differences directly influence the output performance, hysteresis curve morphology, and cyclic stability of powder dampers, providing critical data for selecting optimal filling media and determining discrete element parameters in damping system design.

(2) Under identical geometric dimensions, loading conditions, and cyclic loading scenarios, when the measured parameters of the five powder materials were input into the powder damper PFC model, the resulting hysteresis curves exhibited significant differences. Overall, high-density, high-stiffness materials are more conducive to enhancing the damper's peak reaction force and equivalent stiffness, while materials with high friction characteristics are more effective in expanding the hysteresis loop area and improving energy dissipation capacity. This indicates that the influence of different powder materials on the damper's hysteresis performance is not determined by a single parameter but rather results from the combined effects of load-bearing stiffness characteristics and frictional energy dissipation characteristics.

(3) Taking into comprehensive consideration the continuity of subsequent analyses, the completeness of the parameter system, and material representativeness, this study selects iron powder as the reference filling medium for subsequent parameter sensitivity analyses. As a typical metal powder, iron powder exhibits high density, significant particle contact stiffness, and well-established parameter characteristics. It not only effectively reflects the load-bearing behavior of high-density powder media in dampers but also facilitates single-factor parameter adjustment analyses under unified modeling conditions.

(4) In the parameter sensitivity analysis using iron powder as the reference filling medium, different mechanical parameters exhibit distinct effects on the hysteresis behavior of the powder damper. Specifically, increases in density and equivalent elastic modulus primarily enhance the mid-section reaction force and stiffness response; higher friction coefficients mainly expand the hysteresis loop area and improve energy dissipation capacity; cohesive force primarily influences response stability near the origin and in the central transition zone; while optimized particle size distribution enhances the fullness and smoothness of the hysteresis curve. Overall, optimization of powder damper filling medium parameters should balance load-bearing capacity, energy dissipation capability, and response stability, with friction coefficient and particle size distribution being particularly critical for energy dissipation performance improvement, whereas density and equivalent elastic modulus significantly contribute to load-bearing capacity and stiffness enhancement.

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