

TECHNICAL MEMO



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To: PFC Documentation Set
From: David Potyondy
Re: Material Modeling Support for PFC: Example Materials [mmPkg9.4]
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The Material Modeling support package supports creation and testing of granular (linear and Hill) and bonded (contact-bonded, parallel-bonded, soft-bonded, and flat-jointed) materials. Examples of the creation and testing of each material are provided here. Each example serves as a base case and provides a material at the lowest resolution sufficient to demonstrate system behavior. There is a project for each material, and these projects are in the **mmPkg9.N/ExampleProjects2D** and **mmPkg9.N/ExampleProjects3D** directories, where **N** is the package subversion number. The directories are **mg_M** where **M** is the material type.

This memo is an extension of the base memo "Material Modeling Support for PFC". All citations in this memo are listed in the REFERENCES section of the base memo.

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1.0 GRANULAR MATERIALS

Granular materials use the linear and Hill contact models. Both 2D and 3D models are constructed with disk/sphere and clumped particles. The clumped materials are created by starting with the disk/sphere model and replacing the call to `mpParams.p2dat` in `MatGen.p2dvr` with a call to `mpParams-Clumped.p2dat`.

1.1 Linear Material (2D Disks and Clumps)

The 2D linear material example is in the `mg_linear2D` example-project directory. A 2D linear material (consisting of rigid unit-thickness disks) is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016). We denote our aggregate material as the AG_Linear2D material with microproperties listed in Table 1. The material has a median particle size of 8.8 mm. The 2D material is created in a rectangular-cuboid material vessel (of 240-mm height, 170-mm width and unit depth, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 1. The material is then subjected to compression testing. During the compression test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the effective resilient modulus (see Figure 2).¹ The hysteretic response is the expected behavior.

Table 1 Microproperties of AG_Linear2D Material

Property	Value
Common group:	
N_m	AG_Linear2D
$T_m, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	0, 0.7, 0, 2650
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {7,10,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 150, 1×10^{-2} , 8×10^{-3} , 2×10^6
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	0, 0.25, 0, 1.0
Linear material group:	
$E^* [\text{MPa}], \kappa^*, \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 3 of the base memo.

¹ The confinement is similar to that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

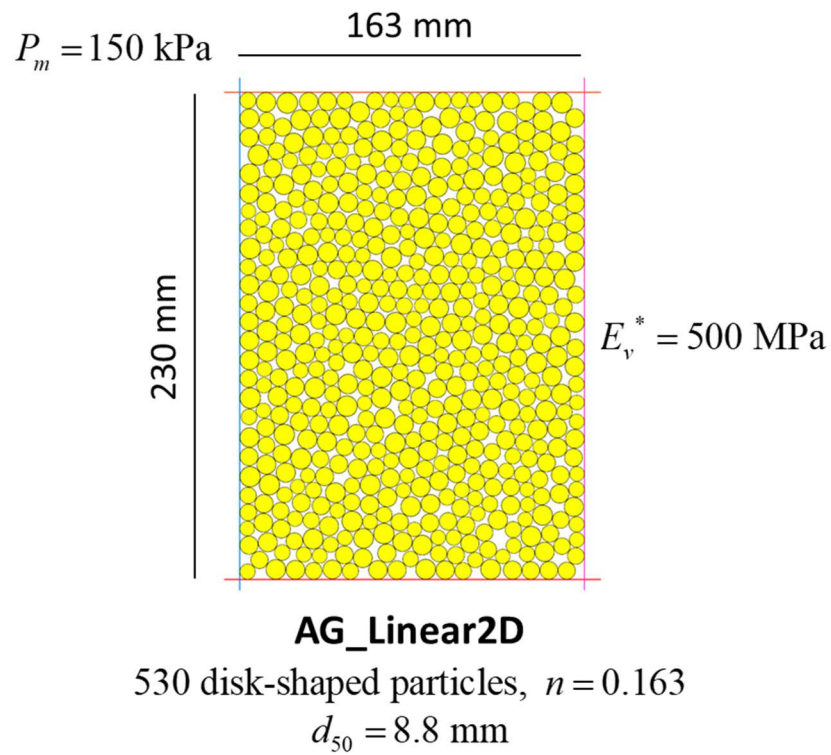


Figure 1 *AG_Linear2D material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

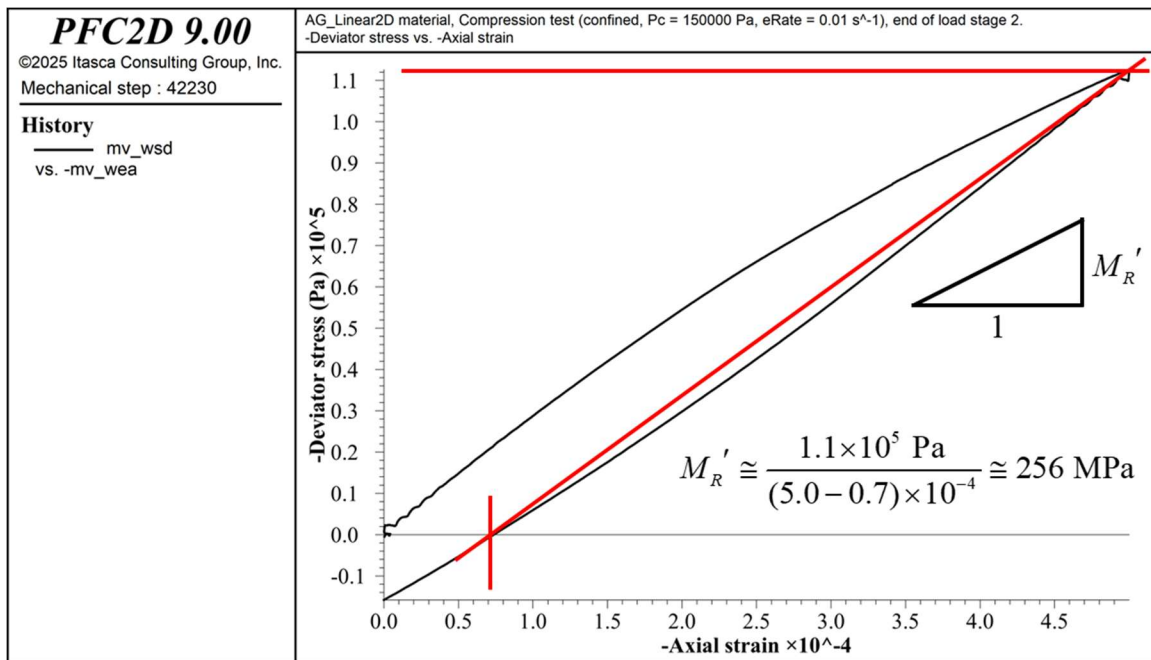


Figure 2 Deviator stress versus axial strain for AG_Linear2D material tested at 150 kPa confinement, and measurement of effective resilient modulus.

The 2D linear material example is modified to replace the disk-shaped particles with clumps by replacing the call to `mpParams.p2dat` in `MatGen.p2dvr` with a call to `mpParams-Clumped.p2dat`. The new material is denoted as a linear clumped material with microproperties listed in Table 2. The clumped material has two particle shapes. The first shape is a dyad consisting of two disk-shaped pebbles, and the second shape is a peanut consisting of three disk-shaped pebbles. The clumped particles are drawn from a uniform size distribution with diameters ranging from 7 to 10 mm, with 75% of the particles being dyads and 25% of the particles being peanuts. The material has a median particle size of 8.9 mm. The material-creation and testing procedures for the clumped material are the same as those for the AG_Linear2D material.

Table 2 Microproperties of AG_Linear2D Clumped Material

Property	Value
Common group:	
N_m	AG_Linear2D [clumped]
$T_m, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	0, 0.7, 0, 2650
$S_g, n_{SD}, T_{SD}, \{N_{cl}, D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	1, 2, 0, $\left\{ \begin{array}{l} \text{dyad, 7,10,0.75} \\ \text{peanut, 7,10,0.25} \end{array} \right\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 150, 1×10^{-2} , 8×10^{-3} , 2×10^6
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	0, 0.25, 0, 1.0
Linear material group:	
$E^* [\text{MPa}], \kappa^*, \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 2 of the base memo.

The 2D clumped material is created in a rectangular-cuboid material vessel (of 240-mm height, 170-mm width and unit depth, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 3. The porosity of the clumped material (0.127) is less than that of the disk-only material (0.163) — the dyads and peanuts have packed to a denser state than the disks. The material is then subjected to compression testing. During the compression test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the effective resilient modulus (see Figure 4). The hysteretic response is the expected behavior. The clumped material is stiffer (477 MPa) than the disk material (256 MPa), with increased stiffness attributed to reduced porosity.

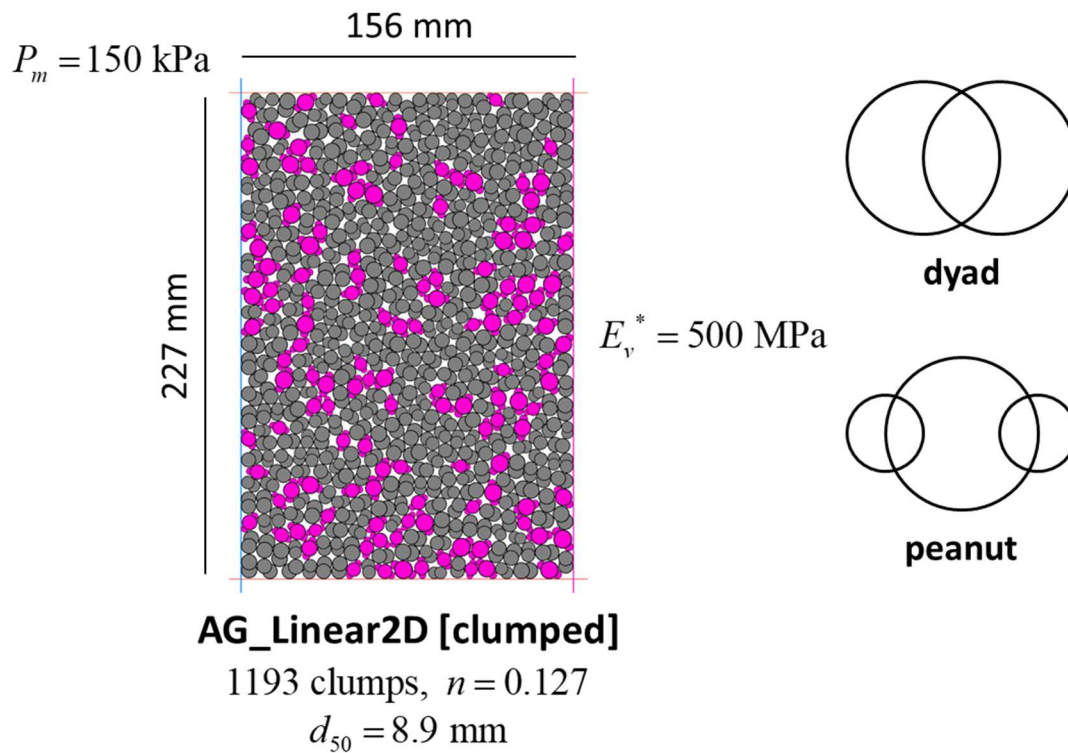


Figure 3 *AG_Linear2D clumped material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

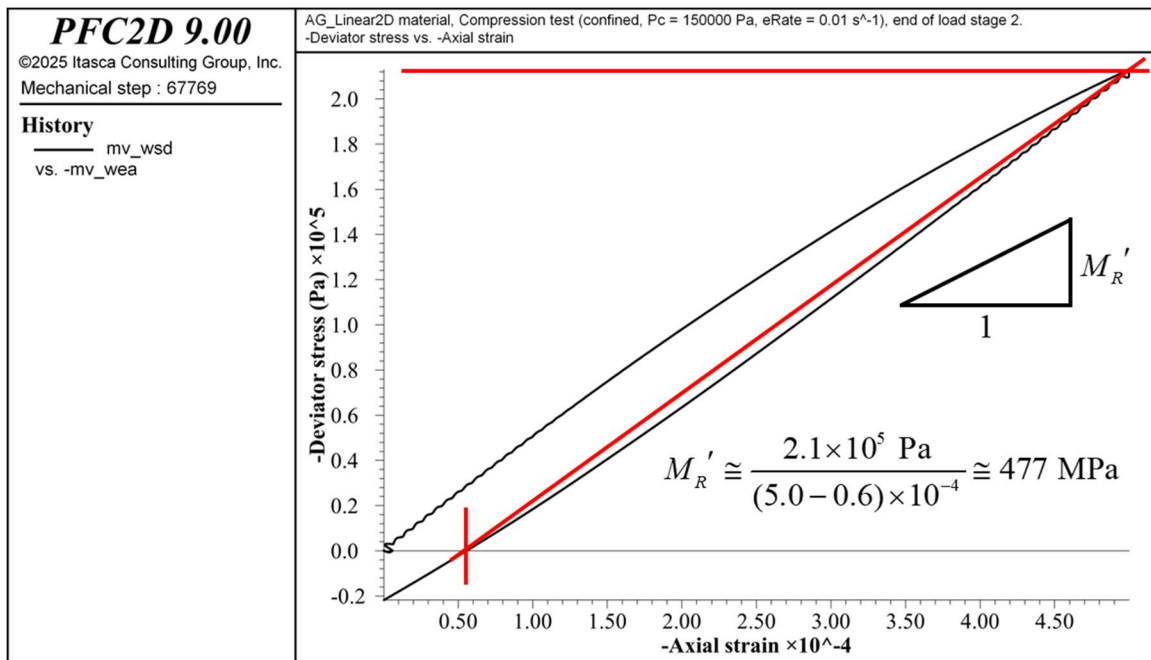


Figure 4 Deviator stress versus axial strain for AG_Linear2D clumped material tested at 150 kPa confinement, and measurement of effective resilient modulus.

1.2 Linear Material (3D Spheres and Clumps)

The 3D linear material example is in the `mg_linear3D` example-project directory. A linear material is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016). We denote our aggregate material as the AG_Linear material with microproperties listed in Table 3. The material has a median particle size of 17.8 mm. The material is created in a cylindrical material vessel (of initial 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure via the boundary-contraction packing procedure as shown in Figure 5. The material is then subjected to triaxial testing. During the triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus (see Figure 6).² The hysteretic response is the expected behavior.

² The confinement is similar to that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

Table 3 Microproperties of AG_Linear Material

Property	Value
Common group:	
N_m	AG_Linear
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	0, 0.7, 0, 2650
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {14,20,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 150, 1×10^{-2} , 8×10^{-3} , 2×10^6
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	0, 0.58, 0, 1.0
Linear material group:	
$E^* [\text{MPa}], \kappa^*, \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 3 of the base memo.

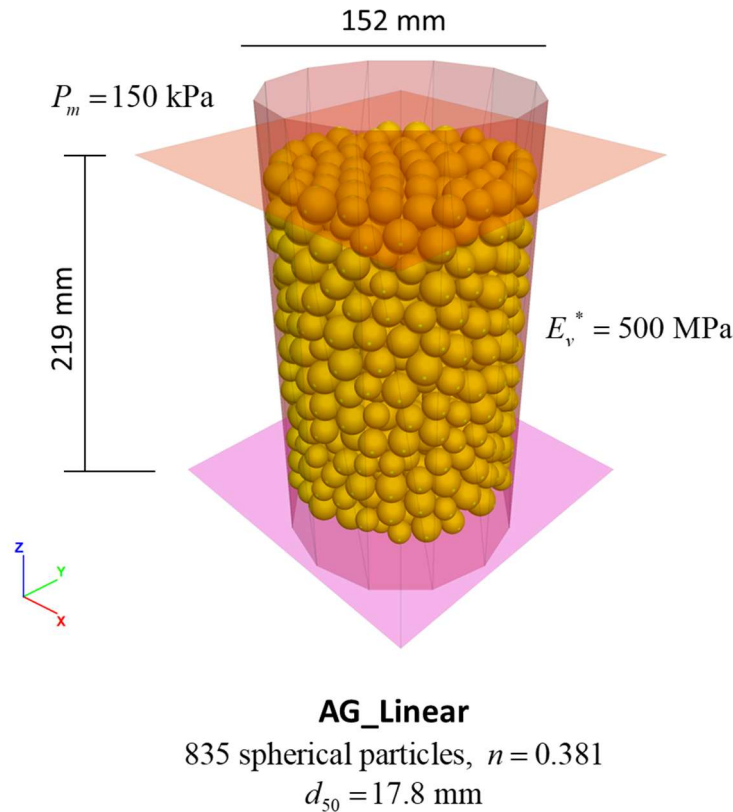


Figure 5 *AG_Linear material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

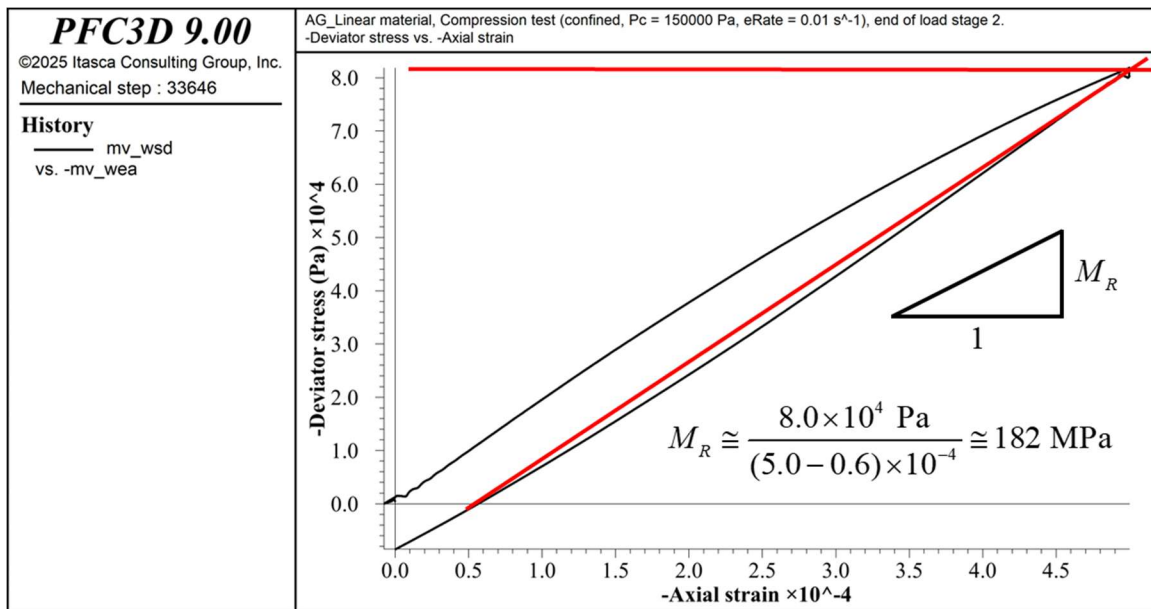


Figure 6 Deviator stress versus axial strain for AG_Linear material tested at 150 kPa confinement, and measurement of resilient modulus.

The 3D linear material example is modified to replace the spherical particles with clumps by replacing the call to `mpParams.p3dat` in `MatGen.p3dvr` with a call to `mpParams-Clumped.p3dat`. The new material is denoted as a linear clumped material with microproperties listed in Table 4. The clumped material has two particle shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles. The clumped particles are drawn from a uniform size distribution with diameters ranging from 14 to 20 mm, with 75% of the particles being dyads and 25% of the particles being peanuts. The material has a median particle size of 17.6 mm. The material-creation and testing procedures for the clumped material are the same as those for the AG_Linear material.

Table 4 Microproperties of AG_Linear Clumped Material

Property	Value
Common group:	
N_m	AG_Linear [clumped]
$T_m, \alpha, C_p, \rho \left[\frac{\text{kg}}{\text{m}^3} \right]$	0, 0.7, 0, 2650
$S_g, n_{SD}, T_{SD}, \{N_{ct}, D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	1, 2, 0, $\left\{ \begin{array}{l} \text{dyad, 14, 20, 0.75} \\ \text{peanut, 14, 20, 0.25} \end{array} \right\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 150, 1×10^{-2} , 8×10^{-3} , 2×10^6
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	0, 0.43, 0, 1.0
Linear material group:	
$E^* [\text{MPa}], \kappa^*, \mu$	500, 1.5, 0.4

* Linear material parameters are defined in Table 2 of the base memo.

The clumped material is created in a cylindrical material vessel (of initial 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure via the boundary-contraction packing procedure as shown in Figure 7. The porosity of the clumped material (0.344) is less than that of the spherical material (0.381) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to triaxial testing. During the triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient modulus (see Figure 8). The hysteretic response is the expected behavior, and the resilient modulus is similar to the effective modulus of the linear material. The clumped material is stiffer (308 MPa) than the spherical material (182 MPa), with increased stiffness attributed to reduced porosity.

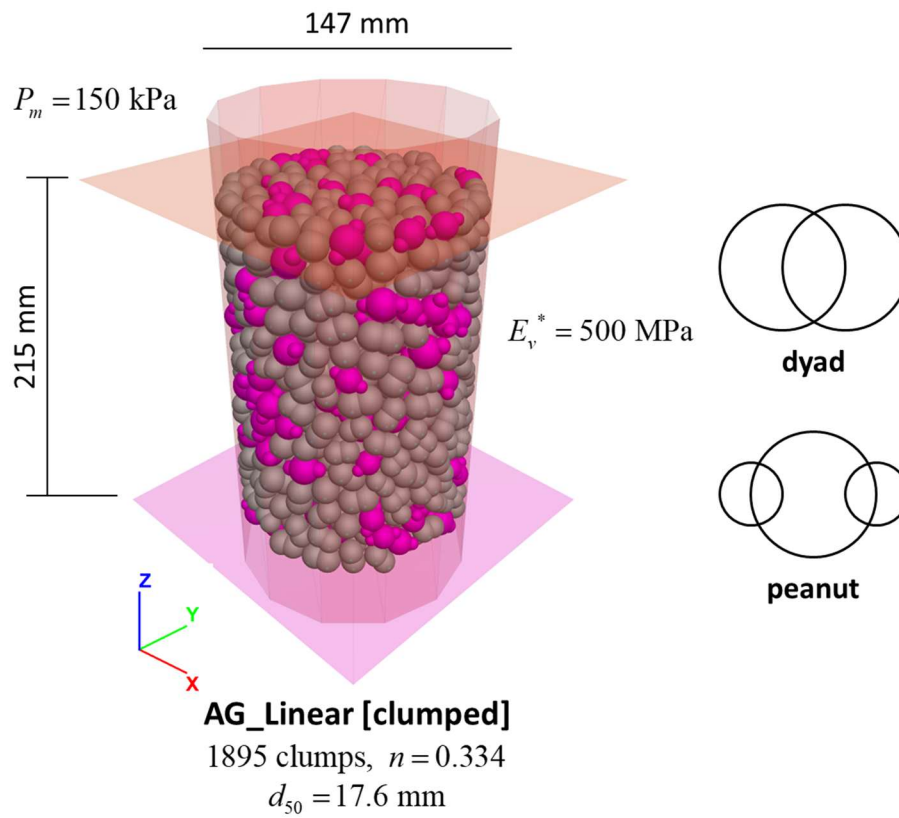


Figure 7 *AG_Linear clumped material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

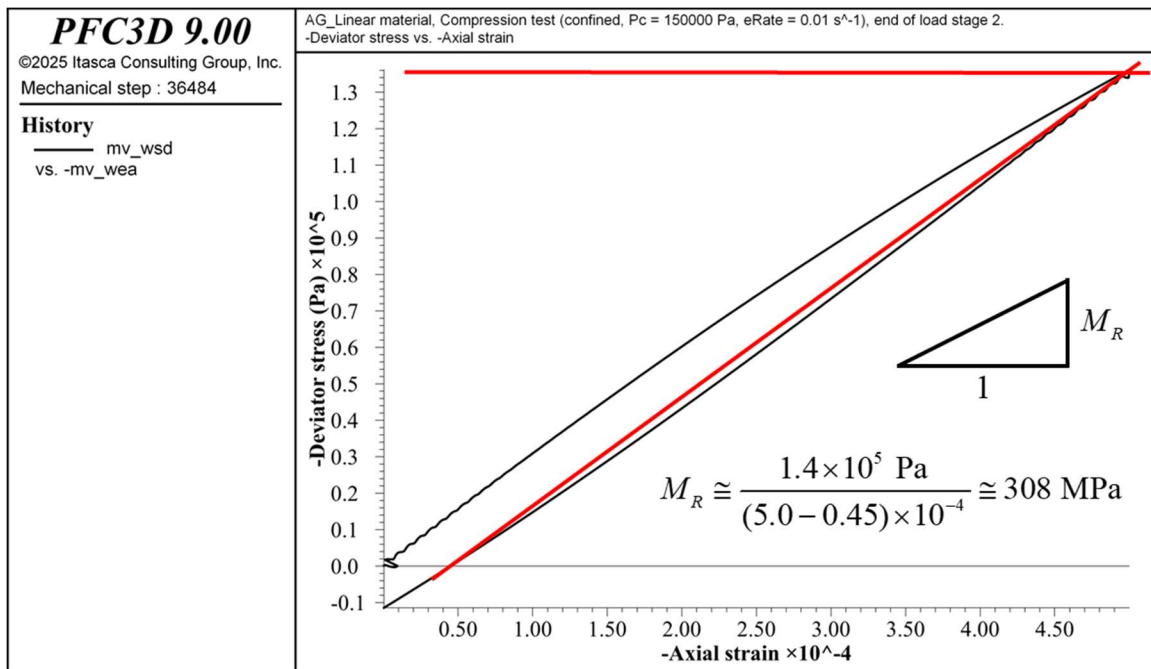


Figure 8 Deviator stress versus axial strain for AG_Linear clumped material tested at 150 kPa confinement, and measurement of resilient modulus.

1.3 Hill Material (3D Spheres and Clumps)

The Hill material example is in the `mg_hill3D` example-project directory. A hill material is created to represent a typical aggregate base layer of an asphalt-surface roadway (Potyondy et al., 2016). We denote our aggregate material as the AG_Hill material with microproperties listed in Table 5. The material has a median particle size of 17.8 mm. The material is dry while being created in a cylindrical material vessel (of 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 9. The material is then subjected to triaxial testing. The material is tested dry and wet. The wet material has a 20 kPa suction added between all particles that are within 3 mm of one another at the end of material genesis.³ During each triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient moduli of the dry and wet materials (see Figures 10 and 11).⁴ The hysteretic response is the expected behavior, and the resilient modulus is increased for the wet material.

Table 5 Microproperties of AG_Hill Material

Property	Value
Common group:	

³ The suction is typical for aggregates with gravimetric moisture content ranging from 5 to 10 percent.

⁴ The confinement is like that defined in resilient modulus laboratory protocols, and axial strains correspond with vertical strains in the aggregate base layer for typical traffic loads.

N_m	AG_Hill
$\{T_m, N_{cm}\}, \alpha, C_p, \rho_v [\text{kg/m}^3]$	$\{5, \text{hill}\}, 0.7, 0, 2650$
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	$0, 0, \{14, 20, 1.0\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	$10000, 150, 1 \times 10^{-2}, 8 \times 10^{-3}, 2 \times 10^6$
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	$0, 0.58, 0, 1.0$
Hill material group:	
$E_g [\text{GPa}], \nu_g, \mu, \alpha_h, \psi [\text{kPa}]$	$29, 0.15, 0.4, 0, 20$

* Hill material parameters are defined in Table 4 of the base memo.

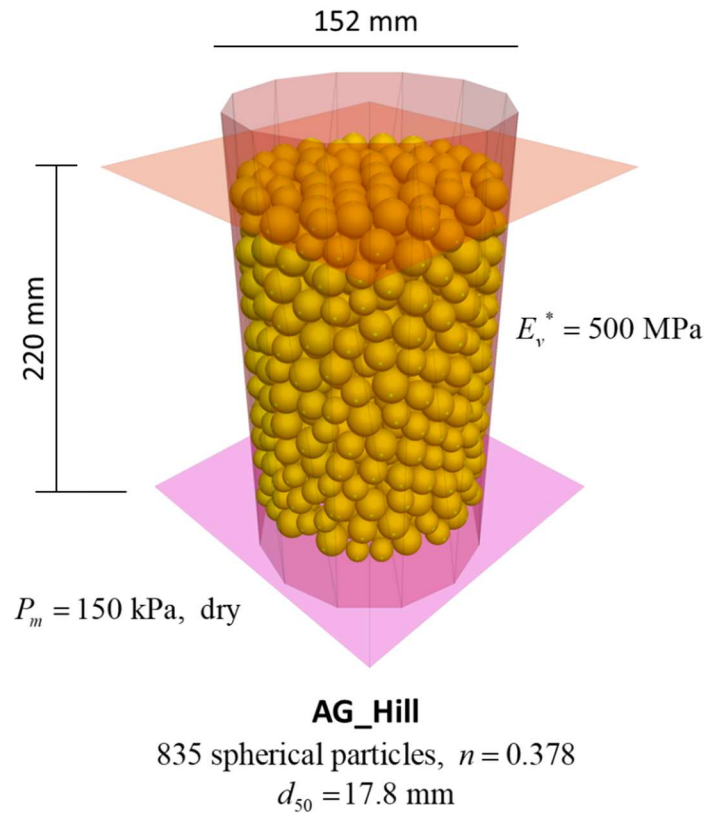


Figure 9 *Dry AG_Hill material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

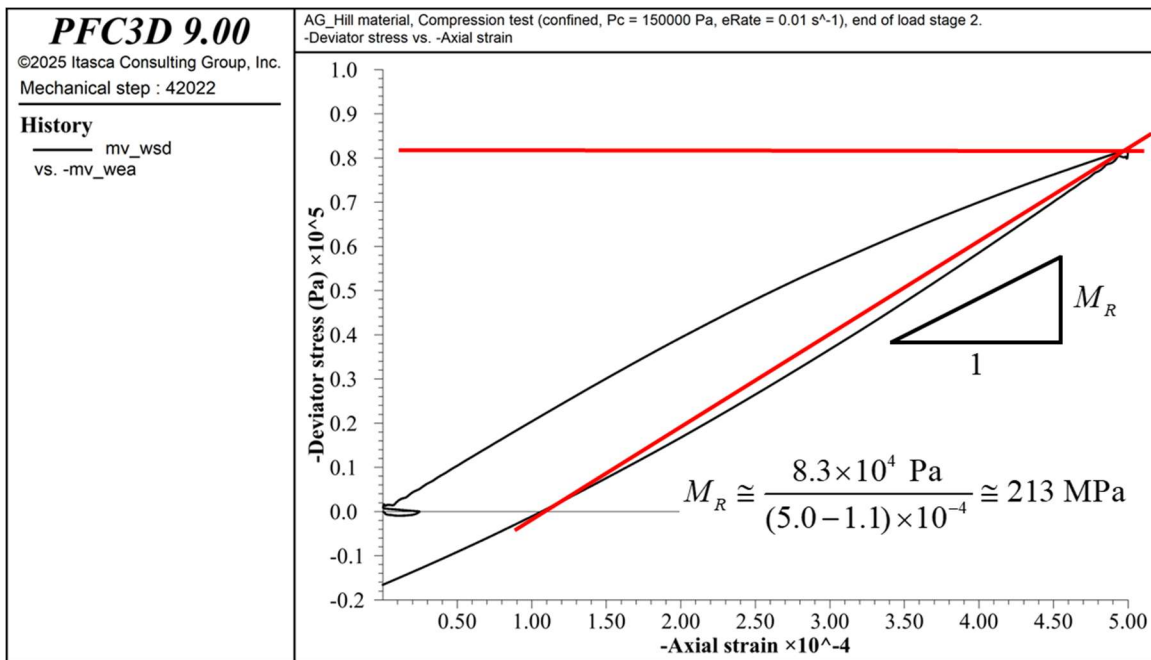


Figure 10 Deviator stress versus axial strain for dry AG_Hill material tested at 150 kPa confinement, and measurement of resilient modulus.

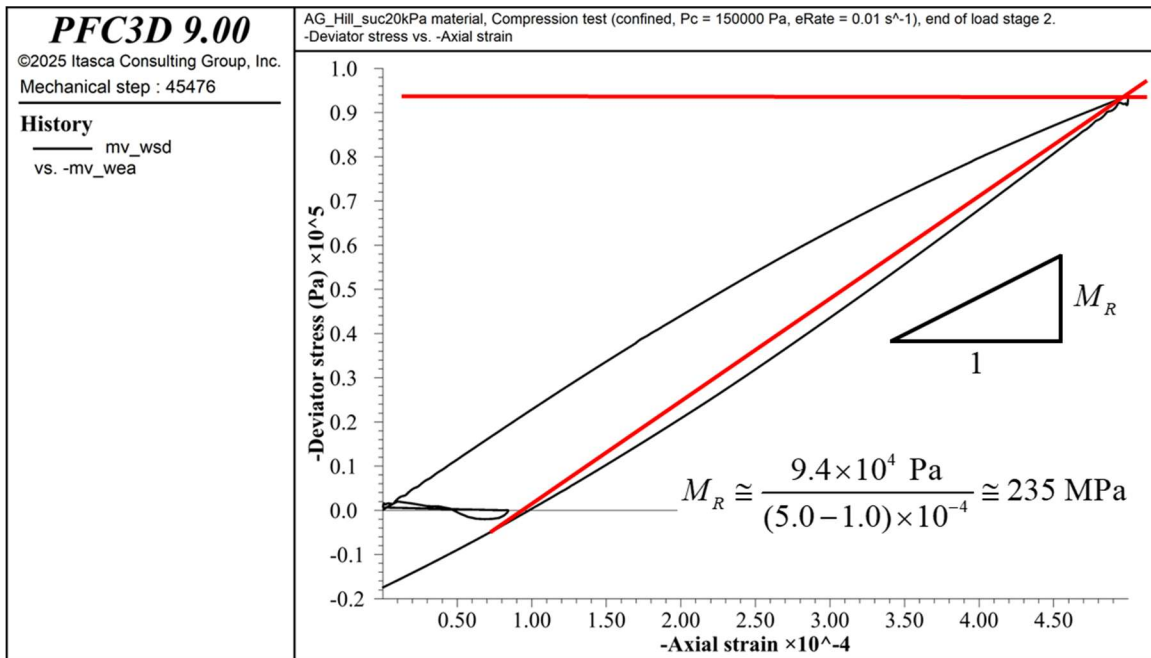


Figure 11 Deviator stress versus axial strain for wet AG_Hill material tested at 150 kPa confinement, and measurement of resilient modulus.

The Hill material example is modified to replace the spherical particles with clumps by replacing the call to `mpParams.p3dat` in `MatGen.p3dvr` with a call to `mpParams-Clumped.p3dat`. The new material is denoted as a Hill clumped material with microproperties listed in Table 6. The

clumped material has two particle shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles. The clumped particles are drawn from a uniform size distribution with diameters ranging from 14 to 20 mm, with 75% of the particles being dyads and 25% of the particles being peanuts. The material has a median particle size of 17.6 mm. The material-creation and testing procedures for the clumped material are the same as those for the AG_Hill material.

Table 6 Microproperties of AG_Hill Clumped Material

Property	Value
Common group:	
N_m	AG_Hill [clumped]
$\{T_m, N_{cm}\}, \alpha, C_p, \rho_v [\text{kg/m}^3]$	$\{5, \text{hill}\}, 0.7, 0, 2650$
$S_g, n_{SD}, T_{SD}, \{N_{ct}, D_{\{l,w\}} [\text{mm}], \phi\}, D_{mult}$	$1, 2, 0, \left\{ \begin{array}{l} \text{dyad, } 14, 20, 0.75 \\ \text{peanut, } 14, 20, 0.25 \end{array} \right\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{kPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	$10000, 150, 1 \times 10^{-2}, 8 \times 10^{-3}, 2 \times 10^6$
$C_p, n_c, \mu_{CA}, v_{lim} [\text{m/s}]$	$0, 0.43, 0, 1.0$
Hill material group:	
$E_g [\text{GPa}], \nu_g, \mu, \alpha_h, \psi [\text{kPa}]$	$29, 0.15, 0.4, 0, 20$

* Hill material parameters are defined in Table 3 of the base memo.

The clumped material is dry while being created in a cylindrical material vessel (of 240-mm height and 170-mm diameter, with a 500 MPa effective modulus) and packed at a 150 kPa material pressure as shown in Figure 12. The porosity of the clumped material (0.333) is less than that of the spherical material (0.378) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to triaxial testing. The material is tested dry and wet. The wet material has a 20 kPa suction added between all particles that are within 3 mm of one another at the end of material genesis. During each triaxial test, the confinement is 150 kPa, and a load-unload cycle is performed at an axial strain of 0.05% to measure the resilient moduli of the dry and wet materials (see Figures 13 and 14). The hysteretic response is the expected behavior, and the resilient modulus is increased for the wet material. The clumped material is stiffer (372 and 414 MPa) than the spherical material (213 and 235 MPa), with increased stiffness attributed to reduced porosity.

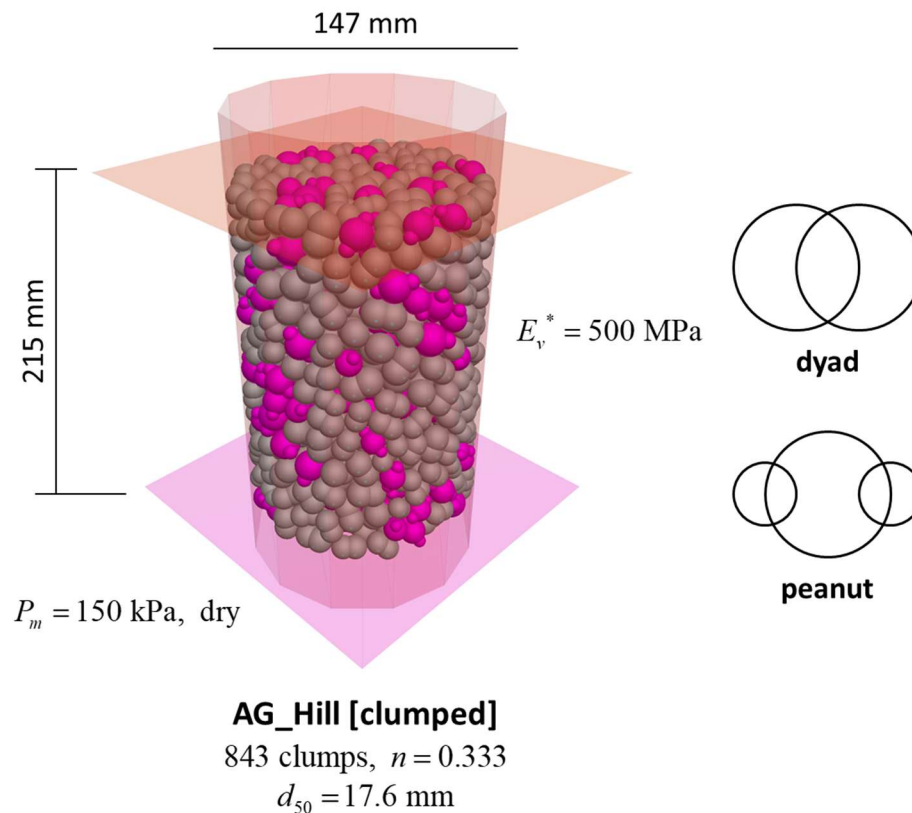


Figure 12 *Dry AG_Hill clumped material packed at 150 kPa material pressure at the end of material genesis. The height and diameter are less than the initial values because the boundary-contraction packing procedure has moved the walls inwards.*

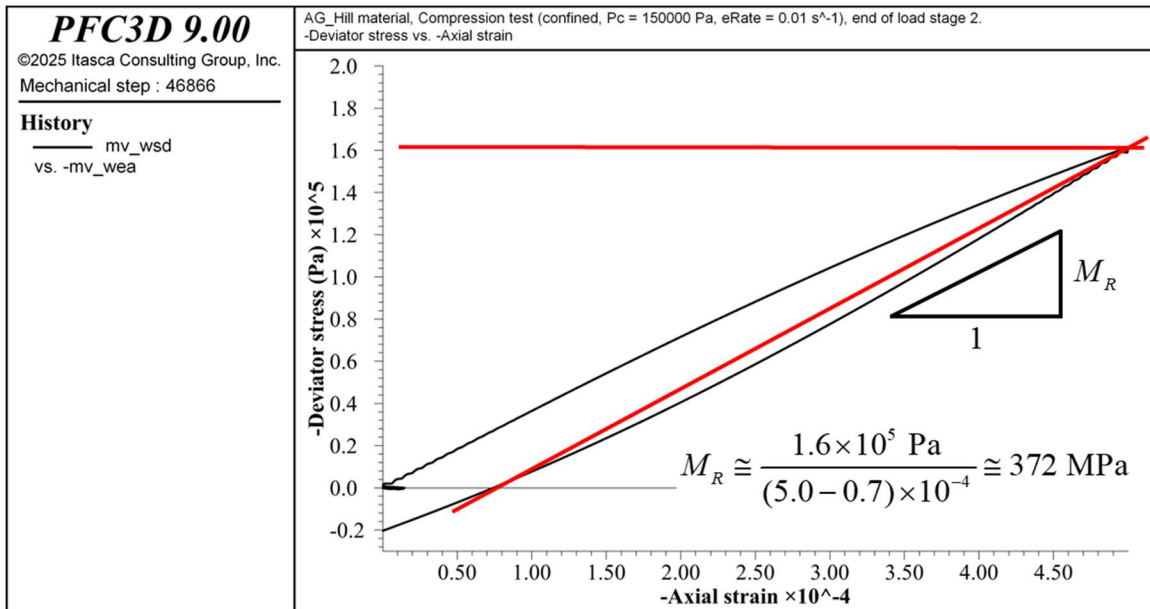


Figure 13 Deviator stress versus axial strain for dry AG_Hill clumped material tested at 150 kPa confinement, and measurement of resilient modulus.

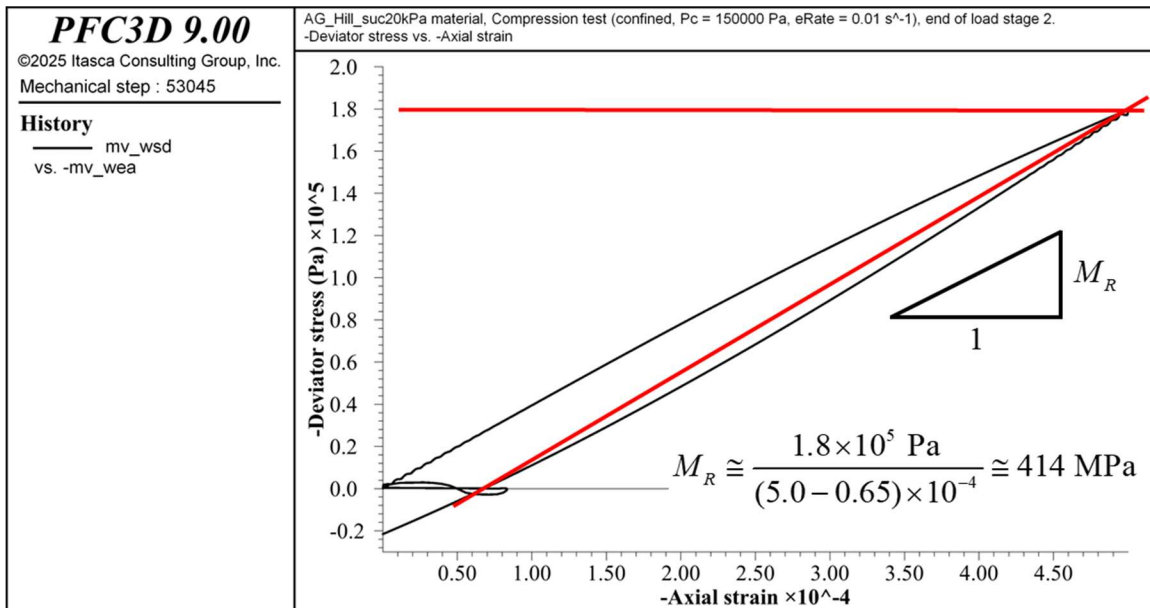


Figure 14 Deviator stress versus axial strain for wet AG_Hill clumped material tested at 150 kPa confinement, and measurement of resilient modulus.

2.0 BONDED MATERIALS

Bonded materials that use the linear contact bond, linear parallel bond, soft bond, and flat joint contact models are created to represent Castlegate sandstone. The following properties are typical of Castlegate sandstone: density of 1960 kg/m^3 ; median grain size of 0.19 mm ; direct-tension strength of 1.0 MPa ; unconfined-compressive strength of 20.0 MPa ; and Young's modulus and Poisson's ratio measured during unconfined-compression tests of 2.9 GPa and 0.33 , respectively. Both 2D and 3D models are constructed with disk/sphere and clumped particles. There are also rigid-block particles for the flat-jointed material. The clumped materials are created by starting with the disk/sphere model and replacing the call to `mpParams.p2dat` in `MatGen.p2dvr` with a call to `mpParams-Clumped.p2dat`.

2.1 Contact-Bonded Material (2D Disks and Clumps)

The 2D contact-bonded material example is in the `mg_cbond2D` example-project directory. A 2D contact-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.⁵ We denote our sandstone material as the `SS_ContactBonded2D` material with microproperties listed in Table 7. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then contact bonds are added between all grains that are in contact with one another (see Figure 15). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 2D contact-bonded clumped material (see Figure 16) can be created, in the same way as the parallel-bonded material example.

Table 7 Microproperties of `SS_ContactBonded2D` Material

Property	Value
Common group:	
N_m	<code>SS_ContactBonded2D</code>
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	1, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, $\{1.6, 2.4, 1.0\}$, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.08
Contact-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	3.0, 1.5, 0.4
Contact-bond group:	
$g_i [\text{mm}]$	0

⁵ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

$(T_{\sigma})_{\{m, sd\}} \text{ [MPa]}, (S_{\sigma})_{\{m, sd\}} \text{ [MPa]}$	$\{1.0, 0\}, \{20.0, 0\}$
Linear material group:	
$E_n^* \text{ [GPa]}, \kappa_n^*, \mu_n$	3.0, 1.5, 0.4

* Contact-bonded material parameters are defined in Table 6 of the base memo.

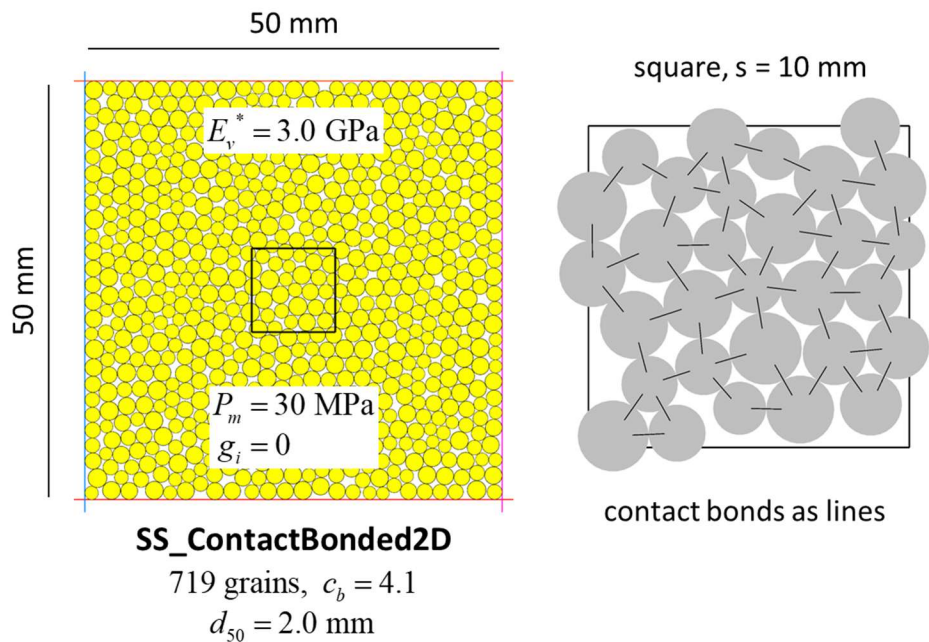


Figure 15 ***SS_ContactBonded2D material at the end of material genesis with grains and intact contact bonds in the microstructural box.***

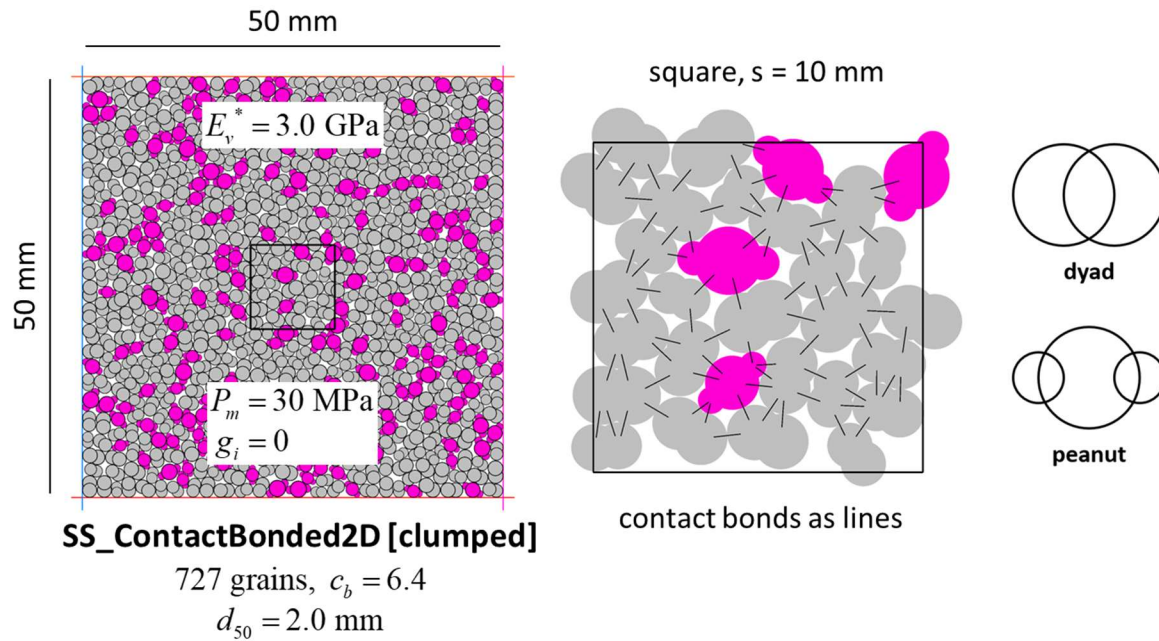


Figure 16 *SS_ContactBonded2D clumped material at the end of material genesis with grains and contact bonds in the microstructural box.*

2.2 Contact-Bonded Material (3D Spheres and Clumps)

The 3D contact-bonded material example is in the **mg_cbond3D** example-project directory. A 3D contact-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.⁶ We denote our sandstone material as the **SS_ContactBonded** material with microproperties listed in Table 8. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then contact bonds are added between all grains that are in contact with one another (see Figure 17). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 3D contact-bonded clumped material can be created, in the same way as the parallel-bonded material example.

Table 8 Microproperties of SS_ContactBonded Material

Property	Value
Common group:	
N_m	SS_ContactBonded
$T_m, \alpha, C_p, \rho_v \left[\frac{\text{kg}}{\text{m}^3} \right]$	1, 0.7, 1, 1960

⁶ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

$S_g, T_{SD}, \{D_{l,ul} [\text{mm}], \phi\}, D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.30
Contact-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	3.0, 1.5, 0.4
Contact-bond group:	
$g_i [\text{mm}]$	0
$(T_\sigma)_{\{m, sd\}} [\text{MPa}], (S_\sigma)_{\{m, sd\}} [\text{MPa}], \gamma$	{1.0,0}, NA, 20
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	3.0, 1.5, 0.4

* Contact-bonded material parameters are defined in Table 6 of the base memo.

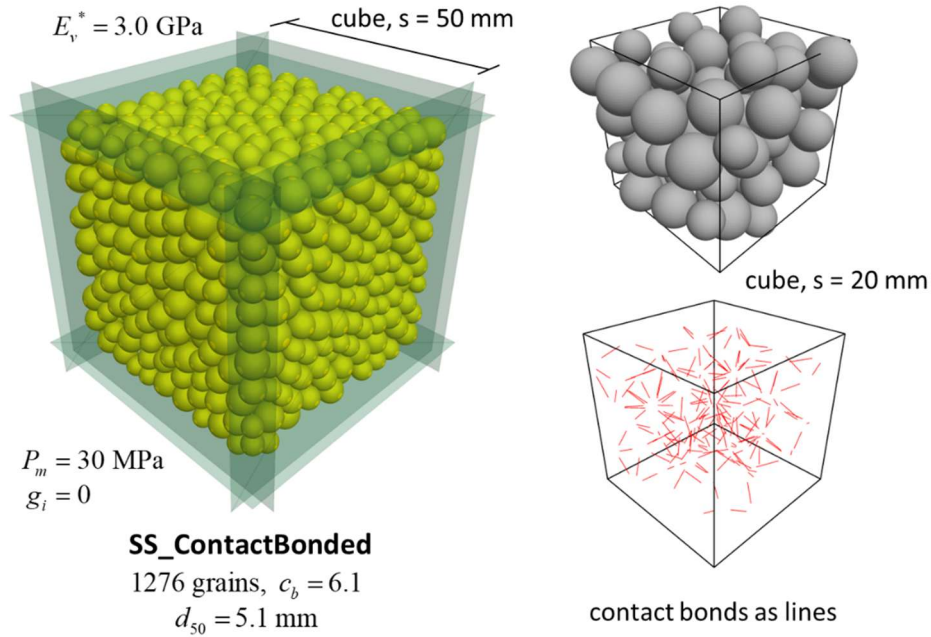


Figure 17 *SS_ContactBonded material at the end of material genesis with grains and intact contact bonds in the microstructural box.*

2.3 Parallel-Bonded Material (2D Disks and Clumps)

The 2D parallel-bonded material example is in the **mg_pbond2D** example-project directory. A 2D parallel-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.⁷ We denote our sandstone material as the **SS_ParallelBonded2D** material with microproperties listed in Table 9. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 18). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results are shown in Figures 19 to 25.

Table 9 Microproperties of SS_ParallelBonded2D Material

Property	Value
Common group:	
N_m	SS_ParallelBonded2D
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	2, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {1.6,2.4,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.08
Parallel-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i [\text{mm}], \bar{\lambda}, \bar{E}^* [\text{GPa}], \bar{\kappa}^*, \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{m, sd\}} [\text{MPa}], (\bar{c})_{\{m, sd\}} [\text{MPa}], \bar{\phi} [\text{degrees}]$	{1.0,0}, {20.0,0}, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 8 of the base memo.

⁷ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

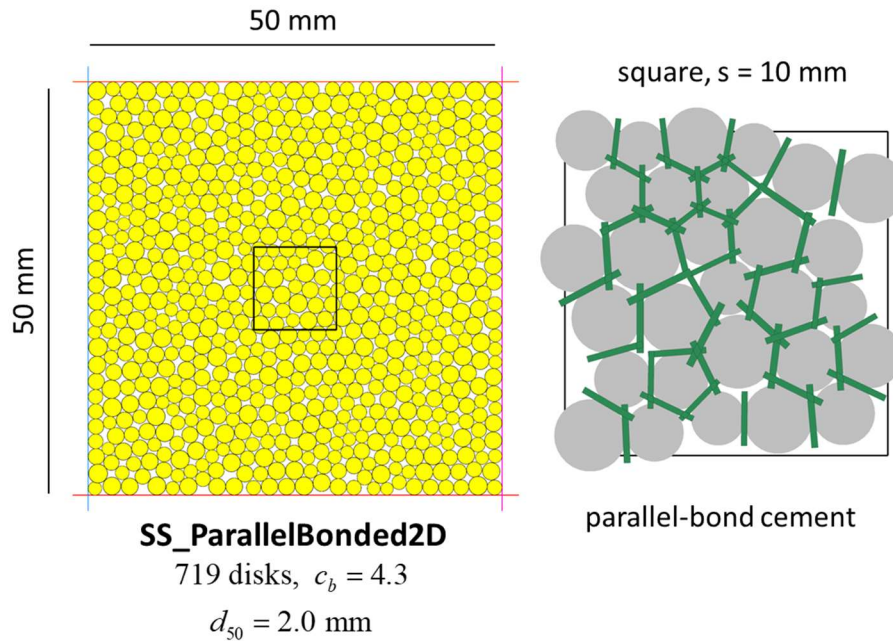


Figure 18 *SS_ParallelBonded2D material at the end of material genesis with grains and intact parallel bonds in the microstructural box.*

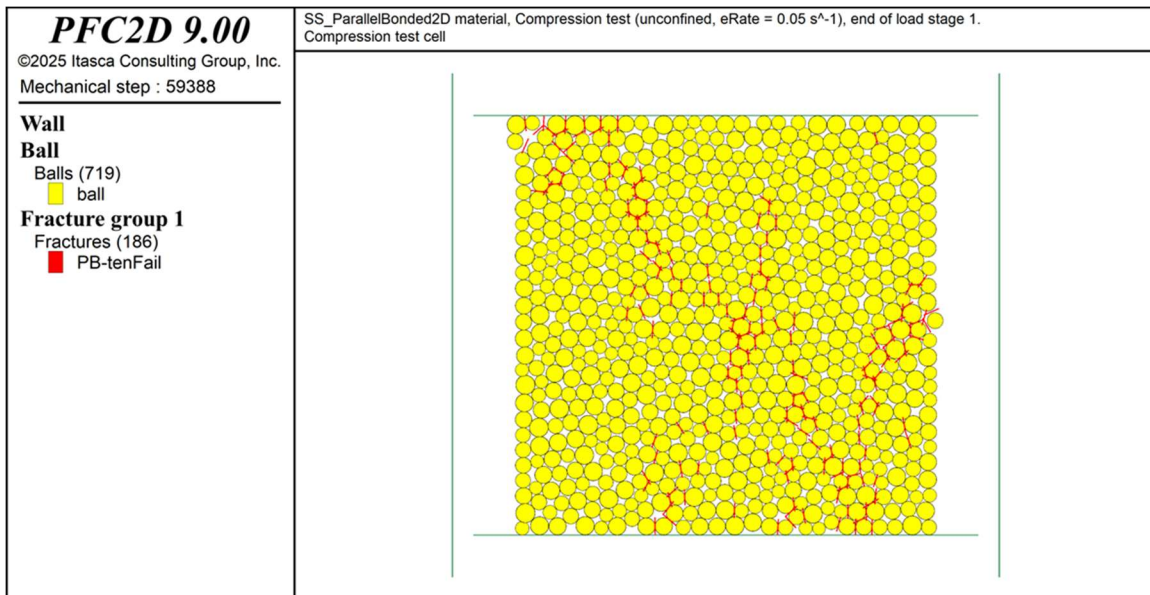


Figure 19 *SS_ParallelBonded2D material at the end of the fully unconfined test with grains and cracks.*

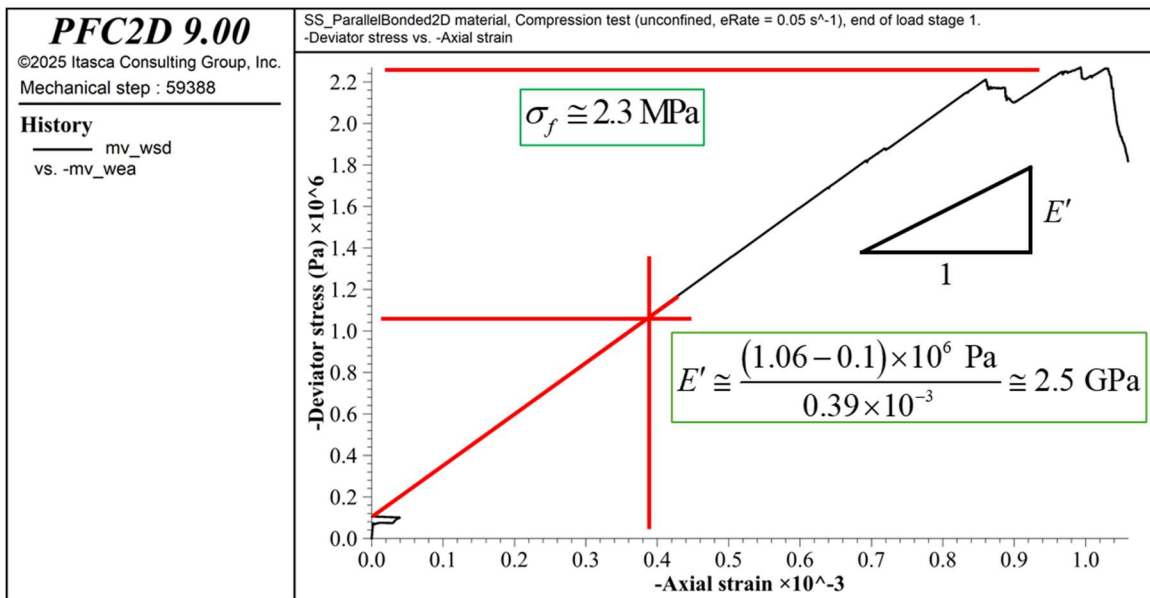


Figure 20 Deviator stress versus axial strain for SS_ParallelBonded2D material tested fully unconfined, and measurement of peak strength and effective Young's modulus.

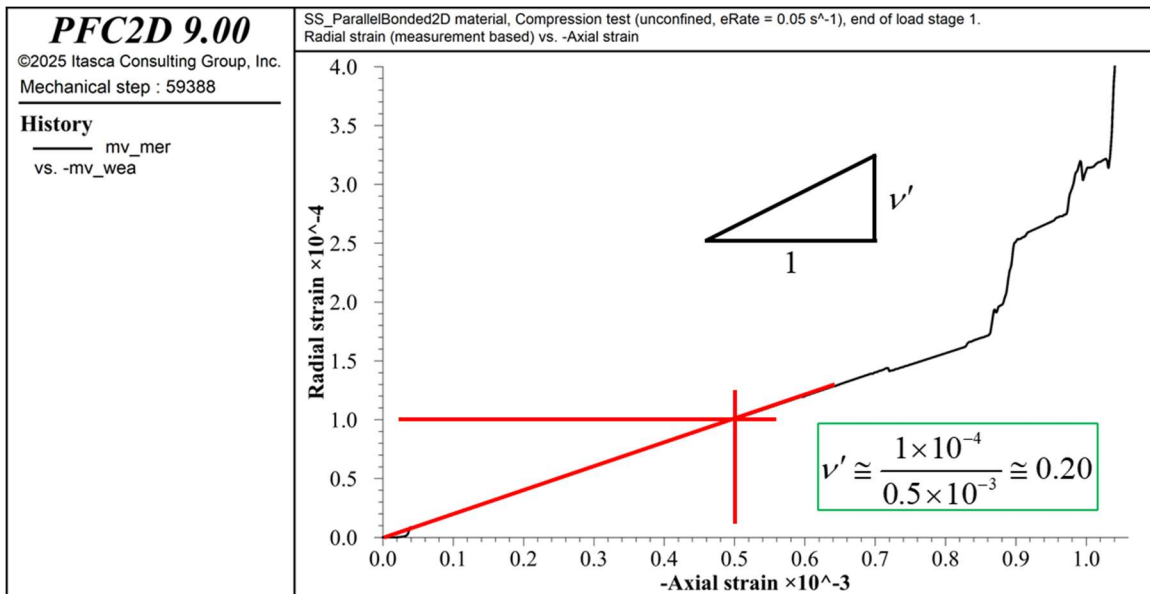


Figure 21 Radial strain versus axial strain for SS_ParallelBonded2D material tested fully unconfined, and measurement of effective Poisson's ratio.

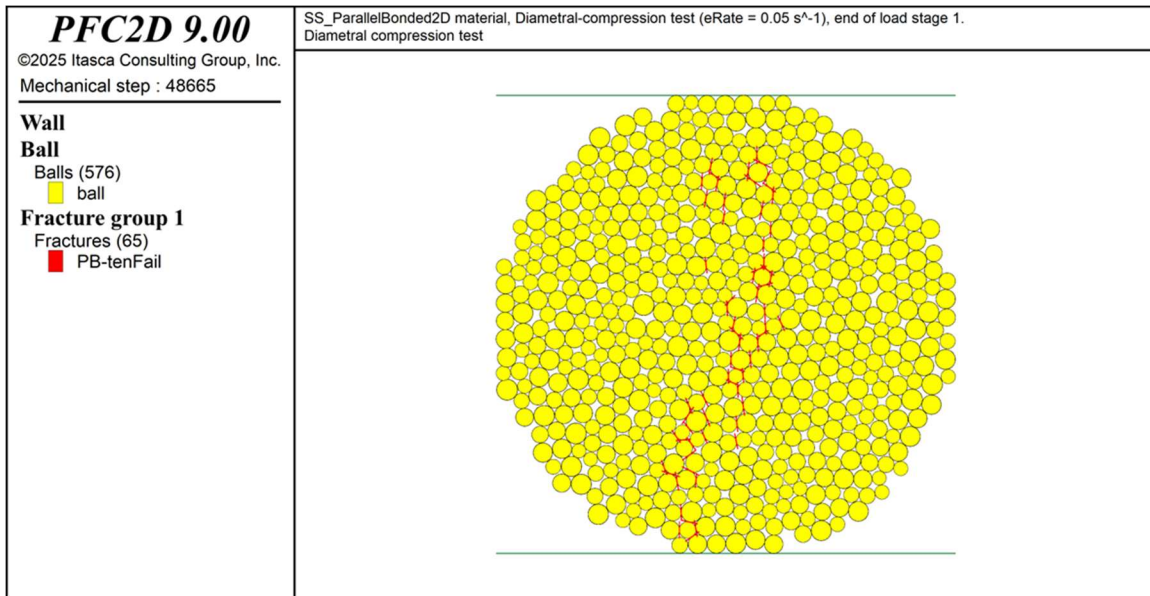


Figure 22 *SS_ParallelBonded2D material at the end of diametral-compression test with grains and cracks.*

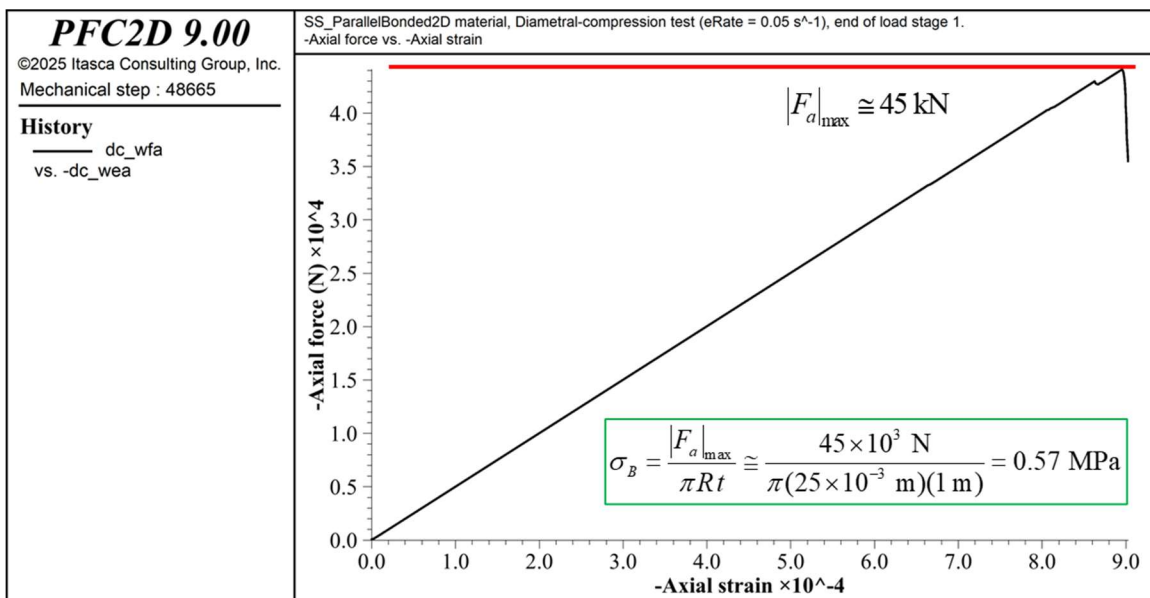


Figure 23 *Axial force versus axial displacement for SS_ParallelBonded2D material during the diametral-compression test, and measurement of Brazilian tensile strength.*

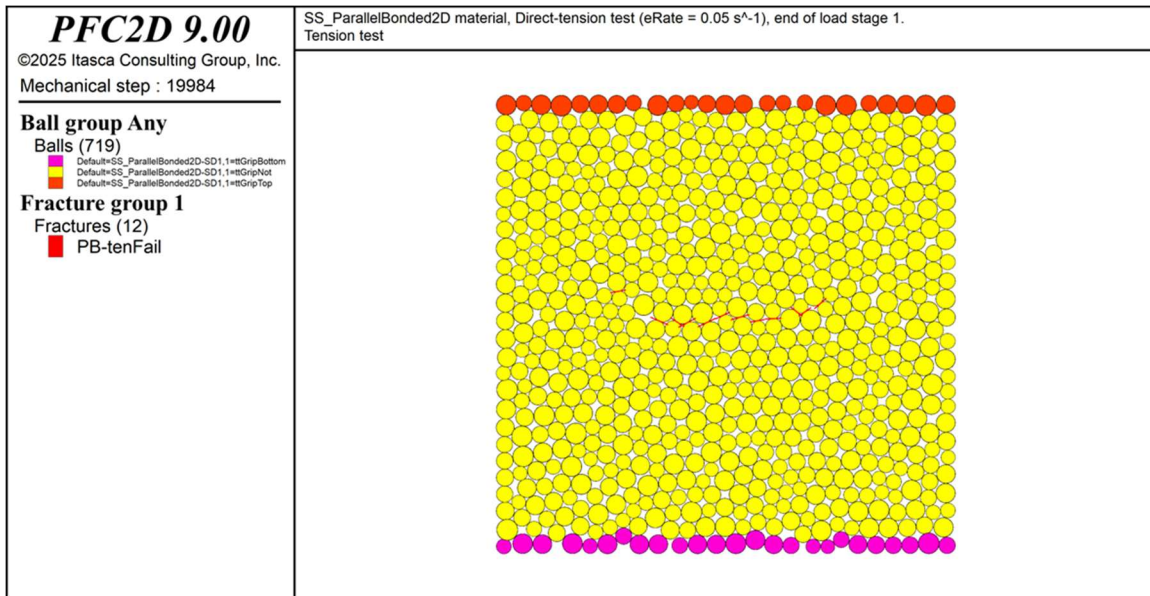


Figure 24 *SS_ParallelBonded2D material at the end of the direct-tension test with grains, grip grains, and cracks.*

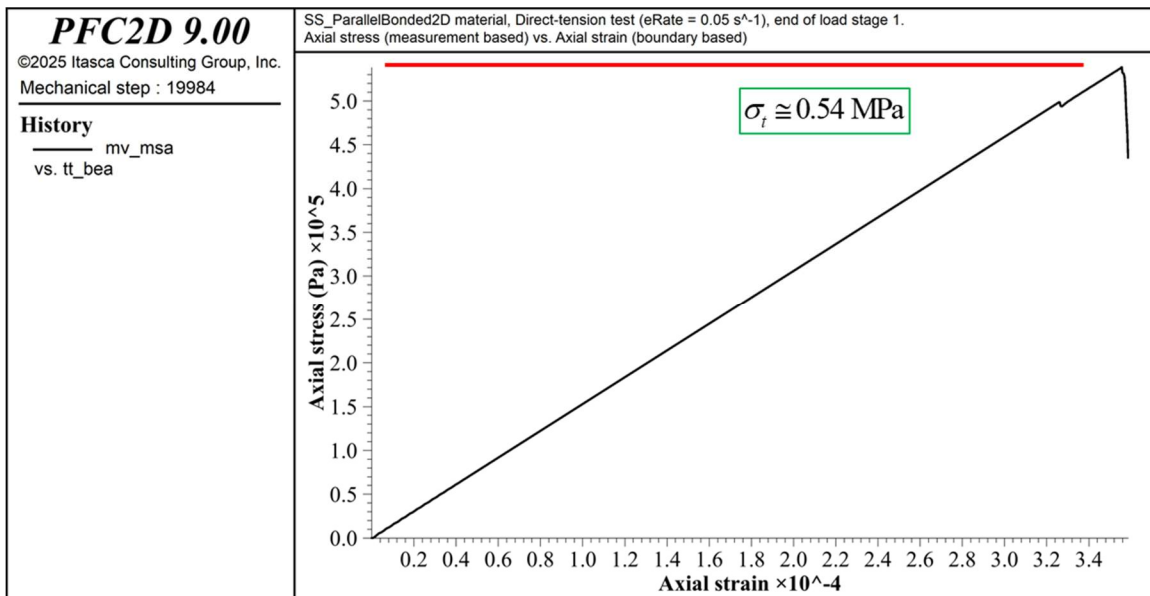


Figure 25 *Axial stress versus axial strain for SS_ParallelBonded2D material during the direct-tension test, and measurement of tensile strength.*

The 2D parallel-bonded material example is modified to replace the disk-shaped particles with clumps by replacing the call to `mpParams.p2dat` in `MatGen.p2dvr` with a call to `mpParams-Clumped.p2dat`. The new material is denoted as a 2D parallel-bonded clumped material with microproperties listed in Table 10. The clumped material has two grain shapes. The first shape is a dyad consisting of two disk-shaped pebbles, and the second shape is a peanut consisting of three disk-shaped pebbles. The clumped grains are drawn from a uniform size distribution with

diameters ranging from 1.6 to 2.4 mm, with 75% of the grains being dyads and 25% of the grains being peanuts. The material has a median particle size of 2.1 mm. The material-creation and testing procedures for the clumped material are the same as those for the AG_ParallelBonded2D material.

Table 10 Microproperties of SS_ParallelBonded2D Clumped Material

Property	Value
Common group:	
N_m	SS_ParallelBonded2D
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	2, 0.7, 1, 1960
$S_g, n_{SD}, T_{SD}, \{N_{ct}, D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	1, 2, 0, $\left\{ \begin{array}{l} \text{dyad, 1.6,2.4,0.75} \\ \text{peanut,1.6,2.4,0.25} \end{array} \right\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{MPa}], \epsilon_p, \epsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.08
Parallel-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i [\text{mm}], \bar{\lambda}, \bar{E}^* [\text{GPa}], \bar{\kappa}^*, \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{m, sd\}} [\text{MPa}], (\bar{c})_{\{m, sd\}} [\text{MPa}], \bar{\phi} [\text{degrees}]$	$\{1.0, 0\}, \{20.0, 0\}, 0$
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 5 of the base memo.

The 2D clumped material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 26). The bond coordination number of the clumped material (6.9) is larger than that of the disk-only material (4.3), and the porosity of the clumped material (0.092) is less than that of the disk-only material (0.121) — the dyads and peanuts have packed to a denser state than the disks. The clumped material is then subjected to compression, diametral-compression and direct-tension tests. The compression-test results are shown in Figures 27 and 28. The clumped material is stronger (3.2 MPa versus 2.3 MPa) and stiffer (3.8 GPa versus 2.5 GPa) than the disk-only material, with increased strength and stiffness attributed to increased bond coordination number and reduced porosity.

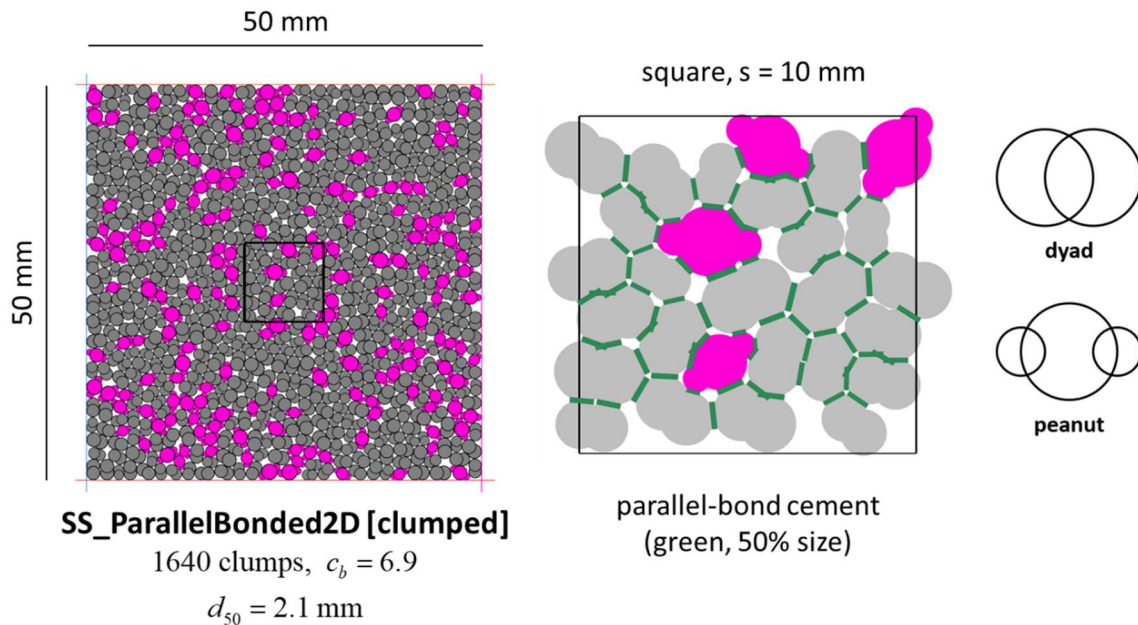


Figure 26 *SS_ParallelBonded2D clumped material at the end of material genesis with grains and parallel bonds in the microstructural box.*

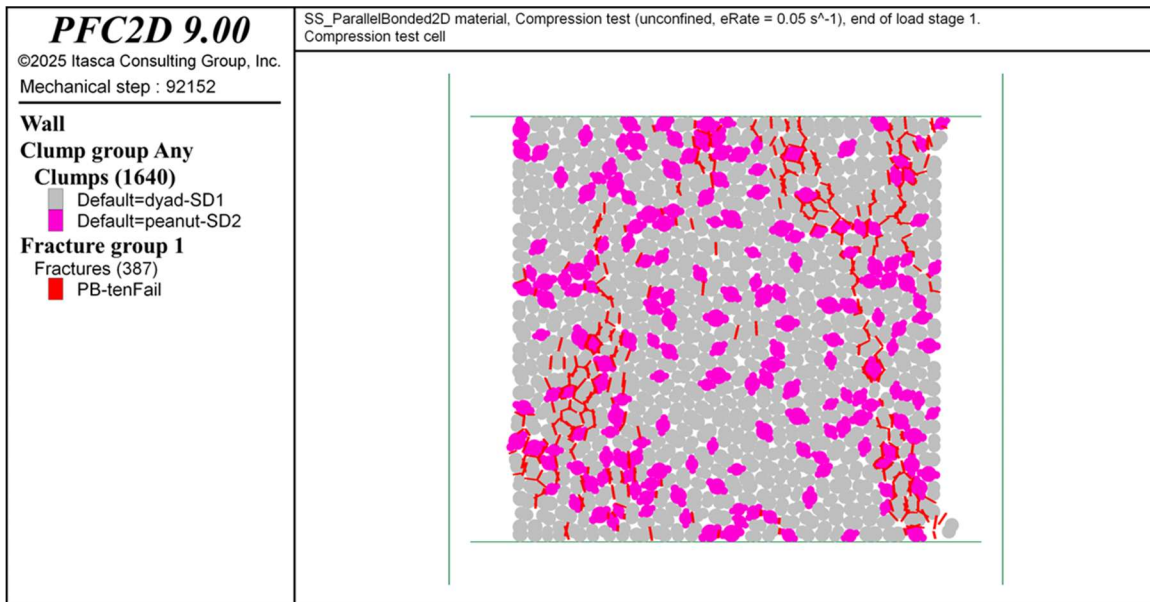


Figure 27 *SS_ParallelBonded2D clumped material at the end of the fully unconfined test with grains and cracks.*

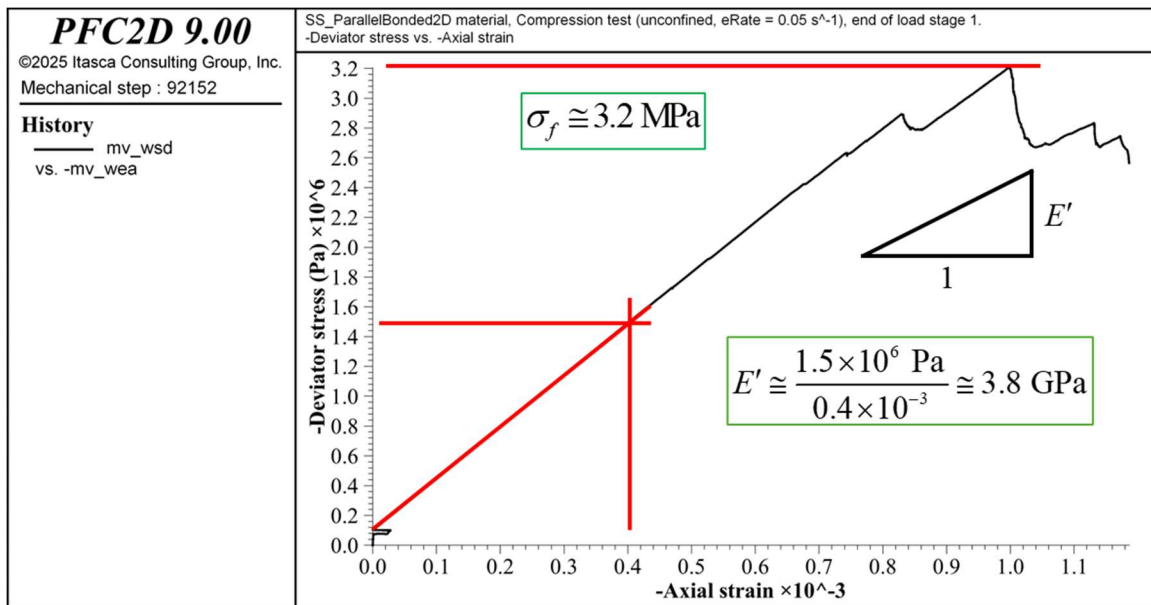


Figure 28 Deviator stress versus axial strain for *SS_ParallelBonded2D* clumped material tested fully unconfined, and measurement of peak strength and effective Young's modulus.

2.4 Parallel-Bonded Material (3D Spheres and Clumps)

The 3D parallel-bonded material example is in the *mg_pbond3D* example-project directory. A parallel-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.⁸ We denote our sandstone material as the *SS_ParallelBonded* material with microproperties listed in Table 11. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 29). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results are shown in Figures 30 to 36.

Table 11 Microproperties of *SS_ParallelBonded* Material

Property	Value
Common group:	
N_m	SS_ParallelBonded
$T_m, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	2, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	

⁸ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

$S_{RV}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{\text{lim}}, n_{\text{lim}}$ C_p, n_c	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6 1, 0.30
Parallel-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i [\text{mm}], \bar{\lambda}, \bar{E}^* [\text{GPa}], \bar{\kappa}^*, \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{m, sd\}} [\text{MPa}], (\bar{c})_{\{m, sd\}} [\text{MPa}], \bar{\gamma}, \bar{\phi} [\text{degrees}]$	$\{1.0, 0\}$, NA, 20, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 8 of the base memo.

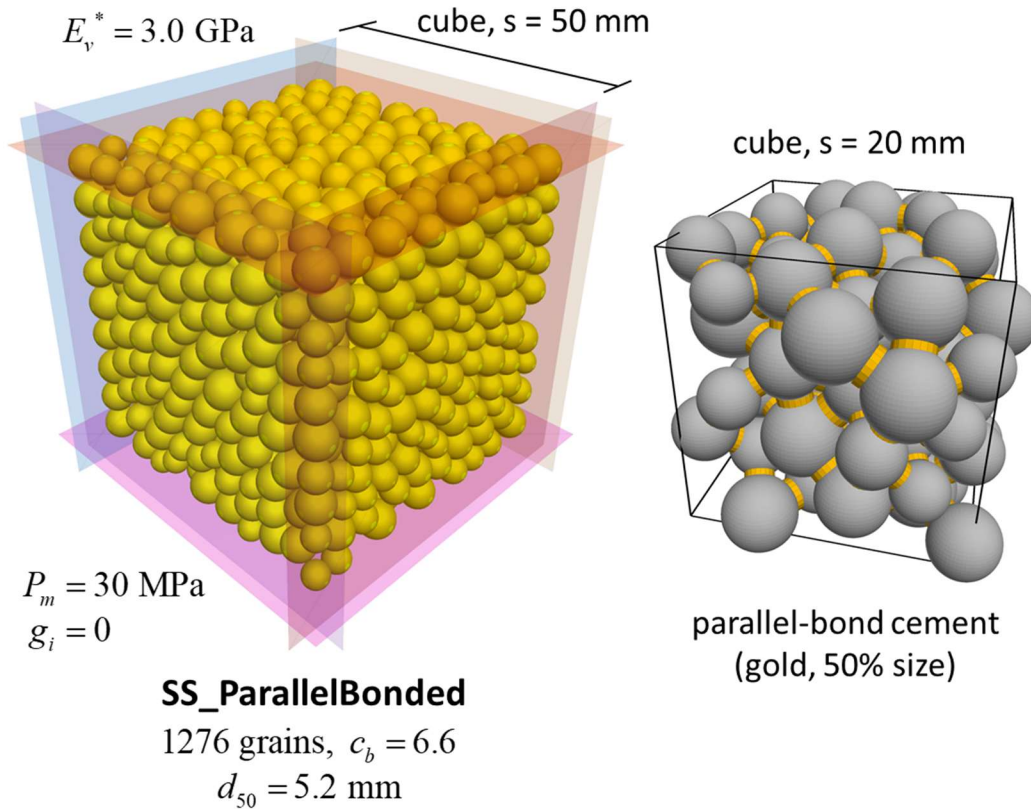


Figure 29 *SS_ParallelBoned material at the end of material genesis with grains and intact parallel bonds in the microstructural box.*

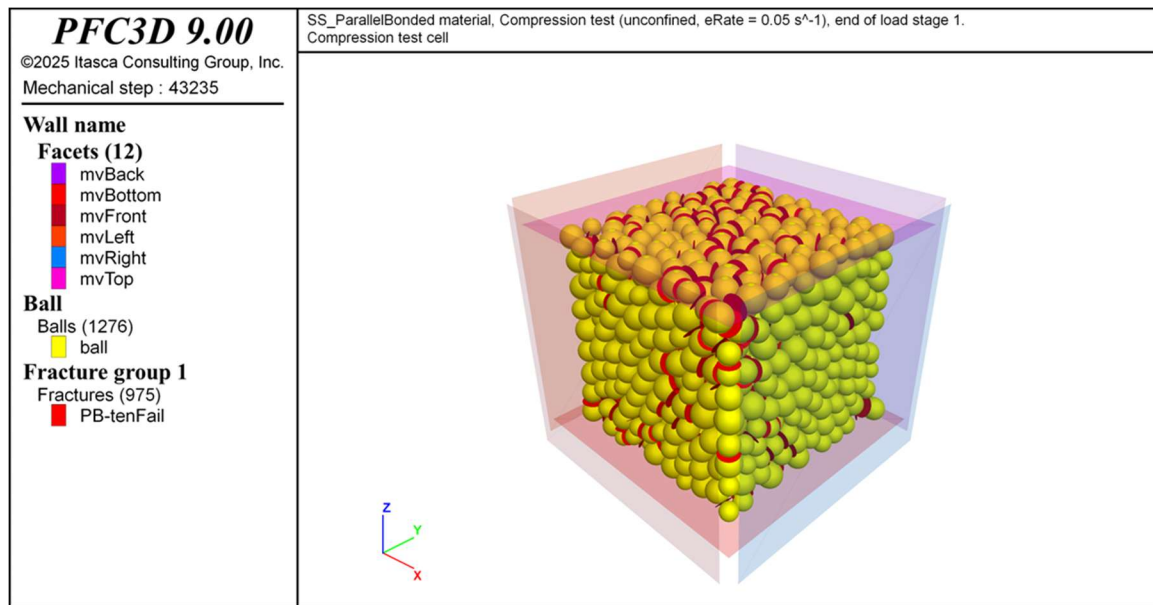


Figure 30 *SS_ParallelBonded2D material at the end of the fully unconfined test with grains and cracks.*

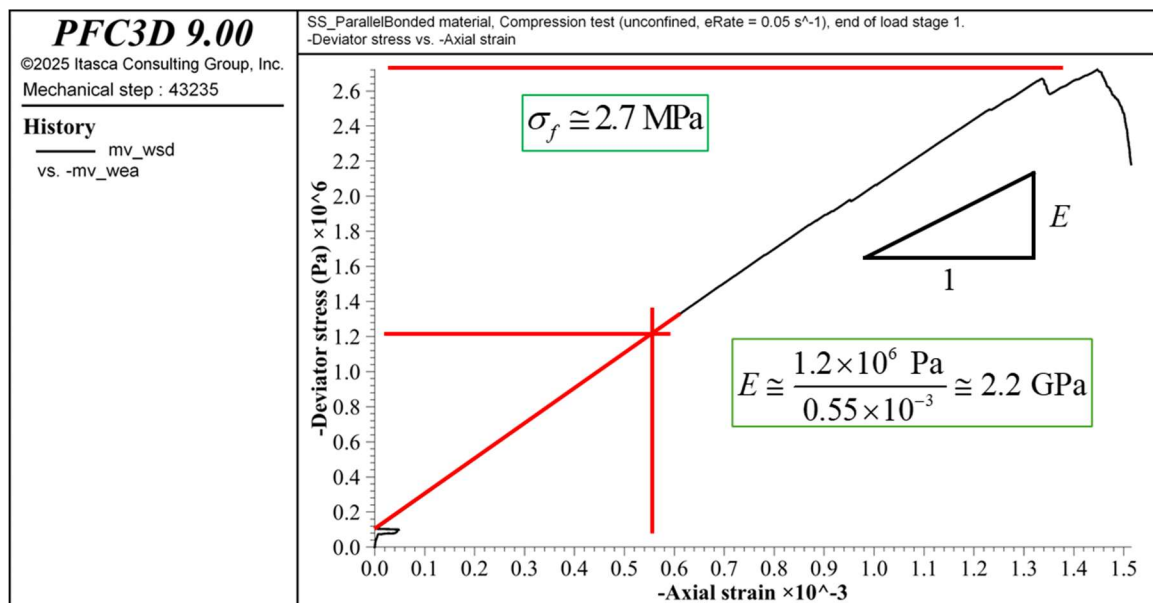


Figure 31 *Deviator stress versus axial strain for SS_ParallelBonded2D material tested fully unconfined, and measurement of peak strength and Young's modulus.*

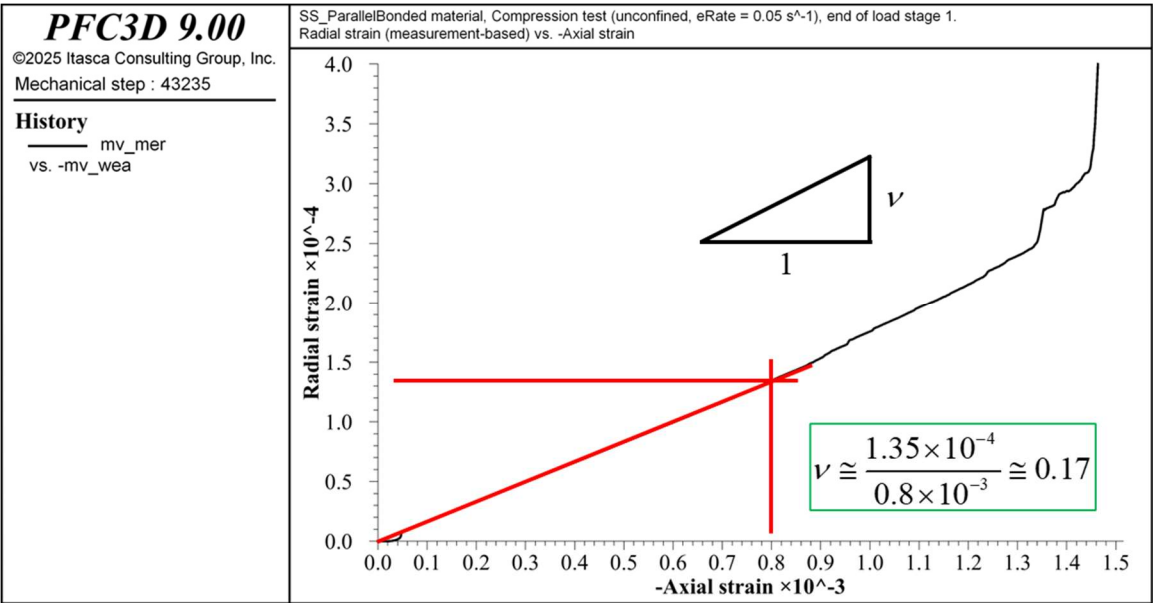


Figure 32 Radial strain versus axial strain for SS_ParallelBonded2D material tested fully unconfined, and measurement of Poisson's ratio.

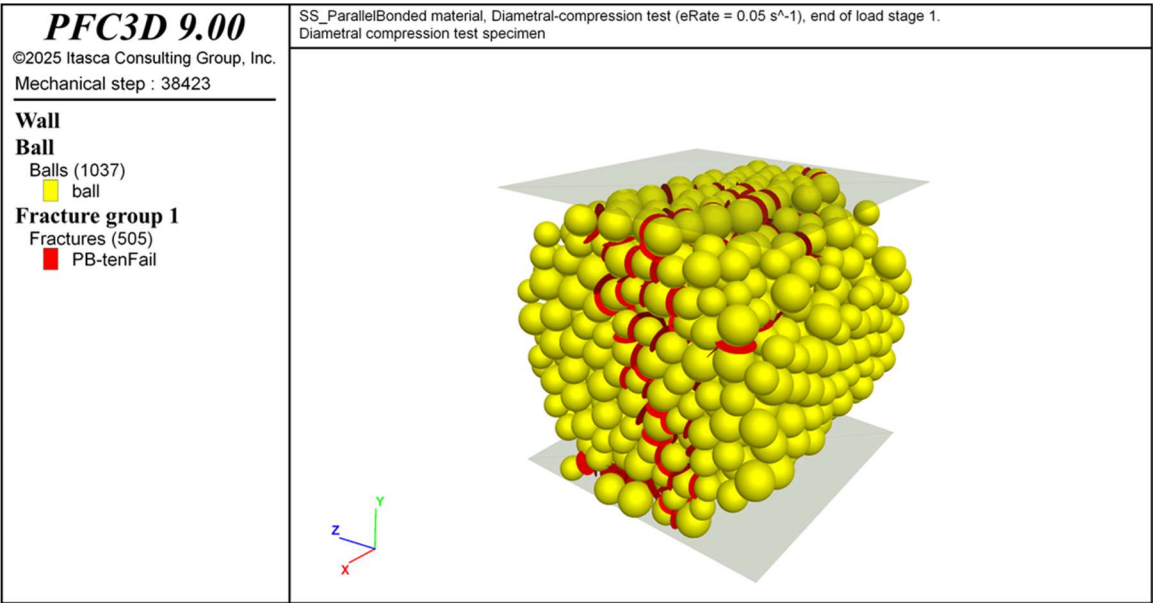


Figure 33 SS_ParallelBonded2D material at the end of diametral-compression test with grains and cracks.

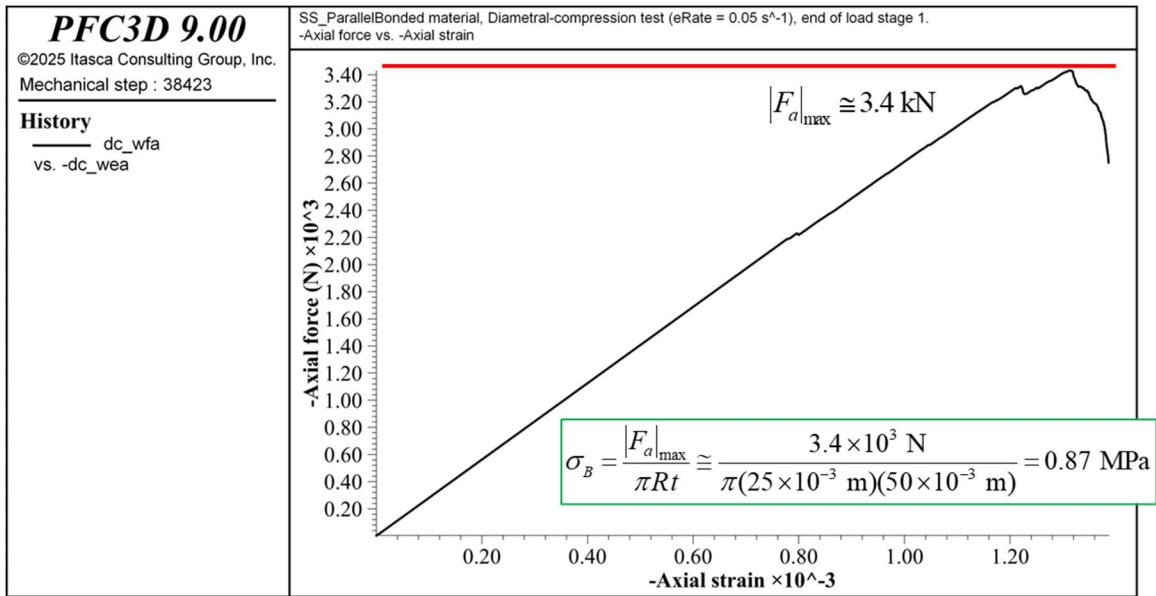


Figure 34 Axial force versus axial displacement for *SS_ParallelBonded2D* material during the diametral-compression test, and measurement of Brazilian tensile strength.

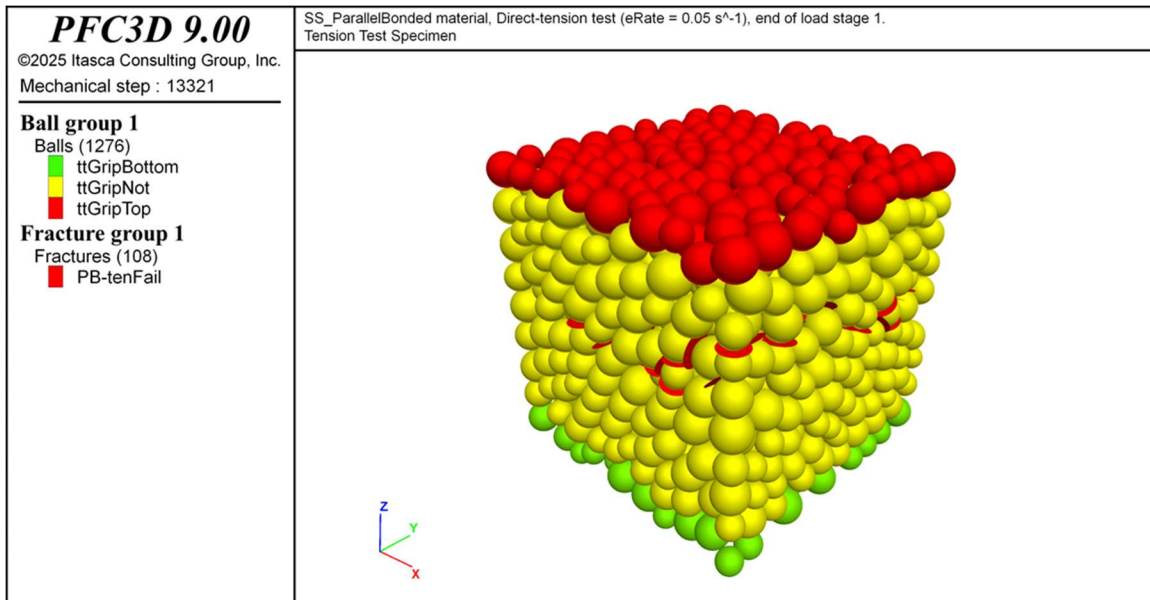


Figure 35 *SS_ParallelBonded2D* material at the end of the direct-tension test with grains, grip grains, and cracks.

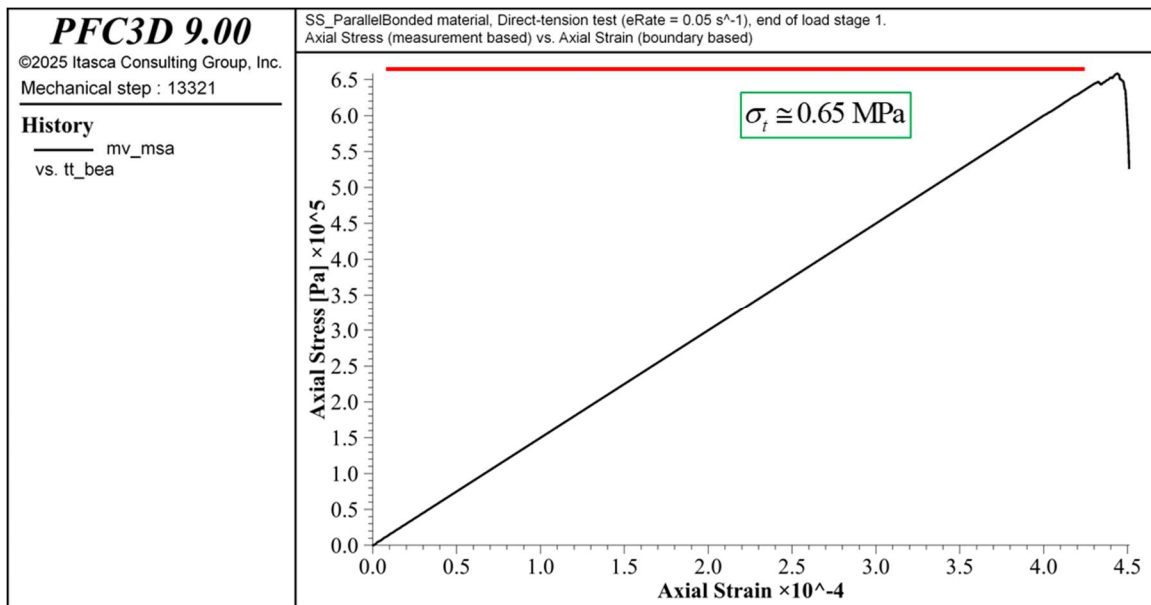


Figure 36 Axial stress versus axial strain for *SS_ParallelBonded2D* material during the direct-tension test, and measurement of tensile strength.

The parallel-bonded material example is modified to replace the spherical particles with clumps by replacing the call to `mpParams.p3dat` in `MatGen.p3dvr` with a call to `mpParams-Clumped.p3dat`. The new material is denoted as a parallel-bonded clumped material with microproperties listed in Table 12. The clumped material has two grain shapes. The first shape is a dyad consisting of two spherical pebbles, and the second shape is a peanut consisting of three spherical pebbles (see Figure 37). The clumped grains are drawn from a uniform size distribution with diameters ranging from 4 to 6 mm, with 75% of the grains being dyads and 25% of the grains being peanuts. The material has a median particle size of 5.3 mm. The material-creation and testing procedures for the clumped material are the same as those for the *SS_ParallelBonded* material.

The clumped material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then parallel bonds are added between all grains that are in contact with one another (see Figure 37). The bond coordination number of the clumped material (11.6) is larger than that of the spherical material (6.6), and the porosity of the clumped material (0.275) is less than that of the spherical material (0.303) — the dyads and peanuts have packed to a denser state than the spheres. The clumped material is then subjected to compression, diametral-compression and direct-tension tests. The compression-test results are shown in Figure 38. The clumped material is stronger (4.5 MPa versus 2.7 MPa) and stiffer (3.0 GPa versus 2.2 GPa) than the spherical material, with increased strength and stiffness attributed to increased bond coordination number and reduced porosity.

Table 12 Microproperties of SS_ParallelBonded Clumped Material

Property	Value
Common group:	
N_m	SS_ParallelBonded [clumped]
$T_m, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	2, 0.7, 1, 1960
$S_g, n_{SD}, T_{SD}, \{N_{cl}, D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	1, 2, 0, $\left\{ \begin{array}{l} \text{dyad, } 4, 6, 0.75 \\ \text{peanut, } 4, 6, 0.25 \end{array} \right\}, 1.0$
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.30
Parallel-bonded material group:	
Linear group:	
$E^* [\text{GPa}], \kappa^*, \mu$	1.5, 1.5, 0.4
Parallel-bond group:	
$g_i [\text{mm}], \bar{\lambda}, \bar{E}^* [\text{GPa}], \bar{\kappa}^*, \bar{\beta}$	0, 1.0, 1.5, 1.5, 1.0
$(\bar{\sigma}_c)_{\{m, sd\}} [\text{MPa}], (\bar{c})_{\{m, sd\}} [\text{MPa}], \bar{\gamma}, \bar{\phi} [\text{degrees}]$	$\{1.0, 0\}$, NA, 20, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Parallel-bonded material parameters are defined in Table 5 of the base memo.

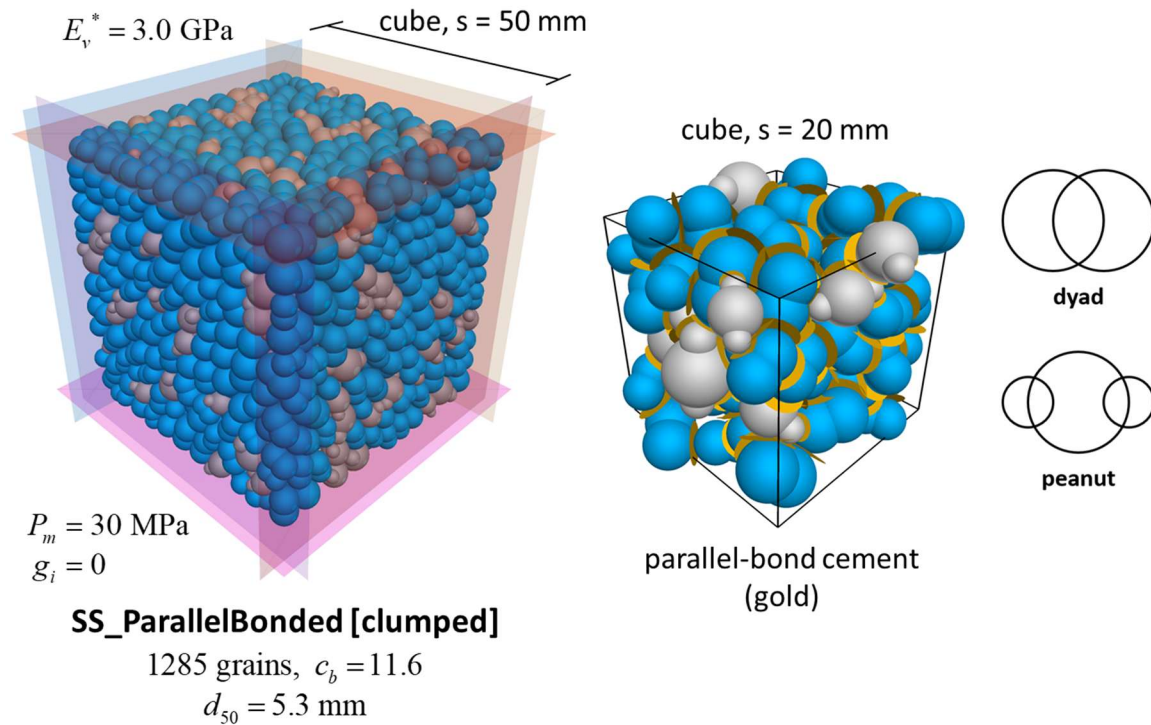


Figure 37 *SS_ParallelBonded clumped material at the end of material genesis with grains and parallel bonds in the microstructural box.*

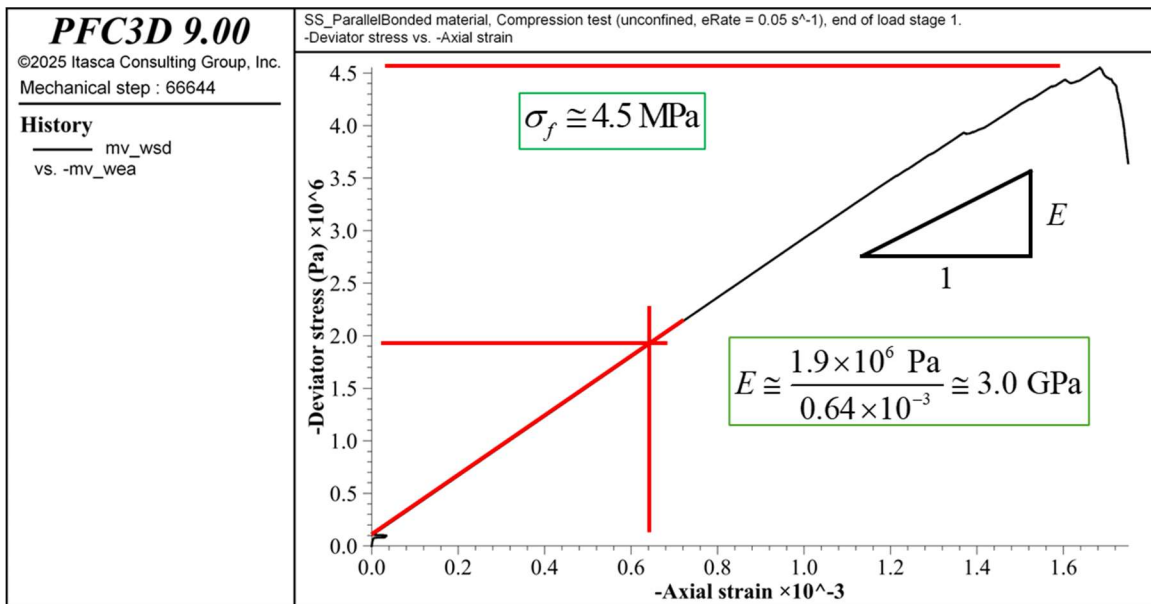


Figure 38 *Deviator stress versus axial strain for SS_ParallelBonded clumped material tested fully unconfined, and measurement of peak strength and Young's modulus.*

2.5 Soft-Bonded Material (2D Disks and Clumps)

The 2D soft-bonded material example is in the **mg_sbond2D** example-project directory. A 2D soft-bonded material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.⁹ We denote our sandstone material as the **SS_SoftBonded2D** material with microproperties listed in Table 13. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then soft bonds are added between all grains that are in contact with one another (see Figure 39). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 2D soft-bonded clumped material can be created, in the same way as the parallel-bonded material example.

Table 13 Microproperties of SS_SoftBonded2D Material

Property	Value
Common group:	
N_m	SS_SoftBonded2D
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	3, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.08
Soft-bonded material group:	
$g_i [\text{mm}], \lambda, E^* [\text{GPa}], \kappa^*, \beta$	0, 1.0, 1.5, 1.5, 1.0
$(\sigma_c)_{\{m, sd\}} [\text{MPa}], (c)_{\{m, sd\}} [\text{MPa}], \gamma, \phi [\text{degrees}]$	{1.0,0}, NA, 20, 0.0
$\zeta, \gamma, \mu, \lambda_b, \lambda_t$	0.0, 0.0, 0.4, 0.0, 0.0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Soft-bonded material parameters are defined in Table 9 of the base memo.

⁹ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

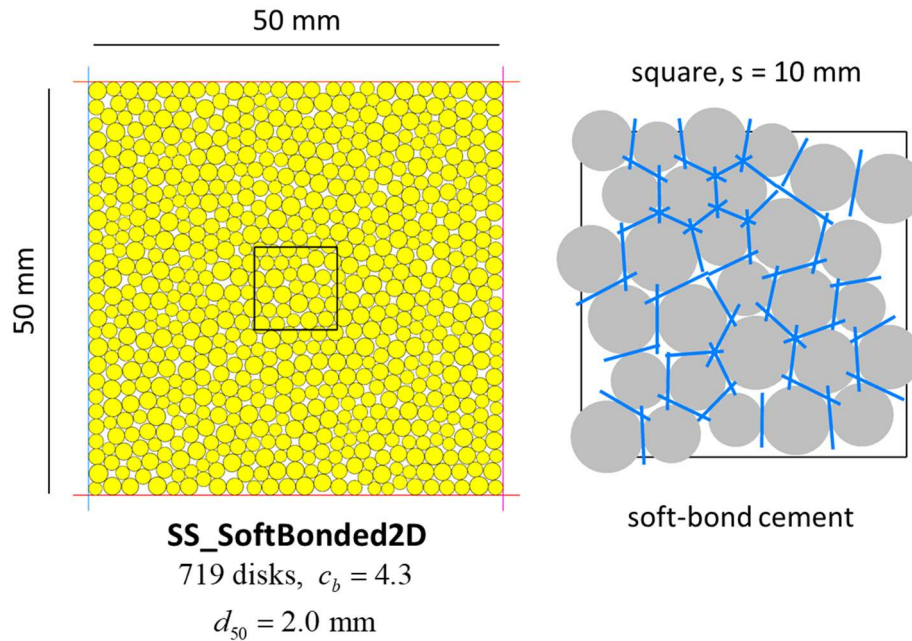


Figure 39 *SS_SoftBonded2D material at the end of material genesis with grains and intact soft bonds in the microstructural box.*

2.6 Soft-Bonded Material (3D Spheres and Clumps)

The 3D soft-bonded material example is in the `mg_sbond3D` example-project directory. A 3D soft-bonded material is created to represent a typical sandstone, which we take to be Castlegate sandstone.¹⁰ We denote our sandstone material as the `SS_SoftBonded` material with microproperties listed in Table 14. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then soft bonds are added between all grains that are in contact with one another (see Figure 40). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 3D soft-bonded clumped material can be created, in the same way as the parallel-bonded material example.

Table 14 *Microproperties of SS_SoftBonded Material*

Property	Value
Common group:	
N_m	SS_SoftBonded
$T_m, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	3, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0

¹⁰ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

Packing group:	
$S_{RV}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.30
Soft-bonded material group:	
$g_i [\text{mm}], \lambda, E^* [\text{GPa}], \kappa^*, \beta$	0, 1.0, 1.5, 1.5, 1.0
$(\sigma_c)_{\{m, sd\}} [\text{MPa}], (c)_{\{m, sd\}} [\text{MPa}], \gamma, \phi [\text{degrees}]$	{1.0, 0}, NA, 20, 0.0
$\zeta, \gamma, \mu, \lambda_b, \lambda_t$	0.0, 0.0, 0.4, 0.0, 0.0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Soft-bonded material parameters are defined in Table 9 of the base memo.

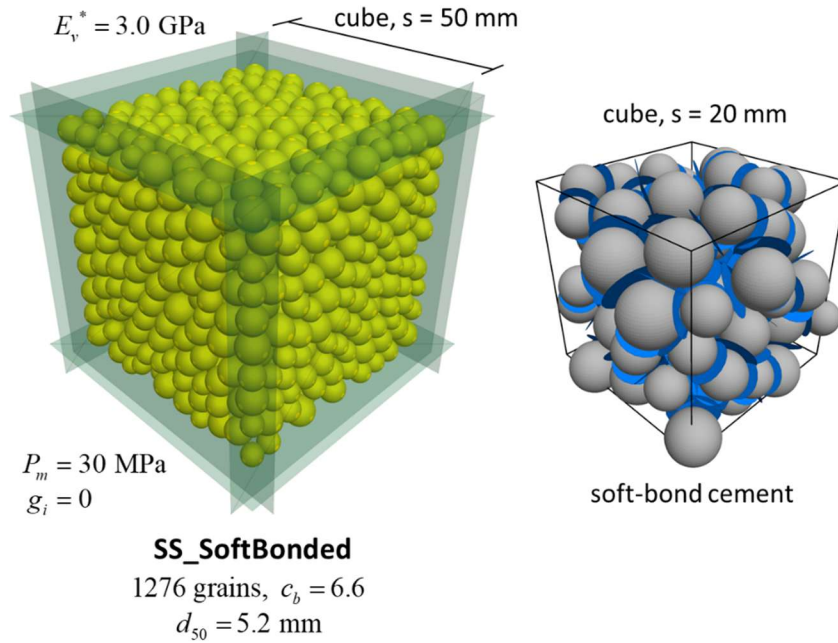


Figure 40 *SS_SoftBonded material at the end of material genesis with grains and intact soft bonds in the microstructural box.*

2.7 Flat-Jointed Material (2D Disks and Clumps)

The 2D flat-jointed material example is in the `mg_2D` example-project directory. A 2D flat-jointed material (consisting of rigid unit-thickness disks) is created to represent a typical sandstone, which we take to be Castlegate sandstone.¹¹ We denote our sandstone material as the `SS_FlatJointed2D` material with microproperties listed in Table 15. The material is created in a square-cuboid material vessel (of 50 mm side length and unit depth, with a 3 GPa effective

¹¹ Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then the flat-joint contact model is installed between all grains that are in contact with one another, with the flat-jointed material properties being assigned to those flat-jointed contacts (see Figure 41). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 2D flat-jointed clumped material can be created, in the same way as the parallel-bonded material example.

Table 15 Microproperties of SS_FlatJointed2D Material

Property	Value
Common group:	
N_m	SS_FlatJointed2D
$T_m, \alpha, C_p, \rho_v [\text{kg/m}^3]$	4, 0.7, 1, 1960
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {1.6,2.4,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.08
Flat-jointed material group:	
$C_{MS}, g_i [\text{mm}], \phi_B, \phi_G, (g_o)_{\{m, sd\}} [\text{mm}], N_r$	false, 0, 1, 0, {0,0}, 2
$\{C_\lambda, \lambda_v\}, E^* [\text{GPa}], \kappa^*, \mu$	{0, 1.0}, 3.0, 1.5, 0.4
$(\sigma_c)_{\{m, sd\}} [\text{MPa}], (c)_{\{m, sd\}} [\text{MPa}], \gamma, c_r, M_r, \phi [\text{degrees}]$	{1.0,0}, NA, 20, 0.0, 0, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Flat-jointed material parameters are defined in Table 11 of the base memo.

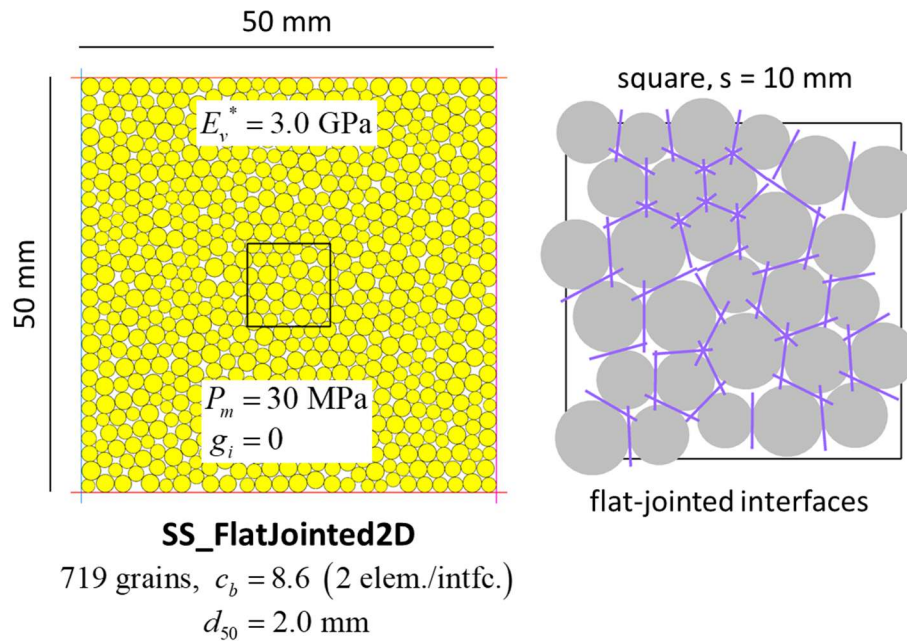


Figure 41 *SS_FlatJointed2D material at the end of material genesis with grains and flat-jointed interfaces in the microstructural box.*

2.8 Flat-Jointed Material (3D Spheres and Clumps)

The 3D flat-jointed material example is in the `mg_fj3D` example-project directory. A 3D flat-jointed material is created to represent a typical sandstone, which we take to be Castlegate sandstone.¹² We denote our sandstone material as the `SS_FlatJointed` material with microproperties listed in Table 16. The material is created in a cubic material vessel (of 50 mm side length, with a 3 GPa effective modulus). The grain-scaling packing procedure is used to pack the grains to a 30 MPa material pressure, and then the flat-joint contact model is installed between all grains that are in contact with one another and the flat-jointed material properties are assigned to those flat-jointed contacts (see Figure 42). The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted, and a 3D flat-jointed clumped material can be created, in the same way as the parallel-bonded material example.

Table 16 Microproperties of SS_FlatJointed Material

Property	Value
Common group:	
N_m	SS_FlatJointed
$T_m, C_r, \varepsilon_s, \varepsilon_a, \alpha, C_p, \rho_v [\text{kg/m}^3]$	4, NA, NA, NA, 0.7, 1, 1960

¹² Properties of Castlegate sandstone are listed in the first paragraph of Section 2.0.

$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}$	0, 0, {4.0,6.0,1.0}, 1.0
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$ C_p, n_c	10000, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6 1, 0.30
Flat-jointed material group:	
$C_{MS}, g_i [\text{mm}], \phi_B, \phi_G, (g_o)_{\{msd\}} [\text{mm}], \{N_r, N_\alpha\}$ $\{C_\lambda, \lambda_v\}, E^* [\text{GPa}], \kappa^*, \mu$ $(\sigma_c)_{\{msd\}} [\text{MPa}], (c)_{\{msd\}} [\text{MPa}], \gamma, c_r, M_r, \phi [\text{degrees}]$	false, 0, 1, 0, {0,0}, {1,3} {0, 1.0}, 3.0, 1.5, 0.4 {1.0,0}, NA, 20, 0.0, 0, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	1.5, 1.5, 0.4

* Flat-jointed material parameters are defined in Table 11 of the base memo.

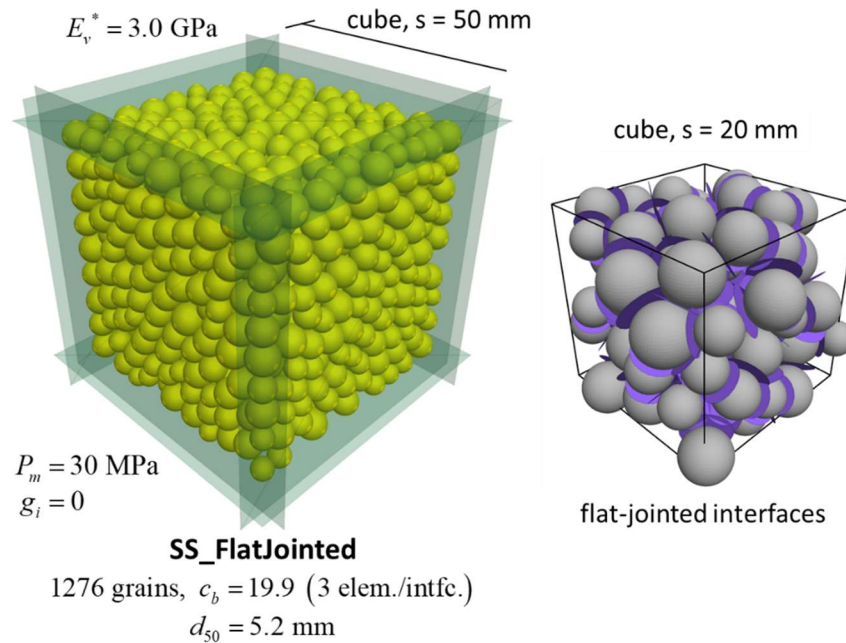


Figure 42 *SS_FlatJointed material at the end of material genesis with grains and flat-jointed interfaces in the microstructural box.*

2.9 Flat-Jointed Material (3D Rigid Blocks)

The 3D flat-jointed Voronoi- and tetrahedral-grain examples are in the **ExampleProjects3D** directory with the subdirectory names of **mg_fjVor3D** and **mg_fjTet3D**, respectively. These materials represent Lac du Bonnet granite and are denoted as LdB_FJvorC and LdB_FJtetC, with microproperties listed in Tables 17 and 18, respectively. The material-creation procedure and

behavior during compression and tension tests are described in Potyondy et al. (2020) and shown in Figure 43. The materials (including a spherical-grain material) are shown in Figure 44. The material is then subjected to compression, diametral-compression and direct-tension tests. The test results can be displayed and interpreted in the same way as the parallel-bonded material example.

Table 17 Microproperties of LdB_FJvorC Material (Voronoi grains)

Property	Value
Common group:	
N_m	LdB_FJvorC
$T_m, C_r, \varepsilon_s, \varepsilon_a, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	4, 1, 0.01, 6, 0.7, 1, 2630
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}, f_s$	0, 0, {1.5,225,1.0}, 1.0, NA
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10001, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.30
Flat-jointed material group:	
$C_{AS}, g_i [\text{mm}], \phi_b, \phi_G, (g_o)_{\{m, sd\}} [\text{m}], \{N_r, N_\alpha\}$	NA, NA, 1, 0, {0,0}, {1,3}
$\{C_\lambda, \lambda_v\}, E^* [\text{GPa}], \kappa^*, \mu$	NA, 60, 1.5, 0.6
$(\sigma_c)_{\{m, sd\}} [\text{MPa}], (c)_{\{m, sd\}} [\text{MPa}], \gamma, c_r, M_r, \phi [\text{degrees}]$	{94,1.13}, {73,8.76}, 0, 0, 0, 53
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	60, 1.5, 0.6

* Flat-jointed material parameters are defined in Table 11 of the base memo.

Table 18 Microproperties of LdB_FJtetC Material (tetrahedral grains)

Property	Value
Common group:	
N_m	LdB_FJtetC
$T_m, C_r, \varepsilon_s, \varepsilon_a, \alpha, C_\rho, \rho_v [\text{kg/m}^3]$	4, 2, 0.01, 6, 0.7, 1, 2630
$S_g, T_{SD}, \{D_{\{l,u\}} [\text{mm}], \phi\}, D_{mult}, f_s$	0, 0, {1.5,2.25,1.0}, 1.0, NA
Packing group:	
$S_{RN}, P_m [\text{MPa}], \varepsilon_p, \varepsilon_{lim}, n_{lim}$	10001, 30, 1×10^{-2} , 8×10^{-3} , 2×10^6
C_p, n_c	1, 0.30
Flat-jointed material group:	
$C_{MS}, g_i [\text{mm}], \phi_B, \phi_G, (g_o)_{\{m, sd\}} [\text{m}], \{N_r, N_\alpha\}$	NA, NA, 1, 0, {0,0}, {1,3}
$\{C_\lambda, \lambda_v\}, E^* [\text{GPa}], \kappa^*, \mu$	NA, 80, 1.5, 0.2
$(\sigma_c)_{\{m, sd\}} [\text{MPa}], (c)_{\{m, sd\}} [\text{MPa}], \gamma, c_r, M_r, \phi [\text{degrees}]$	{12,1.4}, {240,28.8}, 0, 0, 0, 0
Linear material group:	
$E_n^* [\text{GPa}], \kappa_n^*, \mu_n$	180, 1.5, 0.2

* Flat-jointed material parameters are defined in Table 11 of the base memo.

Triaxial Tests

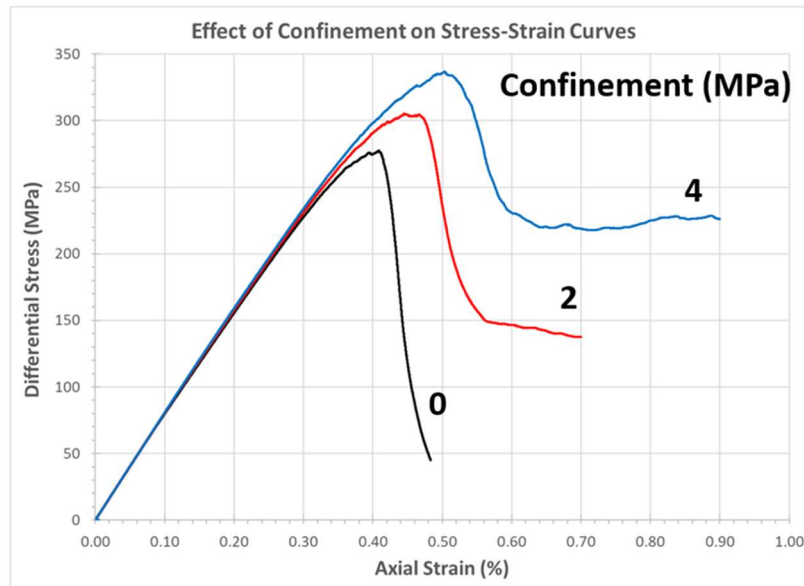


Figure 43 *Stress-strain response during triaxial tests on the flat-jointed Voronoi-grain material.* (From Fig. 31 of Potyondy et al. [2020])

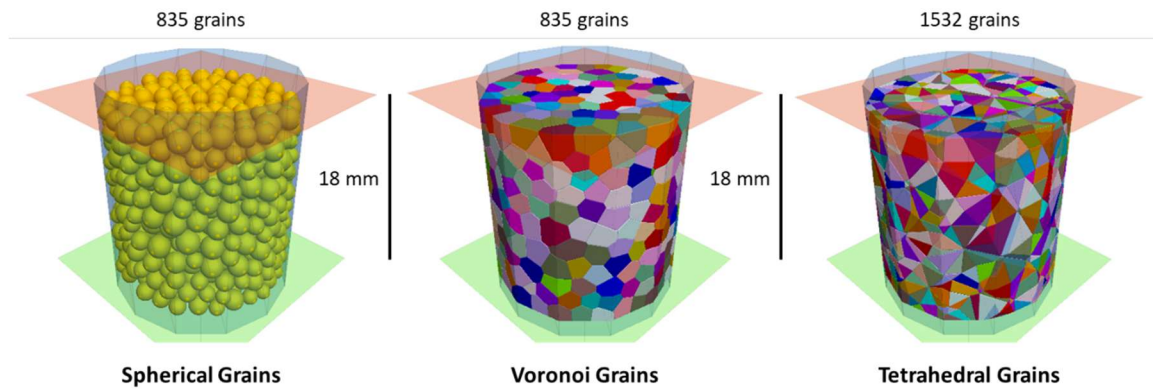


Figure 44 *Flat-jointed materials with spherical, Voronoi and tetrahedral grains.*
(From Fig. 9 of Potyondy et al. [2020])