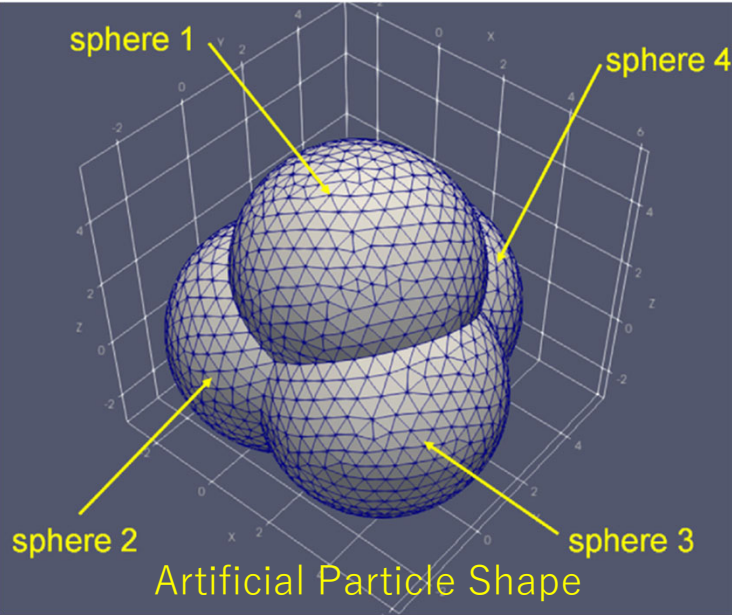


6. Appendix: Particle Shape and Material Properties

Nakata et al. (2022) reported the testing procedures used to determine the material properties of the artificial particles.

Nakata et al., 2022. Experimental data of 3D printed granular material for verification of discrete element modeling simulation. Soils and Foundations, 101178.



Coordinates of Sphere Centers (unit: mm)

Sphere Element	Coordinates (in terms of R)	Numerical Value (for $R = 3.101 \text{ mm}$)
1	$\left(\frac{R}{2}, \frac{\sqrt{3}R}{6}, \frac{\sqrt{6}R}{3}\right)$	(1.551, 0.895, 2.532)
2	(0, 0, 0)	(0.000, 0.000, 0.000)
3	(R , 0, 0)	(3.101, 0.000, 0.000)
4	$\left(\frac{R}{2}, \frac{\sqrt{3}R}{2}, 0\right)$	(1.551, 2.685, 0.000)

Fundamental properties of printing material.

Parameter (unit)	
Tensile strength (MPa)	40 – 55
Compressive strength (MPa)	70 – 80
Poisson’s ratio	0.37
Tensile elastic modulus (MPa)	1800 – 2100
Bulk elastic modulus (MPa)	2307 – 2692
Shear elastic modulus (MPa)	657 – 766
Density (kg/m^3)	1111

Material properties of artificial particle obtained from several tests

Parameter	Test	Object	Mean	Standard deviation
Static friction angle	Inclined surface test	Resin - resin	35.5 degree	3.82 degree
		Acrylic - resin	27.2 degree	4.26 degree
Dynamic friction angle	Inclined surface test	Resin - resin	29.36 degree	2.42 degree
		Acrylic - resin	16.5 degree	7.35 degree
Coefficient of restitution	Drop test	Resin - resin	0.809	0.0115
		Acrylic - resin	0.790	0.0280
Shear elastic stiffness	Cyclic uniaxial test	Resin	560MPa*	158MPa*
		for horizontal bedding plane	680 MPa	70 MPa
		for vertical bedding plane	440 MPa	130 MPa
Normal spring coefficient	Cyclic uniaxial test	Resin	$6.0 \times 10^4 \text{ N/m}^*$	$1.1 \times 10^4 \text{ N/m}^*$
		for horizontal bedding plane	$6.9 \times 10^4 \text{ N/m}^*$	$0.5 \times 10^4 \text{ N/m}^*$
		for vertical bedding plane	$5.2 \times 10^4 \text{ N/m}^*$	$0.5 \times 10^4 \text{ N/m}^*$

*: mean value for both mean values of horizontal and vertical cases.