Numerical investigation of compaction effects on pore structure and hydraulic properties of fluid-saturated granular materials

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Introduction

Temporal changes in the soil hydraulic properties due to compaction can affect a range of near-surface and subsurface flow processes. Soil compaction is generally accompanied by the removal of the soil air, change in the soil structure, reduction in the total volume of pores, alteration in Pore Size Distribution (PSD), and increase in the soil strength. Thus, soil compaction which can induce substantial changes in soil physical, chemical and biological processes, has significant influences on many environmental issues, such as soil erosion, soil degradation and pollution of surface water [1]. Understanding and characterization of the evolution of pore structure during compaction are important to predict the properties of a compact, such as conductivity, permeability, pressure saturation relations and residual saturation in porous media.

Despite available theories and evidence on the nature of soil compaction, efforts to capture the temporal dynamics of soil PSD and incorporate the derived hydraulic properties in modeling studies are quite rare. Studies of compaction effects on the soil hydraulic properties require precise studies of the geometry of sand grains and related pore structures in terms of the prevailing pore body and pore throat sizes. It would be very demanding, if not impossible, to study the PSD evolution during compaction by the previously available experimental methods. And there seems to be no such experimental data in the literature. Numerical simulations are therefore very useful in studying this problem.

Studies of binary particle mixtures provide useful insight into the effects of fine particles on the void ratio of natural multi-sized geomaterials. The relative amount of fine particles in a mixture significantly changes the void structure and influences the behavior of such materials [2].

The focus of this research is placed on the numerical investigation of compaction effects on pore structure and hydraulic properties of fluid-saturated granular media. The granular porous media in this study is glass beads which are simulated as idealized grain geometries which are fully saturated in water. For this purpose, numerical simulations are performed for a variety of sphere packing (mono-sized particles and binary mixtures).

Methods

- ❖ **Numerical Investigation** ➡ Fluid-Solid Coupling Method
- **Methods:**
  - Solid phase: Discrete Element Method (DEM) [3]
  - Fluid phase: Pore-scale Finite Volume (PFV) [4]

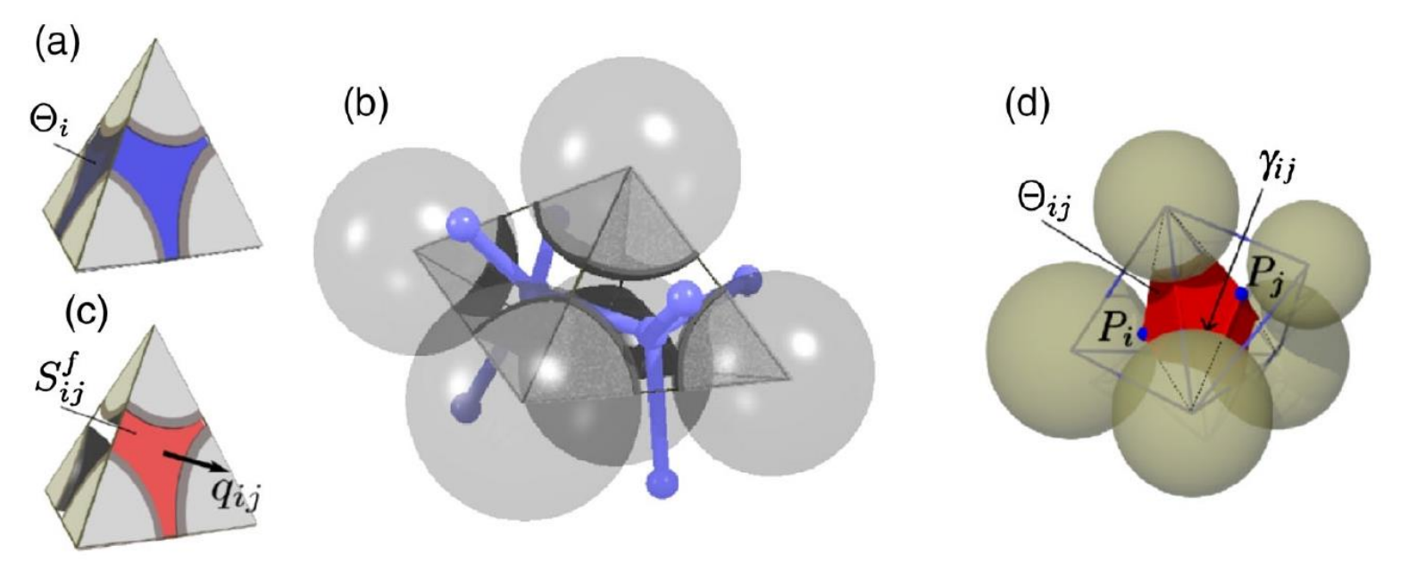

Fig 1. DEM-PFV method (a) Volume of fluid in a pore, (b) pore local connections, (c) fluid domain of pore, (d) pore partition for hydraulic radius [4]

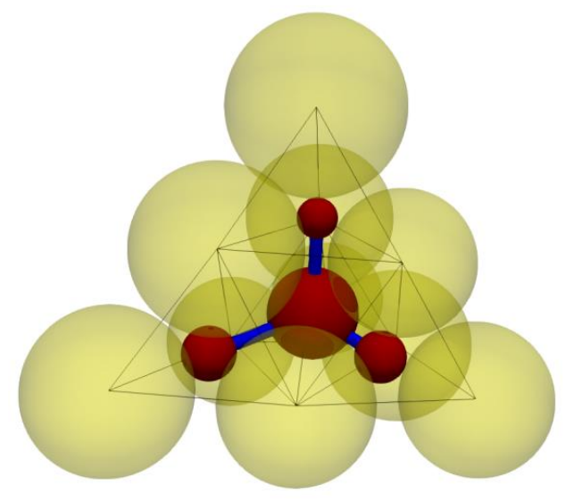

Fig 2. Pore body and pore throat

- **Pore Network Extraction:** Delaunay Triangulation and Voronoi Diagram

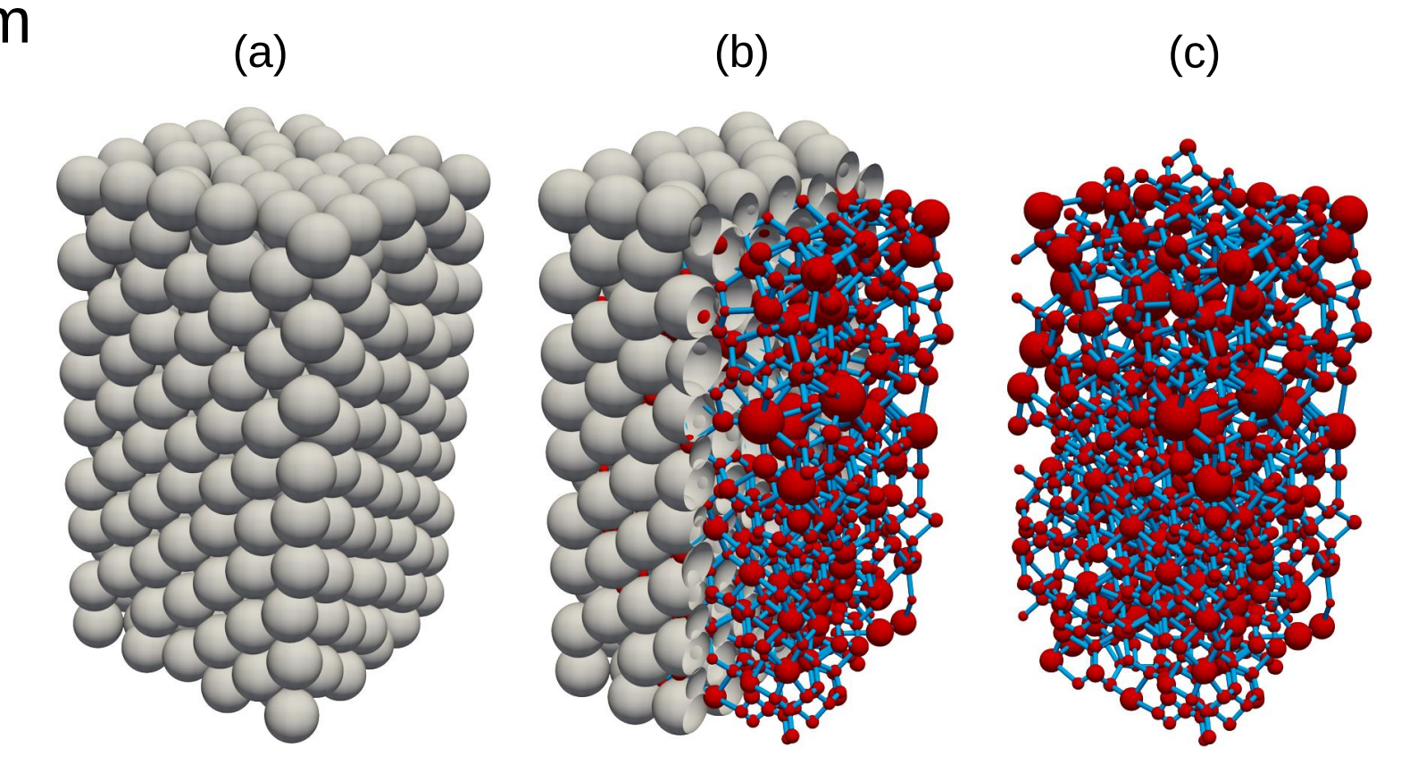

Fig 3. (a) Glass beads packing (b) the packing and extracted pore networks (3) pore networks

- **Numerical Modeling** ➡ **Yade [5] - Open Source DEM**
- **Compaction:**
  - First stage: **Triaxial** Compaction
  - Second stage: **Oedometric** Compaction

Results

❖ A) Mono-sized particle packing

For mono-sized particle packing, the glass beads with 2, 1, 0.6 and 0.4 mm diameters were considered for the numerical modeling.

- **Effect of compaction on porosity and pore networks**

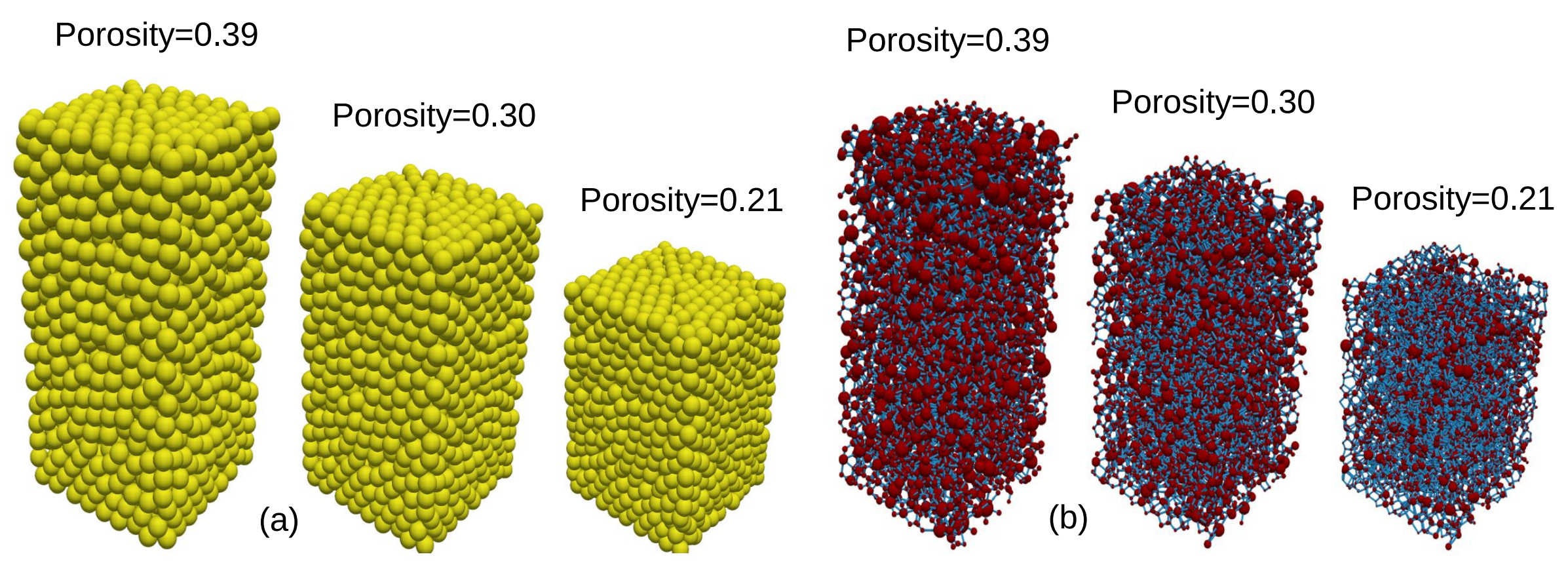

Fig 4. (a) sphere packing and (b) pore networks of 2 mm packing after compaction

- **Effect of compaction on pore size distribution**

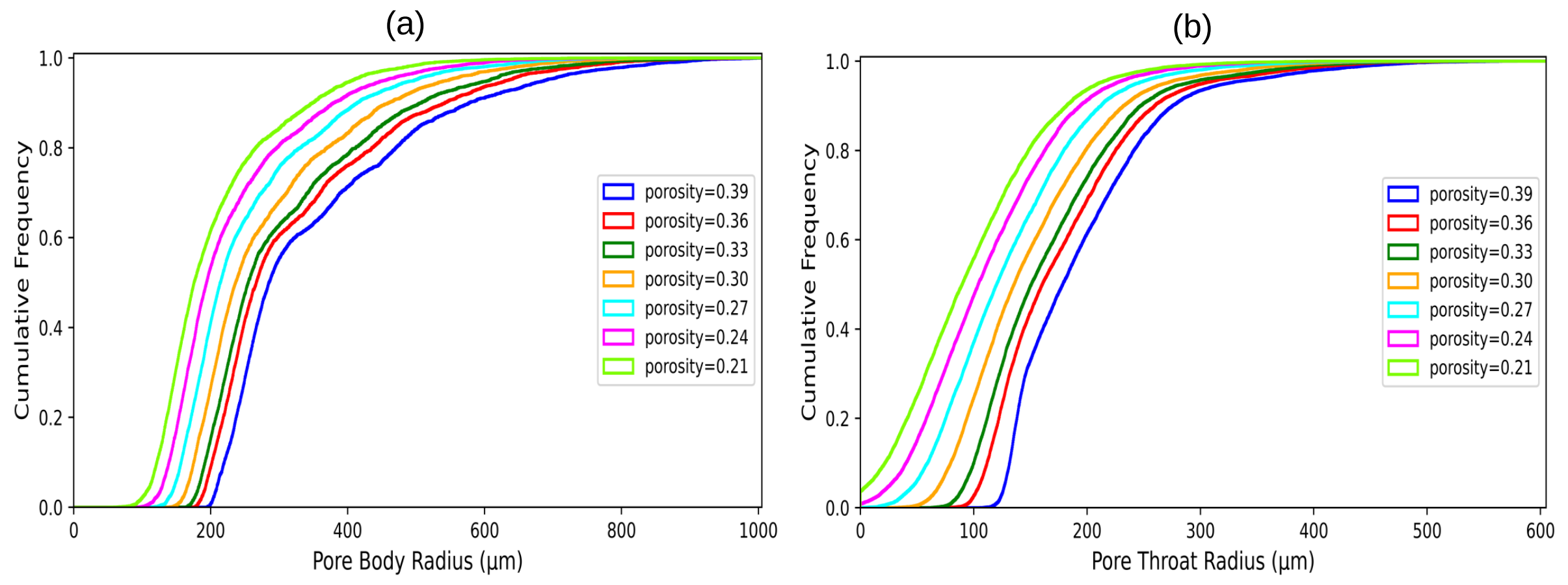

Fig 5. Effects of compaction on (a) pore body and (b) pore throat size distributions of 2 mm packing

- **Effect of compaction on average pore radius**

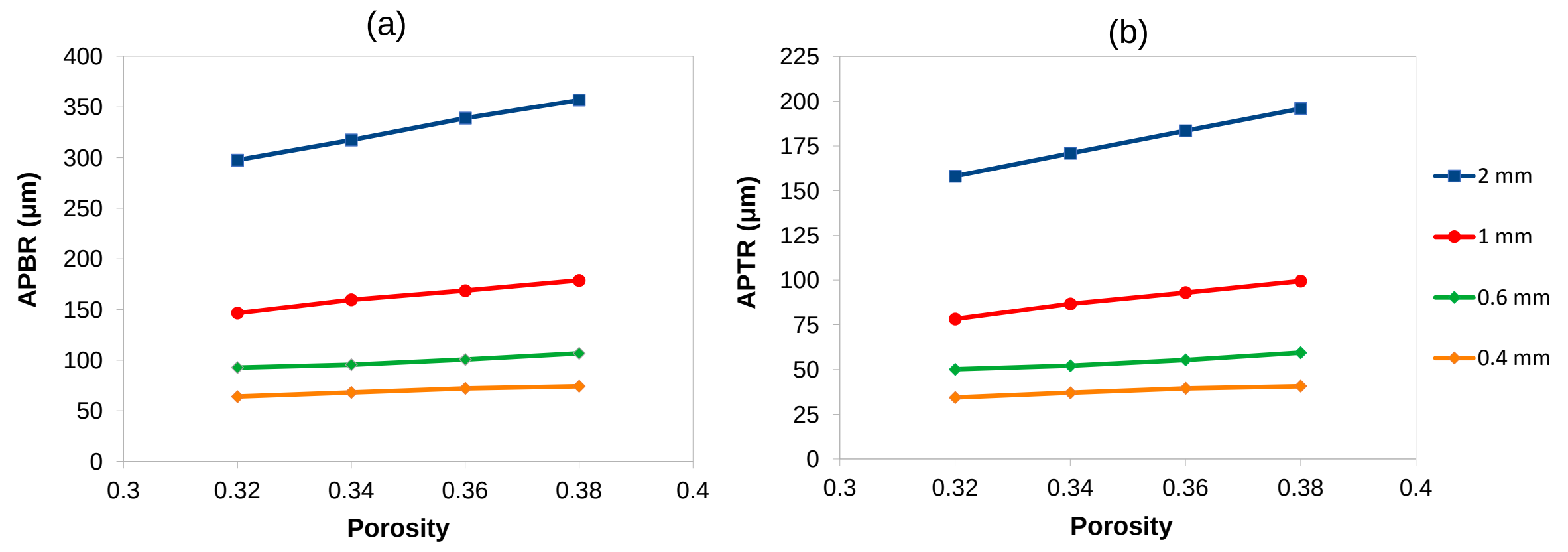

Fig 6. Effects of compaction on average (a) pore body and (b) pore throat radii in mono-sized packings

- **Effect of compaction on permeability of mono-sized particles**

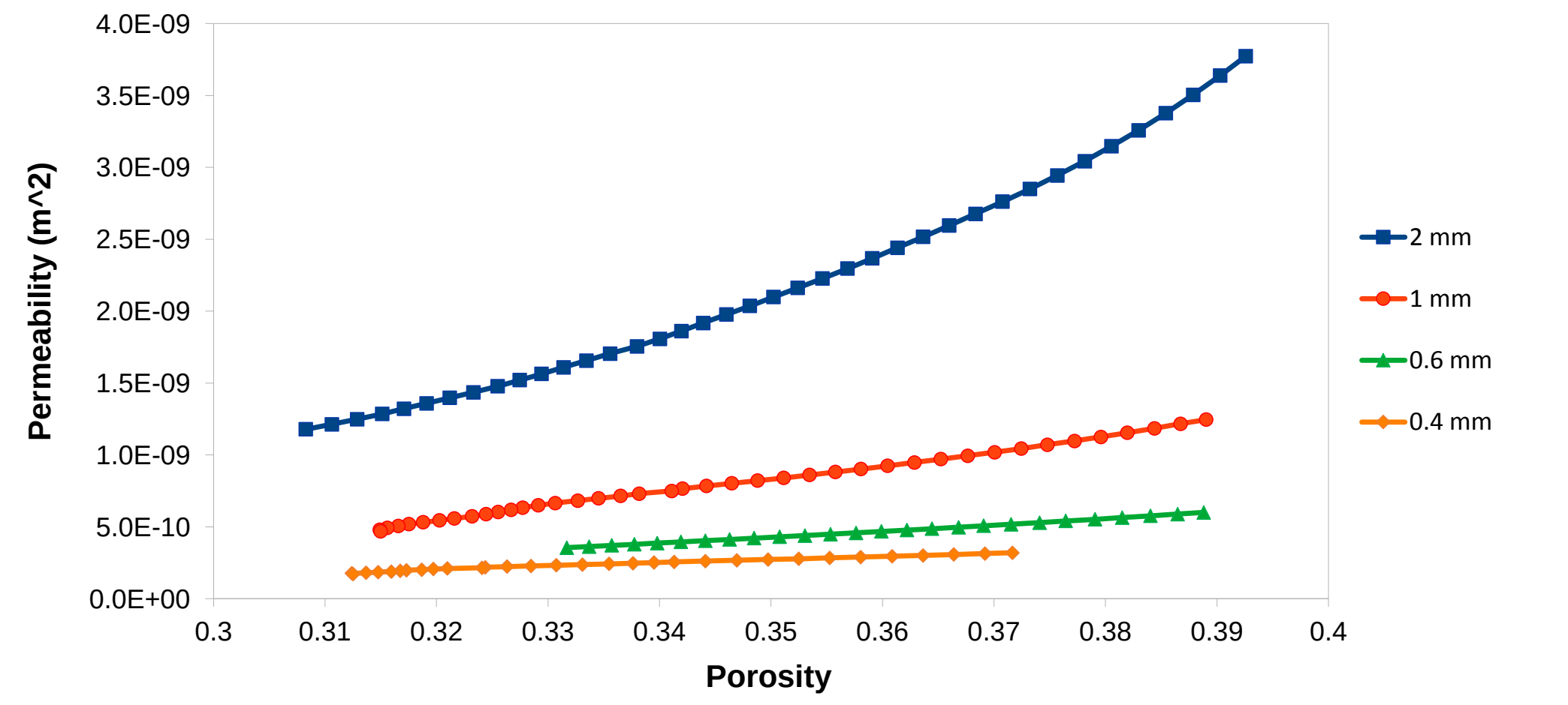

Fig 7. Effects of compaction on permeability of mono-sized particle packings

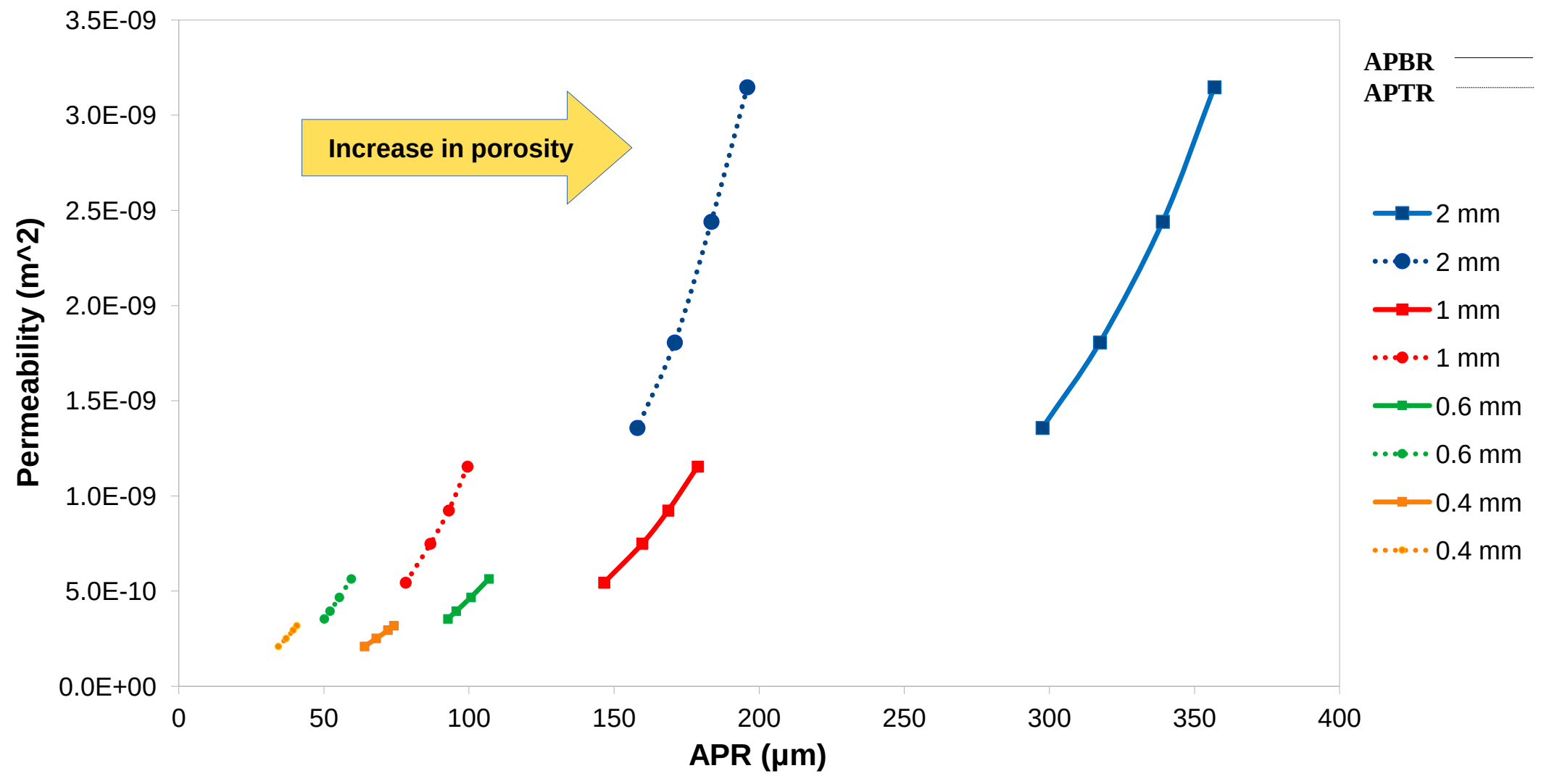

Fig 8. Effects of compaction on permeability of mono-size packings with respect to average pore radius

Results

❖ B) Binary particle mixtures

For binary particle mixtures, the glass beads with 2 mm diameters were considered coarse particles, and the glass beads with 1, 0.6 and 0.4 mm diameters were considered fine particles. Therefore, binary particle mixtures in three different Aspect Ratios (AR): 2, 3.3 and 5 with different fine particle percentages were used for the modeling.

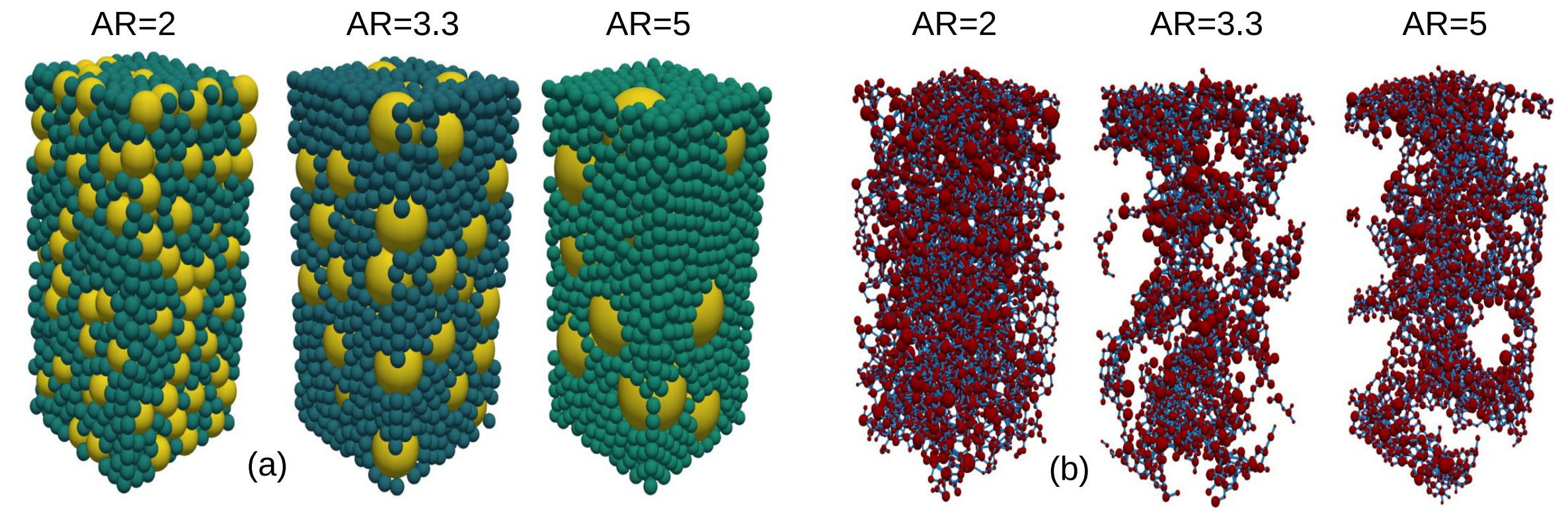

Fig 9. (a) sphere packing and (b) pore networks of binary mixtures with different aspect ratios (50% fines)

- **Effect of fine particles percentage on porosity of binary mixtures**

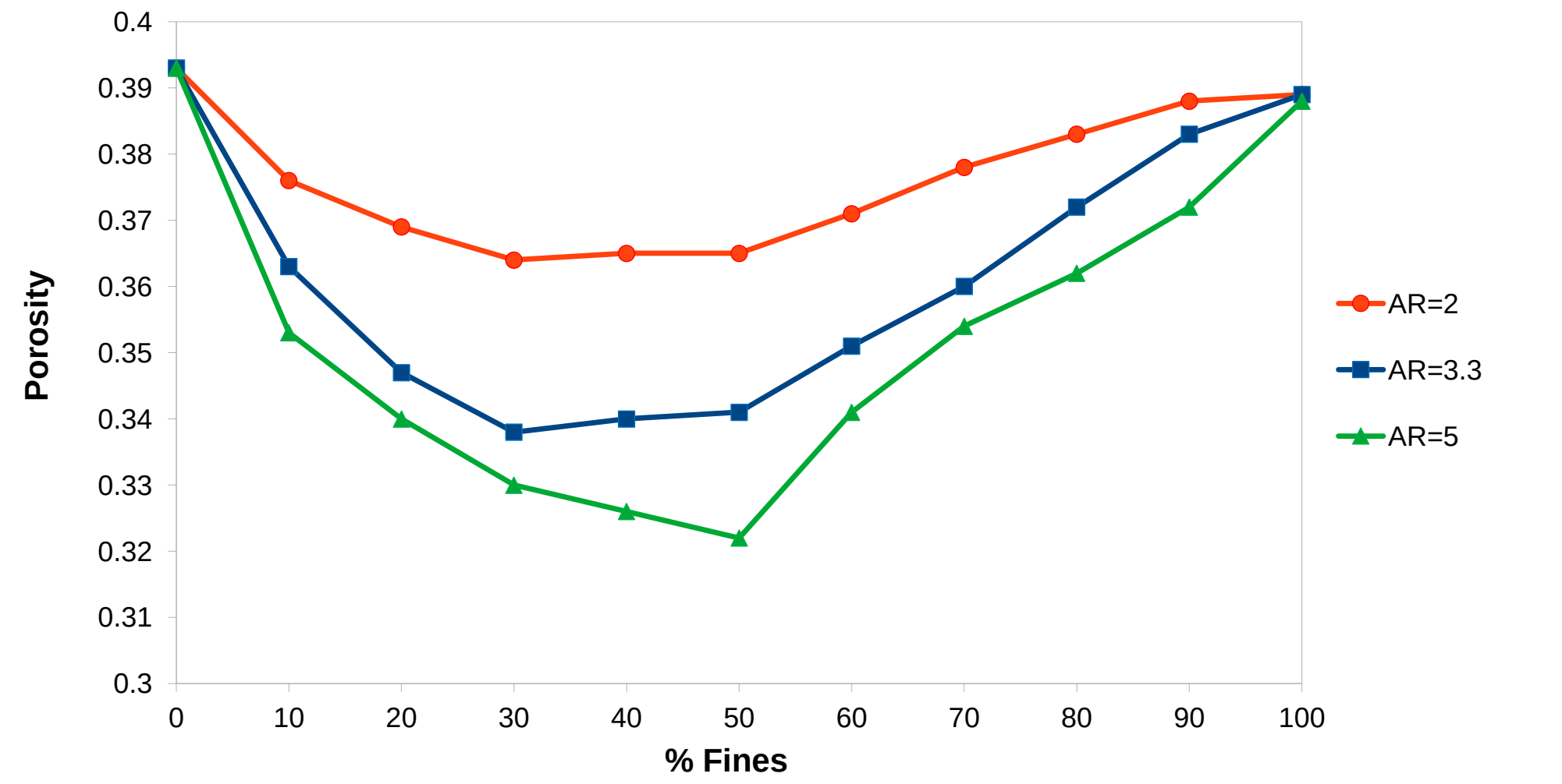

Fig 10. Summary of porosity data for all binary particle mixtures

- **Effect of fine particles percentage on permeability of binary mixtures**

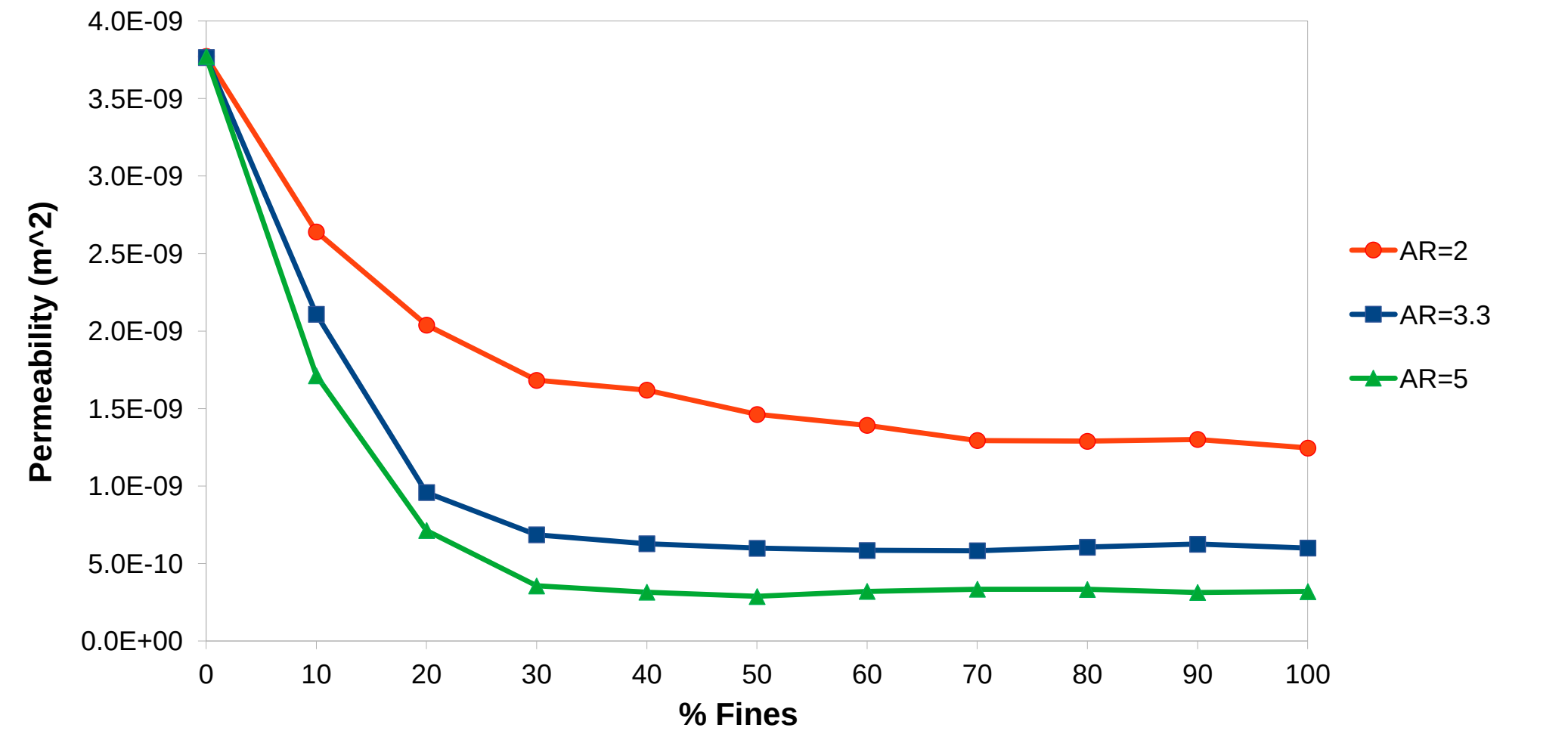

Fig 11. Effects of fine particles percentage on permeability of all binary particle mixtures (porosity 0.33)

- **Effect of compaction on pore size distribution**

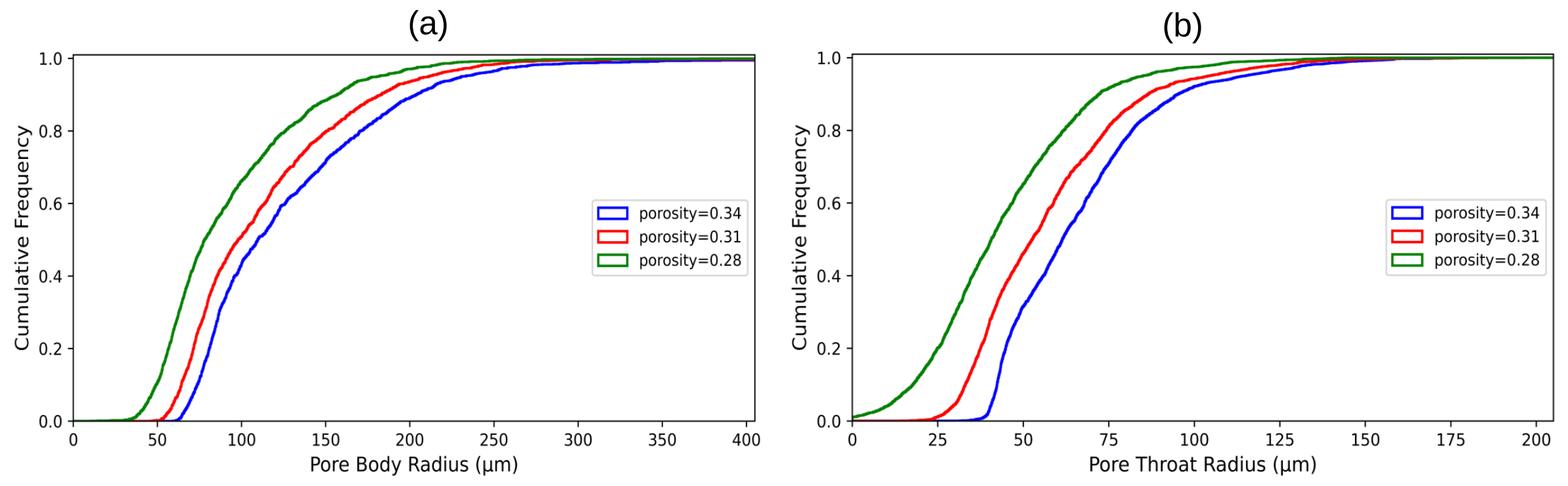

Fig 12. Effects of compaction on (a) pore body and (b) pore throat size distributions in AR=3.3 (40% fines)

- **Effect of compaction on permeability of binary particle mixtures**

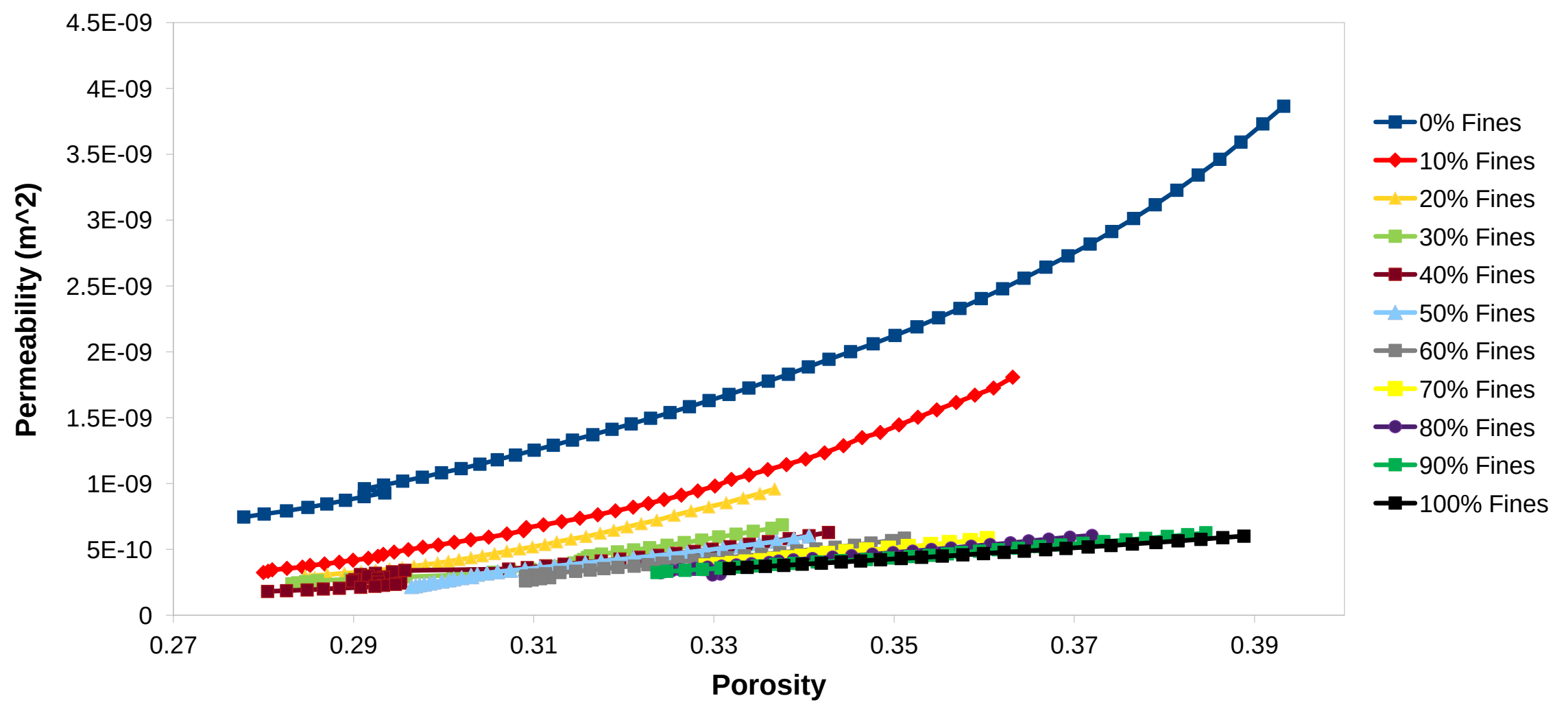

Fig 13. Effects of compaction on permeability of binary mixture with AR=3.3

Conclusions

The results of this research are in good agreement with previous numerical studies [1,2]. The results of this study help to better understand the effects of sand compaction on soil pore structure and macroscopic soil hydraulic properties such as porosity and permeability.

The conclusions of this study are as follows:

- Compaction caused a decrease in the porosity and a uniform change in the pore space.
- An increase in the degree of compaction reduced the pore body and throat radii.
- An exponential decrease in permeability as a function of porosity following compaction is observed. The results showed that the changes in permeability are consistent with the changes in pore body and throat radii during compaction.
- An exponential decrease in permeability as a function of the average pore radius following compaction is observed.
- The properties of binary mixture are highly dependent on their aspect ratios and percentage of fine particles.
- Minimum porosities were reached in larger AR and 20-60% fines in binary mixtures.
- An exponential decrease in permeability as a function of fine particle percentage is observed.

Future Research

Understanding the impact of compaction on soil pore structure and its hydraulic properties is crucial for developing effective land management practices that can help maintain soil health and productivity. Our research aims to provide a quantitative framework to soil compaction researchers and others for the evolution of the PSD and to stimulate interest to pursue experimental and theoretical investigations of PSD dynamics.

Recently, using non-Newtonian fluids for obtaining the PSD of porous media has been identified as a promising safe and cheap alternative method to mercury intrusion porosimetry (MIP) and X-ray computed tomography (CT). In contrast to water (as a Newtonian fluid), the flow of some non-Newtonian fluids through porous media is related to the geometry of the pores in a way that allows backtracking of some information, such as the approximate distribution of the effective pore sizes.

Our project would be based on both laboratory experiments and computational modeling, with an emphasis on the link between the experiments and the modeling. In the experimental part, we will use a triaxial chamber to compact the soil saturated in shear-thinning fluids (xanthan gum solutions) in different concentrations. Regarding the numerical modeling, the DEM-PFV method will be developed for non-Newtonian fluids.

References

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