9 Effective Transport Properties of Porous Media by Modeling

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9.1 INTRODUCTION

For many engineering materials, it has been known since long time ago that there is a rather weak correlation between the properties of the ingredients and those of the resulting products, as revealed by the pioneer works of Griffith[1] on material strength, and independently of Peirce[2] on the weakest link theorem. That is, constituents with improved quality cannot assure a better product, and the internal structure—the way the constituents are arranged in the material system—is just as, if not more, important. On the other hand, the inclusion of different components into a material can be beneficial, acting as reinforcement or supplements to improve the performance of the material—alloys and fiber-reinforced composite are just such examples. Nevertheless, analysis and prediction of behaviors of composites are in general much more intricate. Once mixed together, the components of different types will more or less interact with each other, and the properties at the interfacial

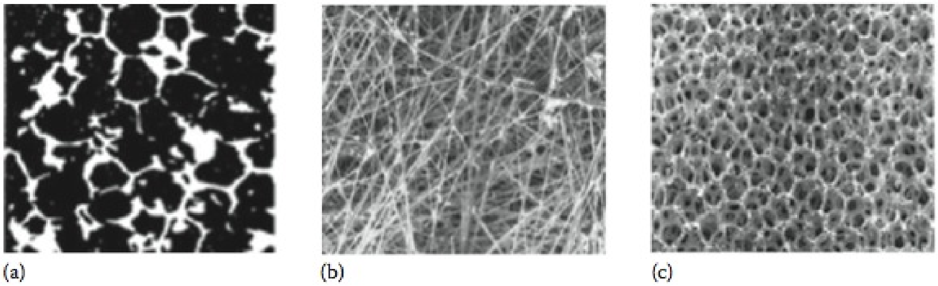

FIGURE 9.1 Three types of porous structures: (a) typical cross section of sand soil, (b) fibrous layer in PEM fuel cells, and (c) porous open-cell foam.

region will exhibit a transition from one component to the other.[3–6] Such effects usually turn even more complicated when the components are at different phase states, such as in a semifrozen soil system.[7,8] The porous multiphase materials are increasingly used in various fields, but analysis and investigation efforts are severely lagging behind.[9,10]

The challenges in studying porous media come mainly from the inherent variety and randomness of their internal microstructures and the coupling between the components of different phases.[11] Figure 9.1 shows three typical such material structures having extensive and important applications. Figure 9.1a shows a typical cross section of sand soil with granular structure.[12–14] For soil, the black stands for the solid phase and the white is the void. The similar structures can be found in wood[15,16] or food.[17–20] For some cases of food, like the bread, since there are lots of granular pores in the flour, the white becomes the solid frame and the black is the pore/voids. The next type is a fibrous structure as shown in Figure 9.1b of another solid–void mixture with the solid in a slender and oriented form, usually existing in polymeric and biomaterials.[21] For a long time, the porous transport layer (PTL) in PEM fuel cell has been thought to possess a granular porous structure; however, very recent investigations have demonstrated that the PTL actually possesses a fibrous structure that exhibits quite different transport behaviors from those with granular structures.[22,23] Another example of fibrous materials is the advanced fiber-reinforced composites where fibers are utilized to enhance the mechanical and thermal properties of the composites up to surprisingly high levels.[24–28] Figure 9.1c shows a cross section of an open-cell foam material.[29–32] It has a netlike porous structure that leads, for metal–foam materials, to the interesting combination of high porosity and low density yet very high thermal and electric conductivities. Such foam materials, typically two-phase systems of solid and void, have played critical roles in advanced aircraft designs, for instance, to improve the catalytic surfaces and enhance the heat exchanger systems.

Given the complexities of the porous systems, the concept of effective properties has become widely accepted.[9–11,33–46] Porous materials are multicomponent and/or multiphase (state) systems. As such, the behaviors of the material are dictated by each and every component of different phases, that is, its overall macroscopic property is not equal to that of any single constituent, rather a collective one contributed by all components forming the system. Therefore, the effective property is actually the equivalent property of a hypothetical simple material (homogeneous with single component and phase), which yields the same response as that of the complex one at the same given conditions and excitations.[9,33–35] Note that, however, this mapping between the complex material system and its equivalent simple material is not unique. The different components and phases in the complex system will exhibit diverse and varying behaviors under different ambient conditions and external excitations.[9,34,47,48] The system overall properties are thus the functions of these external factors as well, thus leading to different equivalent simple systems.[9,33,34,47] Research and investigation of the effective properties of complex materials are important because not only do the porous media/materials have so many significant applications, but it can also shed new light on, and drive further developments of, the related mathematical, physical, and engineering theories.[47–58]