# **11. Porous and cellular ceramics**

## **11.0 Introduction**

Ceramics are seldom completely dense, because in most cases pores cannot completely avoided. Porous ceramics, however, are those where the void space is deliberately introduced to fulfill certain functions. *Total porosity* (volume fraction of pores):  $\phi = 1 - \rho_r$ , where  $\rho_r = \rho/\rho_0$  is the *relative density* ( $\rho = bulk$  density,  $\rho_0 = theoretical density of the solid phase (matrix or skeleton), in practice the density of the fully dense (densely sintered) polycrystalline ceramic. The total porosity is the sum of$ *open*porosity (measurable by intrusion methods, e.g. mercury intrusion) and*closed*porosity (measurable by microscopic image analysis or calculable from Archimedes measurements, when the bulk density is measured and the theoretical density is known).

*Cellular materials* are high-porosity materials with  $\phi > 70$  % (2D arrays – honeycombs or 3D networks – foams with open or closed cells in deterministic or random spatial arrangement). When the pores are nanosized, these high-porosity materials are called *aero- or xerogels*.

### 11.1 Preparation of porous and cellular ceramics

- Partial sintering
- Sintering of hollow spheres (e.g. Al<sub>2</sub>O<sub>3</sub> microballoons)
- Pyrolysis of organic or biopolymer pore-forming agents (e.g. polystyrene, starch)
- Direct foaming of suspensions by foaming agents
- Polymer replica techniques (coating of polymer foams and subsequent burnout)
- Biotemplating (e.g. infiltration of carbonized wood)
- Rapid prototyping
- Extrusion (only for translationally symmetric bodies, i.e. 2D honeycombs such as cordierite catalyst supports or, in larger scale, insulating lightweight bricks)

### 11.2 Microstructure and properties of porous and cellular ceramics

Problem: The effective properties of porous ceramics are not a simple function of porosity, but depend on all features of the microstructure.

Popular models to describe the porosity-property relations are based on load-bearing area, especially the minimum solid cross-sectional area (Rice's MSA-models), but these are mostly based on periodic unit cells with very special pore shapes, i.e.

- pores between solid spheres,
- isolated (closed) spherical pores,
- cylindrical pores,

and are usually not realistic for random materials. Explicit calculations are lengthy and the predictive capability of the resulting equations is low (valid only for very special cases).

3D cellular ceramics (i.e. open or closed cell foams) consist of cell struts (edges) and walls (faces) with thickness t and edge length L: Gibson-Ashby theory (unit cell approach combined with dimensional analysis)  $\rightarrow$  relative densities

• Open cell foam: 
$$\rho_r \propto \left(\frac{t}{L}\right)^2$$

• Closed cell foam: 
$$\rho_r \propto \left(\frac{t}{L}\right)$$
,

where the proportionality constants depend on the cell shape (cube, rhombic dodecahedron, tetrakaidecahedron or Gibson-Ashby unit cell, in which even macroscopic tension leads locally to bending). Note that collection of solid in the nodes of the struts (in open cell materials) or at the struts or edges (in closed cell materials) may change these idealized relations. In practice the wall or struts can be porous themselves  $\rightarrow$  relative density has to be replaced by another normalized density >  $\rho_r$  (Green). Many ceramic foams have cells with approx. 14 faces on the average, each with an average number of approx. 5 edges (corresponding to a tetrakaidecahedron model).

Effective Young's modulus according to the Gibson-Ashby theory (dimensional analysis):

- Open cell foam:  $E_r = \rho_r^2$
- Closed cell foam:  $E_r = \zeta^2 \rho_r^2 + (1 \zeta) \rho_r$ ,

where  $\zeta$  is the fraction of solid in the cell edges (related to the total volume of solid in the walls, including edges). Brezny and Green have successfully applied the Gibson-Ashby theory to analyze measured data on alumina, alumina-mullite, alumina-zirconia and vitreous carbon open cell foams. Similarly, foamed glasses and sintered hollow glass spheres have been successfully modeled as closed cell foams. Further analyses based on this theory concern strength, fracture toughness, thermal shock behavior and creep.

### 11.3 Applications of porous and cellular ceramics

Porous and cellular materials are generally useful in civil engineering design to minimize the weight of structures (constructions), where highest possible strength and stiffness are required (structural applications as lightweight materials). Compared to their dense counterparts porous and cellular ceramics can exhibit relatively high fracture toughness and gradual damage accumulation instead of catastrophic failure.

- Refractory insulation materials
- Thermal and acoustic insulation materials
- Lightweight materials
- Catalyst supports
- High-temperature filters or membranes.