



Functionally graded saturated porous structures: A review

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Abstract

Functionally graded porous materials are porous structures with porosity gradient distributed over volume. The porous structures having valuable properties, such as lightweight and excellent energy absorption, have been considerably used in different engineering implementations such as aerospace, biomedical, and other industries. Two limit cases are usually considered for the porous structures: 1- The fluid pressure of pores is zero and 2- The pores fill by incompressible fluid and is in saturated condition. Many investigations have been reported on the behavior of functionally graded porous structures. But, most of them are concerned on the drained conditions. However, the investigations into saturated porous structures are limited in number. The present paper (a) specially reviews the mechanical properties of functionally graded saturated porous structures; (b) presents a comprehensive review on the mechanical analyses of these structures in saturated condition; (c) discusses the challenges and possible future works.

Keywords: Functionally graded porous; Saturated; Mechanical analyses; Biot.

Nomenclature:

e_0 : Porosity coefficient

e_m : Porosity coefficient for mass density

\bar{M} : Biot's modulus

ν_u : Undrained Poisson's ratio

ν : Poisson's ratio

β : Skempton coefficient

G: Shear modulus

α : Biot coefficient of effective stress

ε_{kk} : Volumetric strain

Ψ : Variation of fluid volume content

K_u : Bulk modulus in the undrained state

K: Bulk modulus in the drained state

C_p : Fluid Compressibility in the pores

C_s : Solid Compressibility

δ_{ij} : Kronecker delta

p: Pore fluid pressure

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1. Introduction

Porous material is a material containing pores filled by a fluid. There are lots of examples for porous materials in the nature and industries (Figure 1). The skeletal part of the material is called matrix or frame and is usually a solid. The porosity is the main characteristics of a porous material. Permeability, tensile strength and electrical conductivity depend on the properties of the matrix and those of the fluid within the pores. If the fluid pressure of pores be zero, the porous structure is called foam. Metallic or polymeric foam depends on the material of skeletal part. Porous structures are widely applied in many industries such as: aerospace, marine, civil, etc. By introducing functionally graded materials (FGMs) [1-28] in which the mechanical properties vary continuously through the structure, functionally graded porous materials (FGPMs) have received much attention by researchers, recently. These are materials with porosity gradually changing throughout their volume. The pores are distributed in the base material with variation in porosity. The variation of porosity may be due to changes in density or size of the pores. Based on the cell structure, FGPMs can be open- or closed-cell structures. In open-cell structures, the pores are interconnected; while in closed-cell structures, each cell is enclosed and isolated by the base material. The gradual change of porosity can impart desirable properties. Examples of nature FGPMs include bamboo with density gradients along the radial direction in its cross section [29], human cancellous bone which is sponge-like cellular structure [30], banana peel [31], and elk antler [32], etc. Artificial FGPMs, such as biomedical implants [32, 33], cushioning materials [34], filtration materials, drug delivery devices [35], and permeable interlocking pavement, etc. are also widely used in industries and daily lives.

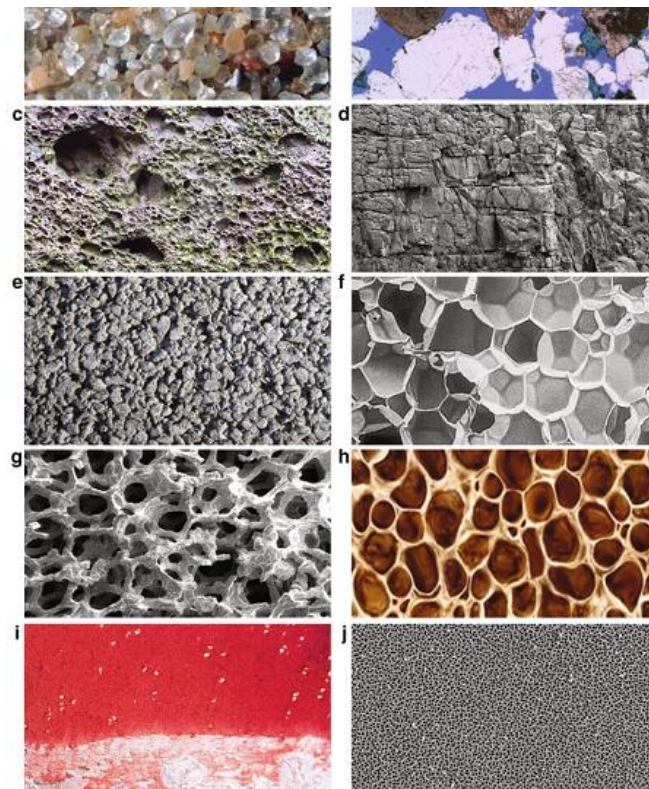


Fig. 1. Various porous materials. (a) Sand. (b) Sandstone. (c) Volcanic rock. (d) Fractured rock. (e) Pervious concrete. (f) Polyurethane foam. (g) Metal foam. (h) Bone with osteoporosis. (i) Articular cartilage. (j) Nanoporous alumina [32].

The extraction of law for description of these materials is a big challenge due to the fluid solid interactions. Two limit states are usually considered for these structures because of their practical application. First state is when the fluid pressure of pores is zero and the second state is when the pores fill by incompressible fluid and is in saturated condition. By this way the fluid be trapped in the pores and the pressure of pores are in the maximum level. Therefore, the stiffness of structures considerably increases. Biot [36] is the pioneer who has studied the behavior of porous structures in saturated condition. Actually, Biot derived the stress- strain relationship of these structures for

the first time. After that many researchers have been conducted a lot of investigation about structural behavior of various shapes of these structures such as beam, plate and shells structures. They considered the arrangement of pores, called porosity distribution, and the size of pores, called porosity coefficient, as a design variable. The kind of fluid which fills the pores can be modeled by Biot modulus. Biot modulus describes the ratio of average pressure of local pores to global pressure which is applied to structure. The details of Biot constitutive law is described in Section 2.

Many investigations have been reported on the behavior of functionally graded porous structures. But, most of which are concerned on the drained conditions [37-49]. In a drained condition, the fluid compressibility inside the cavities is in maximum level, and the structure's behavior represents that of without fluid. In this case, the simple Hooke's law applies for modeling the stress-strain relationships of porous structure [50]. However, the investigations on saturated porous structures are limited in number which is reviewed here in details.

This review article is organized as follows. Section 1 reviews the investigations into FG saturated structures. Section 2 reviews assumption of Biot theory and constitutive law for saturated porous materials followed by Section 3 in which key technical challenges and future research directions in this emerging area are discussed and identified.

There are a lot of investigations on saturated porous structures. In details, Theodorakopoulos and Beskos have extended the classical theory of thin rectangular plates to porous materials including Biot's stress-strain relations in porous media. They have established two coupled governing equations and have given the solutions for a simply supported plate by extending Navier's algebraic solution to the porous case. Leclair *et al.* [51] presented the vibrations of a rectangular saturated porous plate described by two coupled equations involving the time and space derivatives of the deflection and of the relative fluid-solid motion. By using Galerkin's variational method and classical theory of plates, the equations were solved. Buckling of porous beams with varying properties was described by Magnucki and Stasiewicz [52]. They used shear deformation theory for solving the critical load, and also they have investigated the effect of porosity on the strength and buckling load of the beam. Magnucka-Blandzi [53] investigated the problem of axi-symmetrical deflection and buckling of circular porous-cellular plate with the geometric model of nonlinear hypothesis. Magnucka-Blandzi and Magnucki [54] performed an effective design of a sandwich beam with an FG metal foam core and calculated the optimal dimensionless parameters to maximize the critical force and minimize the beam mass. Debowski and Magnucki [55] explored the dynamic stability of a porous rectangular plate to study an axial compressed porous-cellular rectangular plate which is a generalization of sandwich or multilayer plates. Jabbari *et al.* [56] presented an analytical solution for buckling analysis of thin circular FG plates made of saturated porous-soft ferromagnetic materials in transverse magnetic field based on classical plate theory (CLPT). Jabbari *et al.* [57] investigated thermal buckling analysis of functionally graded thin circular plate made of saturated porous materials based on Love-Kirchhoff hypothesis sense and utilizing analytical solution. Based on classical plate theory and shooting method, axisymmetric post-buckling behavior of saturated porous circular plates was presented by Feyzi and Khorshidvand [58]. Rezaei and Saidi [59] presented an analytical solution bases on Navier method for the influence of coupled solid-fluid deformation on natural frequencies of fluid saturated porous plates based on Mindlin plate theory. Analytical solution for deflection and vibration analysis of higher-order shear deformable compositionally graded porous plate were presented by Ebrahimi and Habibi [60]. Panah *et al.* [61] investigated pore pressure and porosity effects on bending and thermal postbuckling behavior of FG saturated porous circular plates based on Love-Kirchhoff theory and by using GDQM. Mojahedin *et al.* [62] performed an investigation about free vibration of functionally graded thin beams made of saturated porous materials based on Euler-Bernoulli theory and by employing analytical solution. A closed form solution for axisymmetric buckling of saturated circular porous-cellular plate based on first-order shear deformation theory was presented by Mojahedin *et al.* [63]. Abjadi *et al.* [64] presented an analytical solution for axisymmetric elasticity solution for an undrained saturated poro-piezoelectric thick disk. Mojahedin *et al.* [65] presented an analytical solution for buckling analysis of functionally graded circular plates made of saturated porous materials based on higher order shear deformation theory. Panah *et al.* [66] investigated axisymmetric nonlinear behavior of functionally graded saturated poroelastic circular plates under thermo-mechanical loading based on CLPT and by employing GDQM in conjunction with Newton-Raphson iterative algorithm. Babaei *et al.* [67] studied the influences of porosity on elastic stability of toroidal shell segments made of saturated porous functionally graded materials on the basis of classical thin shell theory and by applying analytical solution. By employing analytical method, mechanical buckling analysis of saturated porous functionally graded elliptical plates subjected to in-plane force resting on two parameters elastic foundation based on HSDT was presented by Sharifan and Jabbari [68]. Jabbari *et al.* presented an analytical solution for Mechanical buckling of FG saturated porous rectangular plate with piezoelectric actuators [69] and mechanical buckling of FG saturated porous rectangular plate under temperature field [70] based on CLPT. Exact solution for free vibration of thick rectangular plates made of porous materials based on Reddy's third-order shear deformation plate theory was presented by Rezaei and Saidi [71]. Rezaei and Saidi [72] presented an analytical solution for buckling response of moderately thick fluid-infiltrated porous annular

sector plates based on Mindlin plate theory. Askari *et al.* [73] presented an analytical solution based on Navier-type for free vibration analysis of porous smart plates based on Reddy's plate theory. An analytical study on the free vibration of moderately thick fluid-infiltrated porous annular sector plates based on Mindlin plate theory was presented by Rezaei and Saidi [74]. Rad *et al.* [75] presented an analytical solution for elastic buckling of fluid-infiltrated porous plates based on shear deformation theories. Akbari *et al.* [76] investigated free vibration analysis of thick sandwich cylindrical panels with saturated FG-porous core based on the third order shear deformation theory (TSDT) by using GDQ procedure. Arshid and Khorshidvand [77] applied GDQM to study natural frequencies of saturated porous FG circular plates integrated with piezoelectric actuators based on CLPT. On the higher-order thermal vibrations of FG saturated porous cylindrical micro-shells integrated with nanocomposite skins in viscoelastic medium based on sinusoidal theory was presented by Soleimani-Javid *et al.* [78]. Size-dependent magneto-electro-elastic vibration analysis of FG saturated porous annular/circular micro sandwich plates embedded with nano-composite face sheets subjected to multi-physical pre loads via GDQ approach based on Modified couple stress theory in conjunction with FSDT was presented by Amir *et al.* [79]. Natural frequency and dynamic analyses of functionally graded saturated porous annular sector plate and cylindrical panel based on 3D elasticity via FEM approach was presented by Babaei *et al.* [80]. Kiarasi *et al.* [81] applied a novel computational solution (mixed of FE and GDQ approach) to investigate three-dimensional buckling analysis of functionally graded saturated porous rectangular plates under combined loading conditions. Babaei *et al.* applied finite element method to investigate buckling, static [82] and dynamic [83] analyses of functionally graded saturated porous thick beam resting on foundation based on higher order beam theory. Babaei and Asemi [84] employed FEM based on Rayleigh–Ritz approach to investigate static response of saturated FG porous rotating cone based on 2D axisymmetric elasticity. Babaei *et al.* [85] performed an investigation about dynamic analysis of functionally graded rotating thick truncated cone made of saturated porous materials based on 2D axisymmetric elasticity via finite element method. Static response and free-vibration analysis of a functionally graded annular elliptical sector plate made of saturated porous material based on 3D finite element method was presented by Babaei *et al.* [86]. Flexural vibrations analysis of saturated porous circular plates using differential quadrature method based on CLPT was presented by Arshid and Khorshidvand [87]. Alhaifi *et al.* [88] studied large deflection analysis of functionally graded saturated porous rectangular plates on nonlinear elastic foundation via GDQM based on FSDT. Wu *et al.* [89] presented a review investigation on mechanical analysis of functionally graded porous structures with open cell pores. Mojahedin *et al.* [90] presented an exact solution for thermo-elastic analysis of saturated functionally graded porous beam based on the Timoshenko beam theory. Static behavior of functionally graded sandwich beam with fluid-infiltrated porous core based on various beam theories and using Navier's solution was presented by Hung *et al.* [91]. Vibration behavior of poroelastic thick curved panels with graded open-cell and saturated closed-cell porosities based on 3D elasticity theory and using the GDQ procedure was presented by Heshmati *et al.* [92]. Free vibration of saturated FG porous plate using GDQM in conjunction with third-order shear deformation and poroelasticity theories was presented by Ghorbanpour Arani *et al.* [93]. Arshid *et al.* [94] applied GDQ procedure to investigate the bending and buckling behaviors of heterogeneous temperature-dependent micro annular/circular porous sandwich plates integrated by FGPEM nano-Composite layers based on modified couple stress theory (MCST) in conjunction with FSDT. Quasi-3D tangential shear deformation theory for size-dependent free vibration analysis of three-layered FG porous micro rectangular plate integrated by nano-composite faces in hygrothermal environment was presented by Amir *et al.* [94]. Analytical solution for longitudinal vibration of a floating pile in saturated porous media based on a fictitious saturated soil pile model was presented by Cui *et al.* [95]. Sharifian and Jabbari [68] applied Ritz method to investigate mechanical buckling analysis of saturated porous functionally graded elliptical plates subjected to in-plane force resting on two parameters elastic foundation based on HSDT. Thermal and mechanical stability of a circular porous plate with piezoelectric actuators based on CLPT and using analytical procedure was presented by Mojahedin *et al.* [96]. Mojahedin *et al.* [57] presented an analytical solution for buckling analysis of a functionally graded thin circular plate made of saturated porous materials based on Love-Kirchhoff hypothesis.

2. Porosity distribution and constitutive law of saturated porous material

The literature review denotes that there are many mathematical functions reported for estimation of material properties of functionally graded saturated porous structures. In this manner, researchers generally consider three different patterns for porosity distribution along with the thickness of structure ($0 \leq z \leq h$; i.e. for a plate), which are (See Fig.2): a) porous material with nonlinear non-symmetric distribution (PNND) and b) nonlinear symmetric distribution (PNSD) and c) uniform distribution (PUD). In PNSD, the porosity is a symmetrical parabolic curve, which its value in the mid-plane is higher than the upper and lower surfaces (i.e. for a plate). In PNND, a non-uniform non-symmetric porosity distribution is considered; its value on the bottom surface is higher. Except for uniform porosities, the mechanical properties of the material in terms of shear modulus, Young's modulus and mass density, for a PNND and PNSD, are defined as [84-86]:

$$\begin{aligned}
 E &= E_1 [1 - e_0 Q] \\
 G &= G_1 [1 - e_0 Q] \\
 \rho &= \rho_1 [1 - e_m Q]
 \end{aligned} \tag{1}$$

in which

$$Q(z) = \begin{cases} (a)\text{PNND} & \cos\left(\frac{\pi \cdot z}{2 \cdot h}\right) \\ (b)\text{-PNSD} & \cos\left(\frac{\pi}{2} - \left(\frac{\pi \cdot z}{h}\right)\right) \end{cases} \tag{2}$$

and $0 \leq e_0 \leq 1$ is the porosity coefficient. Moreover, E_1 , G_1 and ρ_1 denote the Young's modulus, the shear modulus and the mass density at $z = h$ (for a PNND) and at $z = 0$ (for a PNSD), whereby $E_j = 2G_j(1 + \nu)$, $j = 0, 1$, and the Poisson's ratio ν is assumed to be constant in the z - direction (thickness direction).

Shear modulus, Young's modulus and density for Porous material with uniform distribution are as following [64-66]:

$$\begin{aligned}
 G &= G_1 [1 - e_0] \\
 E &= E_1 [1 - e_0] \\
 \rho &= \rho_1 [1 - e_m]
 \end{aligned} \tag{3}$$

The porosity coefficient e_0 and the porosity coefficient for mass density e_m are described by:

$$\begin{aligned}
 e_0 &= 1 - \frac{G_0}{G_1} = 1 - \frac{E_0}{E_1} \\
 e_m &= 1 - \sqrt{1 - e_0}
 \end{aligned} \tag{4}$$

Constitutive equations of FG saturated porous structure are based on Biot theory [11]. Biot theory deals with the displacements of the skeleton and the pore fluid movement, as well as their interactions due to the applied loads. The main assumptions of this theory are:

1. Infinitesimal transformations occur between the reference and current states of deformation. Displacements, strains and particle velocities are small. Consequently, the Eulerian and Lagrangian formulations coincide up to the first-order. The constitutive equations, dissipation forces, and kinetic momentum are linear (The strain energy, dissipation potential, and kinetic energies are quadratic forms in the field variables).

2. The principles of continuum mechanics can be applied to measurable macroscopic values. The macroscopic quantities used in Biot theory are volume averages of the corresponding microscopic quantities of the constituents.

3. The wavelength is large compared with the dimensions of a macroscopic elementary volume. This volume has well-defined properties, such as porosity, permeability and elastic modules, which are representative of the medium. Scattering effects are thus neglected.

4. The liquid phase is continuous. The matrix consists of the solid phase and disconnected pores, which do not contribute to the porosity.

5. In most cases, the material of the frame is isotropic. Anisotropy occurs by a preferential alignment of the pores (or cracks).

The linear poroelasticity theory of Biot has two characteristics [11]:

1. An increase of pore pressure induces a dilation of the pore.

2. The compression of the pore causes a rise of pore pressure. Particularly when the fluid cannot move freely within the network of pores. These coupled mechanisms display the time -dependent character of the mechanical behavior of the porous structures.

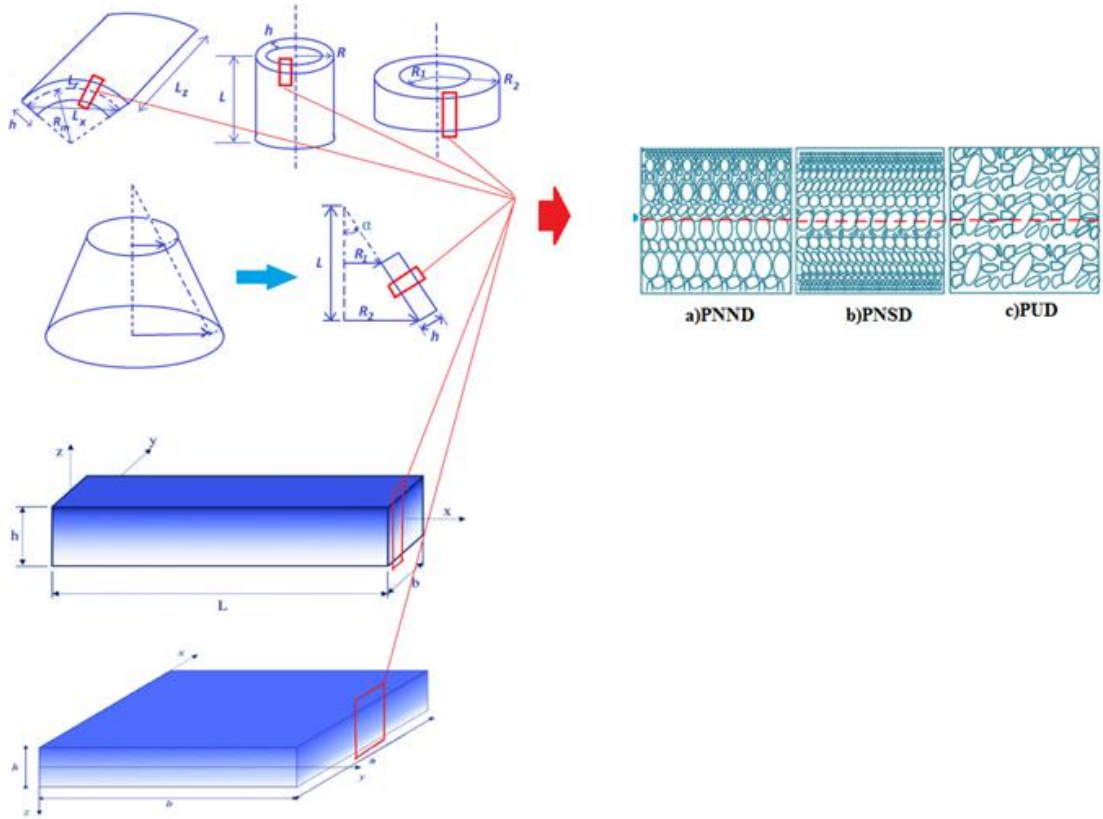


Fig. 2. Porosity distributions [60].

According to the Biot theory, the constitutive law is as [11]:

$$\sigma_{ij} = 2G \varepsilon_{ij} + \lambda \varepsilon_{kk} \delta_{ij} - p \alpha \delta_{ij}$$

$$p = \bar{M} (\Psi - \alpha \varepsilon_{kk})$$

$$\bar{M} = \frac{2G (v_u - v)}{\alpha^2 (1 - 2v_u)(1 - 2v)}$$

$$v_u = \frac{v + \alpha \beta (1 - 2v) / 3}{1 - \alpha \beta (1 - 2v) / 3}$$

$$v = \frac{\varepsilon_{jj}}{\varepsilon_{ii}} \Big|_{\sigma_{ii}=0, p=0, i \neq j}$$

$$v_u = \frac{\varepsilon_{jj}}{\varepsilon_{ii}} \Big|_{\sigma_{ii}=0, \Psi=0, i \neq j}$$

(5)

$$\alpha = 1 - \frac{K}{K_s}$$

$$K = \frac{2(1+\nu)}{3(1-2\nu)}G$$

$$K_u = \frac{2(1+\nu_u)}{3(1-2\nu_u)}G$$

where p denotes pore fluid pressure, for $p=0$, the Biot law reduces to conventional Hook's law or drained condition. λ is Lamé constant, δ_{ij} is Kronecker delta, and α is the Biot coefficient of effective stress ($0 < \alpha < 1$). The porosity effect on the behaviour of the porous material without fluid is indicated by this coefficient, and also states that due to porosity, the resistance of the body varies a few percents. \bar{M} is Biot's modulus, G is shear modulus, ν_u is undrained Poisson's ratio ($\nu < \nu_u < 0.5$), ϵ_{kk} is the volumetric strain, Ψ is variation of fluid volume content, K_s is the bulk modulus of a homogeneous material. β is the Skempton coefficient introducing the pore fluid property. It is an important dimensionless parameter for describing the effect of the fluid inside the cavities on the behavior of the porous material in the undrained state ($\Psi = 0$), and is the ratio of the cavity pressure to the total body stress.

$$\beta = \frac{dp}{d\sigma} \Big|_{\Psi=0} = \frac{1}{1 + e_0 \frac{C_p}{C_s}} = \frac{K_u - K}{\alpha K_u} \quad (6)$$

where K_u is the bulk modulus in the undrained state, K is the bulk modulus in the drained state, C_p is the fluid Compressibility in the pores and C_s is solid Compressibility, And also Skempton coefficient can show the effect of fluid Compressibility on the elastic modulus and the compressibility of the entire porous material.

3. Challenges and future work

Functionally graded porous structures have excellent potentials to enhance lightweight structures that have great importance in aerospace, automotive, marine, mechanical, and other engineering applications. However, many initial research studies have been developed on this subject; there are still many problems yet to be discussed.

Many investigations have been reported on the behavior of functionally graded porous structures. But, most of them are concerned on the drained conditions. However, the investigations into saturated porous structures are limited in number. Although significant efforts have been devoted to the fabrication of these structures, existing manufacturing processes exhibit limitations on either the fabrication of closed-cell structures or the exact controlling of pore geometry and porosity gradient. The manufacturing techniques for the micro-/nano FG saturated porous structures have also not investigated yet. In addition, the majority of the reported analyses of FG saturated porous structures are concentrated on elastic analyses, including bending, buckling, natural frequency and dynamic analyses of FG saturated porous beams, plates and shells type structures. There is no research reported about plasticity, failure, fracture and fatigue analyses of these structures so far. Furthermore, there is no study about the optimization of these structures. The multi-objective optimization process with different design variables such as distribution of porosity and coefficient of porosity seems to be useful for the practical design of these structures.

4. Concluding remarks

Functionally graded saturated porous structures have been proved to be very promising in many engineering applications where lightweight structures are of great importance. This paper has comprehensively discussed and summarised the state-of-the-art of these structures. The review covers all of the important aspects in this emerging and fast-growing area, including the mechanics based model for determining the effective material properties, analytical and numerical analyses of mechanical and structural behaviors of FG saturated porous beam, plate, and shell structures under various loading conditions. The key technical challenges and future research directions have also been identified and highlighted.

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