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THEORETICAL PERMEABILITY CHARACTERIZATION OF SYNTHETIC POROUS CORES: DARCY, KOZENY–CARMAN, FORCHHEIMER, AND ERGUN APPROACHES

**CARACTERIZACIÓN TEÓRICA DE LA PERMEABILIDAD DE
NÚCLEOS POROSOS SINTÉTICOS: ENFOQUES DE DARCY,
KOZENY-CARMAN, FORCHHEIMER Y ERGUN**

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Theoretical Permeability Characterization of Synthetic Porous Cores: Darcy, Kozeny–Carman, Forchheimer, and Ergun Approaches

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ABSTRACT

This work presents a theoretical characterization of permeability in synthetic porous cores fabricated by sintering glass beads with different particle sizes. The objective was to evaluate the influence of porosity and grain diameter on hydraulic behavior using the Darcy, Kozeny–Carman, Forchheimer, and Ergun models. Four synthetic cores with porosities ranging from 2.6% to 10.1% and grain diameters between 0.125 and 0.600 mm were analyzed. Permeability estimated using the Kozeny–Carman model ranged from 9.39 to 2583.40 mD, whereas the equivalent permeability obtained from the Ergun formulation ranged from 11.26 to 3100.08 mD. In addition, a parametric sensitivity analysis was performed to quantify the relative influence of porosity and grain diameter on permeability. The results show that both parameters significantly affect hydraulic behavior and that the highest permeability values occur when porosity and grain diameter increase simultaneously. Reynolds number analysis and the evaluation of viscous and inertial contributions indicated that the analyzed conditions remain predominantly within the Darcy flow regime. Comparison with permeability ranges reported for sedimentary rocks, granular media, sintered glass beads, and filtration materials demonstrated that the fabricated cores reproduce hydraulic conditions representative of a broad spectrum of natural and engineered porous systems. The results confirm that theoretical permeability models, combined with parametric simulation and sensitivity analysis, provide a useful framework for the evaluation and design of synthetic porous materials.

Keywords: permeability, synthetic porous media, Kozeny–Carman model, Ergun equation, sensitivity analysis

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Caracterización Teórica de la Permeabilidad de Núcleos Porosos Sintéticos: Enfoques de Darcy, Kozeny-Carman, Forchheimer y Ergun

RESUMEN

En este trabajo se presenta una caracterización teórica de la permeabilidad en núcleos porosos sintéticos fabricados mediante sinterización de esferas de vidrio de diferentes tamaños de grano. El objetivo fue evaluar la influencia de la porosidad y del diámetro de partícula sobre el comportamiento hidráulico de los materiales mediante los modelos de Darcy, Kozeny–Carman, Forchheimer y Ergun. Se analizaron cuatro núcleos sintéticos con porosidades entre 2.6 % y 10.1 % y diámetros de grano entre 0.125 y 0.600 mm. La permeabilidad estimada mediante Kozeny–Carman varió entre 9.39 y 2583.40 mD, mientras que la obtenida mediante la formulación de Ergun osciló entre 11.26 y 3100.08 mD. Adicionalmente, se realizó un análisis de sensibilidad paramétrico para evaluar la influencia relativa de la porosidad y del diámetro de grano sobre la permeabilidad. Los resultados muestran que ambos parámetros controlan significativamente la respuesta hidráulica y que los mayores valores de permeabilidad se obtienen cuando aumentan simultáneamente. El análisis de Reynolds y de las contribuciones viscosas e inerciales indicó que las condiciones evaluadas permanecen principalmente dentro del régimen de Darcy. La comparación con valores reportados para rocas sedimentarias, medios granulares y materiales filtrantes mostró que los núcleos sintéticos reproducen condiciones hidráulicas representativas de una amplia variedad de medios porosos naturales e industriales. Los resultados confirman que los modelos teóricos, complementados con simulación paramétrica y análisis de sensibilidad, constituyen una herramienta útil para la evaluación y diseño de materiales porosos sintéticos.

Palabras clave: permeabilidad, medios porosos sintéticos, Kozeny–Carman, Ergun, análisis de sensibilidad

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INTRODUCCIÓN

Permeability is one of the most important transport properties in porous media because it determines the capacity of a material to transmit fluids under an applied pressure gradient (Bear, 1972). In applications such as filtration, water treatment, hydrogeology and reservoir engineering, permeability controls the hydraulic response of the medium and directly affects flow rate, pressure losses and operational performance (Bear, 1972). Although permeability is commonly associated with porosity, it also depends on grain diameter, pore connectivity, tortuosity and pore-throat structure, which collectively govern the pathways available for fluid transport (Koponen et al., 1996; Nishiyama & Yokoyama, 2017). Therefore, materials with similar porosity may exhibit substantially different hydraulic behavior depending on their internal geometry and pore-network characteristics (Schulz et al., 2019; Nishiyama & Yokoyama, 2017).

Synthetic porous media provide a useful strategy for studying permeability under controlled structural conditions. Unlike natural rocks, which commonly exhibit mineralogical heterogeneity, anisotropy, fractures and complex pore-network architectures, synthetic porous materials can be fabricated with predefined grain sizes and reproducible geometrical characteristics (Bear, 1972; Schulz et al., 2019). This makes them suitable as simplified analogues for evaluating the relationship between pore structure and macroscopic flow behavior under well-controlled conditions. In particular, porous media manufactured from glass beads have been widely employed as model systems because they allow the effects of grain size, porosity and packing structure on permeability to be investigated independently from the geological complexity of natural materials (Childs & Collis-George, 1950; Marshall, 1958). Several theoretical models have been developed to describe fluid flow through porous media across different hydraulic regimes. Darcy's law constitutes the classical macroscopic framework relating volumetric flow rate to the applied pressure gradient under linear laminar conditions (Darcy, 1856). To connect permeability with the structural characteristics of the porous medium, the Kozeny–Carman equation estimates intrinsic permeability as a function of porosity and grain diameter (Kozeny, 1927). When flow velocity increases and inertial effects become significant, the linear Darcy relationship can be extended using the Forchheimer equation, which incorporates an additional nonlinear term associated with inertial resistance (Forchheimer, 1901).



For granular porous systems and packed beds, the Ergun equation provides a practical formulation that combines viscous and inertial pressure losses and establishes a direct connection between pore structure and hydraulic behavior (Ergun, 1952). Together, these models provide a multiscale theoretical framework capable of describing flow behavior from the pore-structure level to the macroscopic hydraulic response of porous materials.

Although Darcy, Kozeny–Carman, Forchheimer and Ergun formulations are widely used to describe flow through porous media, their comparative behavior is rarely analyzed within a unified framework for synthetic porous structures. In particular, understanding how these models respond to variations in porosity and grain size is essential for the design of porous materials intended for filtration, water treatment and fluid transport applications. Numerical simulation provides an effective approach for evaluating the predictive capabilities and physical consistency of these models under controlled structural conditions.

The objective of this work is to perform a comparative theoretical analysis of Darcy, Kozeny–Carman, Forchheimer and Ergun models for the characterization of permeability in synthetic porous cores fabricated from glass beads. The study combines structural characterization and numerical simulation to evaluate the influence of porosity and grain diameter on permeability, flow rate and inertial resistance under controlled conditions. The study combines structural characterization and numerical simulation to evaluate the influence of porosity and grain diameter on permeability, flow rate and inertial resistance under controlled conditions, with particular emphasis on quantifying their relative contribution to hydraulic performance through sensitivity analysis.

Recent studies on synthetic porous media have shown that sintered glass beads are suitable analogues for investigating the relationship between pore structure and permeability under controlled conditions. These materials allow grain size, porosity and thermal consolidation to be modified systematically, reducing the heterogeneity typically observed in natural rocks. Experimental and numerical studies on sintered glass-bead systems have reported good agreement between measured permeability and permeability obtained from three-dimensional numerical simulations, supporting their use as model porous media for hydraulic characterization. In addition, synthetic glass-bead samples produced at temperatures between 700 and 750 °C have been reported to achieve porosity values from

approximately 3% to 40%, which is comparable to the porosity interval explored in the present work (Gueven et al., 2017).

The main contribution of this study is the development of an integrated theoretical and simulation-based framework for evaluating synthetic porous cores. Four experimentally characterized cores are analyzed using their measured porosity and grain diameter, and a parametric sensitivity simulation is performed to investigate the hydraulic response predicted by each model. This approach allows the quantification of the relative influence of porosity and grain diameter, the comparison of theoretical predictions among models, and the assessment of their applicability to filtration and water-treatment systems. Furthermore, the combined use of Darcy, Kozeny–Carman, Forchheimer and Ergun formulations provides a consistent framework for linking pore structure to macroscopic hydraulic behavior across different flow regimes.

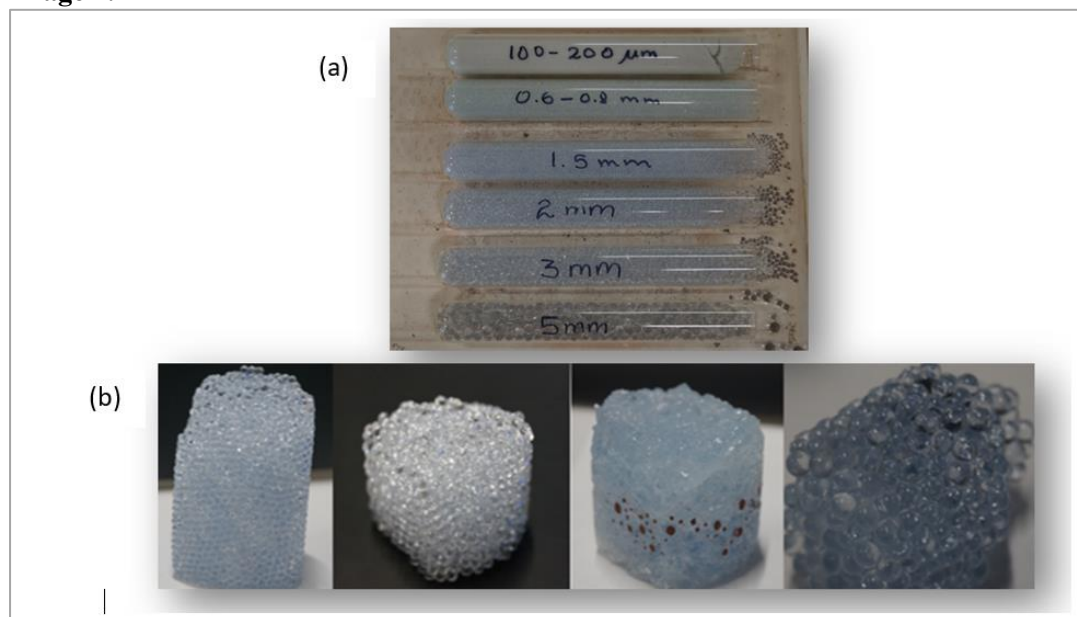
The working hypothesis is that permeability in synthetic porous cores emerges from the coupled effect of porosity and grain diameter rather than from a single dominant parameter. Therefore, numerical simulations are expected to reveal that increases in both pore volume fraction and particle size contribute synergistically to the enhancement of permeability, flow rate and hydraulic performance. Accordingly, the highest permeability values are expected to occur when both parameters increase simultaneously, reflecting the combined structural control exerted by pore volume and particle-scale geometry on fluid transport.

MATERIALS AND THEORETICAL METHODOLOGY

Fabrication of synthetic porous cores

Synthetic porous cores were fabricated using glass beads of different diameters as a controlled granular medium. The fabrication procedure was based on methodologies previously reported in the literature for the preparation of synthetic porous materials, with modifications introduced to achieve different porosity levels and to generate specimens suitable for hydraulic characterization.

Image 1.



Fabrication process of synthetic porous cores. (a) Glass beads of different diameters. (b) Representative synthetic cores obtained after thermal treatment.

Glass beads (Image 1 (a)) with nominal diameters of 100–200 μm , 0.6–0.8 mm, 1.5 mm, 2 mm, 3 mm and 5 mm were used as the raw material. The particles were placed inside borosilicate glass molds with dimensions of 16×100 mm, 20×150 mm and 10×75 mm, depending on the desired specimen geometry.

The sintering process was performed using a Vulcan 3-550 muffle furnace. Different thermal cycles were evaluated in order to produce cores with distinct pore structures and porosity levels. Variations in mold dimensions, heating ramps, holding times and cooling schedules resulted in specimens with different morphologies and hydraulic properties. In Image 1 (b) is presented the representative synthetic cores obtained after thermal treatment.

For high-porosity specimens, a heating period of 6 h followed by a cooling stage of 4 h was employed. For lower-porosity specimens, the heating period was increased to 8 h and the cooling stage to 7 h. In both cases, thermal ramps from 30°C to 750°C were applied. The higher exposure time promoted stronger particle fusion and consequently reduced pore volume. The resulting samples exhibited different degrees of particle bonding, pore connectivity and structural consolidation, providing a suitable set of synthetic porous media for subsequent hydraulic analysis.

The sensitivity analysis completes the parametric simulation described in Section 2.5 and provides quantitative support for the hypothesis that grain diameter has a stronger effect on permeability than porosity. Thus, the theoretical framework is not limited to the four fabricated cores, but also allows the hydraulic behavior of possible synthetic porous structures to be predicted within a broader design space.

Morphological characterization of synthetic cores

Representative synthetic cores produced during the fabrication campaign are shown in Figure 2. Variations in grain size, thermal treatment and mold geometry generated samples with distinct pore structures and consolidation levels. Visual inspection revealed differences in surface texture, particle fusion and apparent pore distribution. Samples manufactured with longer sintering times exhibited greater particle bonding and lower visible porosity, whereas shorter thermal cycles preserved larger interparticle voids.

From the complete set of fabricated specimens, four representative cores were selected for detailed hydraulic characterization and theoretical analysis. These samples covered the widest range of porosity and grain-size combinations achieved during the fabrication process.

Determination of structural parameters

The total volume of each core was determined from its geometric dimensions. Solid volume was calculated from the measured mass and glass density, while pore volume was obtained as $V_p = V_T - V_s$, where V_T is the total volume and V_s is the solid volume. Porosity was calculated according to $\phi = V_p / V_T$. The four selected cores are summarized in Table 1. These samples span a porosity range from 2.6% to 10.1% and grain diameters from 0.125 mm to 0.600 mm, providing a suitable basis for evaluating the influence of structural parameters on hydraulic behavior. Their structural parameters were derived from the measured solid volume, pore volume and grain diameter. The total core volume was $V_T = 57 \text{ cm}^3$, and porosity was calculated as $\phi = \frac{V_p}{V_T}$. The analyzed core dimensions for hydraulic calculations were taken as $L = 0.15 \text{ m}$ and diameter $D = 0.07 \text{ m}$, yielding a cross-sectional area of $A = \frac{\pi D^2}{4} = 3.85 \times 10^{-3} \text{ m}^2$. The dynamic viscosity of water was assumed to be $\mu = 1.0 \times 10^{-3} \text{ Pa} \cdot \text{s}$. A reference pressure drop of 1 kPa was used to estimate the corresponding Darcy flow rate for each theoretical permeability value.

Table 1. Structural parameters of the synthetic cores

Core	m (g)	V _s (cm ³)	V _φ (cm ³)	φ (%)	dg (mm)
C1 (F1)	141.61	55.53	1.46	2.6	0.300
C2 (M1)	139.34	54.64	2.35	4.1	0.200
C3 (N7)	132.71	52.04	4.95	8.7	0.125
C4 (N10)	130.62	51.22	5.77	10.1	0.600

Parametric simulation and sensitivity analysis

A parametric numerical simulation was performed to investigate the influence of porosity and grain diameter on permeability predictions. Porosity was varied over a representative range while grain diameter was systematically modified according to the particle sizes employed during fabrication.

For each parameter combination, permeability was calculated using both the Kozeny–Carman and Ergun formulations. The resulting permeability values were subsequently used to estimate Darcy flow rates and Forchheimer inertial coefficients. Sensitivity was quantified by evaluating the relative variation of permeability with respect to changes in porosity and grain diameter. This procedure allowed the dominant structural parameter controlling hydraulic behavior to be identified and provided a theoretical validation of the trends observed in the fabricated synthetic cores.

THEORETICAL FRAMEWORKS

The theoretical framework of this work is based on four complementary models that describe fluid flow through porous media at different levels of approximation: Darcy, Kozeny–Carman, Forchheimer and Ergun. These models were selected because they allow the hydraulic behavior of synthetic porous cores to be interpreted from both macroscopic and structural perspectives. Darcy’s law describes the linear relationship between pressure gradient and flow rate, Kozeny–Carman relates permeability to porosity and grain diameter, Forchheimer introduces inertial corrections at higher velocities, and Ergun provides a viscous–inertial formulation commonly used for granular packed beds.

This combination is particularly useful for synthetic cores fabricated from glass beads because their pore structure is mainly controlled by grain size, packing arrangement and degree of particle sintering. Previous studies on sintered glass-bead systems have shown that permeability decreases as porosity is reduced during sintering and that Kozeny–Carman-type models provide a useful reference for

describing the relationship between porosity, particle size and permeability. Therefore, the models used in this study are not treated as isolated equations, but as a comparative predictive framework for estimating hydraulic response under controlled structural conditions.

Darcy model

Darcy's law provides the classical macroscopic description of incompressible laminar flow through porous media and remains the foundation of most permeability analyses (Darcy, 1856; Bear, 1972). The relationship is expressed as:

$$Q = \frac{kA \Delta P}{\mu L} \quad (1)$$

where Q is the volumetric flow rate, k is the intrinsic permeability, A is the cross-sectional area, μ is the dynamic viscosity of the fluid, ΔP is the pressure drop, and L is the sample length.

This formulation assumes steady-state, single-phase, laminar flow in which viscous forces dominate over inertial effects. Under these conditions, the pressure gradient is linearly proportional to flow velocity (Bear, 1972). Darcy's law has been successfully applied to a wide range of porous systems including sedimentary rocks, filtration media, packed beds and groundwater aquifers (Bear, 1972; Childs & Collis-George, 1950).

Because Darcy's law does not explicitly account for pore geometry, permeability must be obtained either experimentally or through predictive models based on structural parameters. For this reason, Darcy's law is combined in this work with Kozeny–Carman and Ergun formulations in order to estimate the hydraulic response of synthetic porous cores.

Kozeny–Carman model

The Kozeny–Carman model provides a structural estimate of intrinsic permeability based on porosity and representative grain diameter. For a granular porous medium, the relationship can be expressed as

$$k_{KC} = \frac{d_g^2 \phi^3}{180 (1-\phi)^2} \quad (2)$$

where d_g is the representative grain diameter and ϕ is the porosity.

This equation predicts that permeability increases with the square of the grain diameter and with the cubic contribution of porosity. Therefore, the model indicates that small changes in grain diameter may generate large changes in permeability.



This is relevant for the present study because the synthetic cores were fabricated using glass beads of different sizes and thermal treatments, producing different degrees of pore opening and particle consolidation.

The Kozeny–Carman model is widely used as a first-order approximation for granular porous media, but it has important limitations. It assumes idealized pore geometry, relatively homogeneous packing, interconnected pores and predominantly viscous flow. In natural rocks, its predictive capacity may decrease due to cementation, anisotropy, fractures, pore-throat constrictions and complex pore connectivity. For this reason, in this work Kozeny–Carman is used as a theoretical baseline rather than as an absolute experimental validation model.

The Kozeny–Carman model remains one of the most widely used predictive formulations for estimating permeability from porosity and particle diameter in granular porous media. However, recent studies emphasize that permeability is not governed by porosity alone, because pore-throat size, connectivity, tortuosity and pore-network geometry strongly affect hydraulic behavior. In sintered materials, the relationship between porosity and permeability changes as sintering modifies the pore network from a loose granular arrangement to a more consolidated structure. Therefore, Kozeny–Carman should be interpreted in this work as a first-order structural predictor rather than as an exact permeability model (Wadsworth et al., 2023).

Forchheimer model

At higher velocities, the relationship between pressure gradient and flow velocity may deviate from Darcy's linear law due to inertial effects. This nonlinear behavior can be described using the Forchheimer equation:

$$\frac{-\Delta P}{L} = \frac{\mu}{K} v + \beta \rho V^2, \quad (3)$$

where v is the superficial velocity, ρ is the fluid density, and β is the inertial coefficient.

The first term represents viscous resistance and corresponds to the Darcy contribution. The second term accounts for inertial losses, which become relevant when pore-scale velocities increase or when the pore network produces strong local accelerations. In the present study, the Forchheimer model is used to estimate the potential transition from linear Darcy flow to nonlinear flow behavior.

Because experimental pressure–velocity curves are not available, β is not fitted from experimental data. Instead, it is estimated through the Ergun formulation and used as a predictive parameter to compare the tendency of each synthetic core to develop inertial resistance. This allows the nonlinear behavior of the cores to be evaluated theoretically, even in the absence of direct flow experiments.

Ergun model

The Ergun equation is commonly used to describe pressure drop in packed beds and granular porous materials. It combines viscous and inertial contributions according to

$$\frac{\Delta P}{L} = 150 \frac{(1-\phi)^2}{\phi^3} \frac{\mu v}{d_g^2} + 1.75 \frac{(1-\phi)}{\phi^3} \frac{\rho v^2}{d_g}, \quad (4)$$

The first term represents viscous pressure losses and has the same functional dependence as Darcy-type flow. From this term, an Ergun-equivalent permeability can be defined as

$$k_E = d_g^2 / 150 \cdot \phi^3 / (1 - \phi)^2, \quad (5)$$

The second term represents inertial losses and allows the Ergun inertial coefficient to be written as

$$\beta_E = 1.75(1 - \phi) / (\phi^3 d_g), \quad (6)$$

The Ergun model is especially useful for this work because the synthetic cores were produced from glass beads, which makes them structurally comparable to consolidated granular beds. Unlike Darcy's law, Ergun directly incorporates grain diameter and porosity, allowing permeability and inertial resistance to be predicted from measurable structural parameters.

The Ergun and Forchheimer formulations complement the Darcy and Kozeny–Carman approaches because they incorporate nonlinear inertial effects that may become relevant at higher flow velocities. Recent work comparing Forchheimer and Ergun-type expressions shows that both formulations can be used to describe porous-media flow when viscous and inertial contributions coexist. In particular, the Ergun equation provides expressions for permeability and inertial coefficients as functions of porosity and grain size, with a structure similar to Kozeny–Carman but with different empirical constants. This makes the Ergun formulation especially useful for comparing granular synthetic cores and identifying whether the predicted flow remains within the Darcy regime or approaches a non-Darcy transition (Pang, Zhang, Meng, & Ling, 2021).

Parametric sensitivity analysis using representative synthetic porous media

The four models are used in this work in a complementary manner. The Kozeny–Carman and Ergun formulations are employed to estimate permeability from the measured structural parameters of the synthetic cores, namely porosity and grain diameter. These permeability values are subsequently incorporated into Darcy’s law to estimate the expected flow rate under a prescribed pressure drop. Finally, the Forchheimer–Ergun formulation is used to evaluate inertial effects and determine whether the predicted flow conditions remain within the validity range of Darcy’s law.

The comparison between Kozeny–Carman and Ergun is particularly relevant because both formulations exhibit the same dependence on grain diameter and porosity, although they differ in their empirical coefficients. Consequently, agreement between both models in terms of permeability trends and hydraulic ranking increases confidence in the physical interpretation of the results.

To evaluate the predictive consistency of the theoretical framework, a comparative analysis was performed using representative synthetic porous samples with porosity values ranging from 0.28 to 0.40 and a constant grain diameter of 0.25 mm. Permeability, flow rate, Reynolds number and inertial contributions were calculated using the different theoretical formulations. The results are summarized in Tables 2–4. The samples S1–S4 do not correspond to the fabricated cores listed in Table 1. They represent idealized porous media generated for sensitivity analysis, in which porosity was varied between 0.28 and 0.40 while grain diameter was kept constant at 0.25 mm.

Table 2 presents the permeability estimates obtained from the Kozeny–Carman and Ergun models together with the corresponding Darcy flow rates. In addition, Reynolds numbers and inertial-to-viscous force ratios are reported in order to identify the expected flow regime. Table 3 summarizes the hydraulic response predicted by the Ergun–Forchheimer formulation and compares the equivalent porous-media classification associated with the predicted permeability values. Finally, Table 4 compares the hydraulic ranking generated by the Kozeny–Carman and Ergun models, allowing the consistency of both formulations to be evaluated.

In addition, the predicted permeability values are compared with permeability ranges reported for natural rocks, sediments and porous filtration media. This comparison allows the synthetic cores to be positioned within a physically meaningful hydraulic context.



Depending on their permeability range, the cores may behave similarly to low-permeability sandstones, permeable sandstones, compact granular sediments or highly permeable filtration media.

RESULTS AND DISCUSSION

The permeability values predicted for the synthetic cores fall within a physically meaningful range when compared with natural porous materials. Reported permeability values for sandstones may vary from less than 1 mD to more than 50,000 mD, although common sandstone permeabilities are frequently in the range of tens to hundreds of millidarcies. In this context, the lower-permeability synthetic cores are comparable to compact or low-permeability sandstones, whereas the highest-permeability core approaches the range of permeable sandstone or coarse granular filtration media. This comparison supports the interpretation that the fabricated synthetic cores can function as controlled analogues of natural sedimentary porous materials.

From a filtration perspective, the synthetic cores can also be compared with granular media used in water-treatment systems. Gravel and sand filters commonly rely on intergranular pore networks, where particle size, roundness, packing and porosity determine hydraulic capacity and pressure losses. Reported filtration media include sand sizes from approximately 0.2–0.3 mm to 2.0–3.0 mm and gravel layers ranging from a few millimeters to several centimeters, depending on the filter function. Therefore, the glass-bead cores analyzed in this work occupy an intermediate scale between fine granular filters and consolidated porous rocks, making them useful for theoretical evaluation of flow capacity, pressure drop and potential filtration performance (USDA-NRCS, 1994).

Table 2.

Predictive comparison of permeability and flow behavior using Kozeny–Carman and Ergun models.

Sample	Porosity, ϕ (-)	Grain Diameter, d_g (mm)	kKC (m^2)	kErgun (m^2)	QDarcy-KC (m^3/s)	QDarcy-Ergun (m^3/s)	Rep (-)	Inertial/Viscous Ratio (-)	Flow Regime
S1	0.28	0.25	1.47×10^{-11}	1.76×10^{-11}	1.47×10^{-7}	1.76×10^{-7}	0.438	0.0071	Darcy-dominated
S2	0.32	0.25	2.46×10^{-11}	2.95×10^{-11}	2.46×10^{-7}	2.95×10^{-7}	0.729	0.0125	Darcy-dominated
S3	0.36	0.25	3.96×10^{-11}	4.75×10^{-11}	3.96×10^{-7}	4.75×10^{-7}	1.162	0.0212	Weak Transition
S4	0.40	0.25	6.17×10^{-11}	7.41×10^{-11}	6.17×10^{-7}	7.41×10^{-7}	1.790	0.0348	Weak Transition

Table 2. Predictive comparison of permeability, Darcy flow rate, Reynolds number and inertial contribution estimated from the Kozeny–Carman and Ergun formulations. Both models predict



increasing permeability and flow capacity with increasing porosity, while inertial effects remain relatively small under the analyzed conditions. The results indicate that viscous forces dominate the hydraulic behavior, although the most permeable samples exhibit a weak tendency toward non-Darcy flow.

The results presented in Table 2 show a systematic increase in permeability as porosity increases from 0.28 to 0.40. Both the Kozeny–Carman and Ergun formulations predict the same trend, although the Ergun model consistently produces slightly higher permeability values due to differences in its empirical coefficient. The predicted Darcy flow rates increase proportionally with permeability, indicating that relatively small structural changes can generate substantial differences in hydraulic performance.

The Reynolds numbers remain below 2 for all analyzed samples, while the inertial-to-viscous force ratio remains below 0.04. These values indicate that viscous forces dominate the flow behavior and confirm that the analyzed conditions remain primarily within the Darcy regime. Nevertheless, samples S3 and S4 exhibit the highest Reynolds numbers and inertial contributions, suggesting the onset of a weak transition toward non-Darcy behavior.

Table 3. Hydraulic response predicted by the Ergun–Forchheimer formulation and equivalent porous-media classification.

Sample	Superficial Velocity, v (m/s)	Flow Rate, $Q_{\text{Forchheimer}}$ (m ³ /s)	KC Equivalent Material	Ergun Equivalent Material
S1	1.75×10^{-3}	1.75×10^{-7}	High-permeability fine sand/gravel	High-permeability fine sand/gravel
S2	2.92×10^{-3}	2.92×10^{-7}	High-permeability fine sand/gravel	High-permeability fine sand/gravel
S3	4.65×10^{-3}	4.65×10^{-7}	High-permeability fine sand/gravel	High-permeability fine sand/gravel
S4	7.16×10^{-3}	7.16×10^{-7}	High-permeability fine sand/gravel	High-permeability fine sand/gravel

Table 3. Predicted superficial velocity and flow rate obtained from the Ergun–Forchheimer formulation. The permeability values estimated by both Kozeny–Carman and Ergun place the analyzed samples within the hydraulic range commonly associated with highly permeable granular materials such as fine sands and gravels. These results support the use of the fabricated synthetic cores as controlled analogues of unconsolidated sediments and filtration media.

The hydraulic response predicted by the Ergun–Forchheimer formulation is summarized in Table 3. The calculated superficial velocities increase progressively with porosity, reflecting the reduction in hydraulic resistance as the pore network becomes more open. The predicted flow rates span approximately one order of magnitude, demonstrating the strong sensitivity of hydraulic performance to structural parameters.

All analyzed samples fall within permeability ranges commonly associated with highly permeable granular materials such as fine sands and gravels. This observation supports the use of the fabricated synthetic cores as controlled analogues for natural unconsolidated sediments and engineered filtration media.

Table 4. Hydraulic ranking predicted by the Kozeny–Carman and Ergun permeability models.

Sample	kKC (m ²)	Rank (KC)	kErgun (m ²)	Rank (Ergun)
S4	6.17×10^{-11}	1	7.41×10^{-11}	1
S3	3.96×10^{-11}	2	4.75×10^{-11}	2
S2	2.46×10^{-11}	3	2.95×10^{-11}	3
S1	1.47×10^{-11}	4	1.76×10^{-11}	4

Table 4. Hydraulic ranking of synthetic porous samples predicted by the Kozeny–Carman and Ergun formulations. Despite differences in the absolute permeability values, both models predict the same ordering of samples, with S4 exhibiting the highest permeability and S1 the lowest. The identical ranking demonstrates that both formulations consistently capture the dominant influence of porosity on hydraulic behavior and provide a robust basis for comparative permeability assessment.

Sample S4 consistently exhibits the highest permeability, followed by S3, S2 and S1. This agreement indicates that the dominant physical mechanisms represented by both formulations are consistent and that grain diameter and porosity remain the primary structural variables controlling permeability. The identical ranking predicted by both models strengthens the reliability of the theoretical interpretation and supports the use of these formulations for comparative hydraulic analysis of synthetic porous materials.

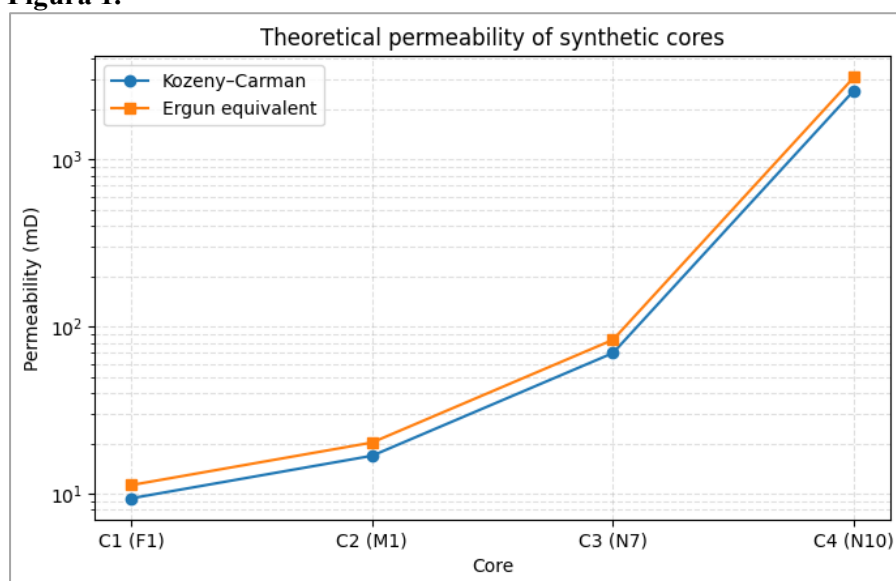
Predictive comparison of permeability models

The permeability values predicted by the Kozeny–Carman and Ergun formulations are summarized in Table 2. Both models show a consistent increase in permeability as porosity and grain diameter increase,

confirming the strong dependence of hydraulic behavior on the structural properties of the porous medium.

The lowest permeability corresponds to sample C1, which combines the smallest porosity with a relatively small grain diameter. In contrast, sample C4 exhibits permeability values more than two orders of magnitude higher owing to the combined effect of its larger grain diameter and higher porosity. This behavior is expected because both formulations contain the term $dg^2\phi^3/(1-\phi)^2$, making permeability particularly sensitive to grain size variations.

Figura 1.



Comparison of permeability predictions obtained using the Kozeny–Carman and Ergun models. Predicted permeability values for the four synthetic cores (C1–C4) as a function of porosity and grain diameter. Both models exhibit the same dependence on grain size and porosity, resulting in an identical hydraulic ranking of the samples. Core C4 (N10) shows the highest permeability due to its combination of relatively high porosity and large grain diameter, while C1 (F1) presents the lowest permeability. The close agreement between both models supports the robustness of the permeability estimates.

Although the Ergun model predicts permeability values approximately 20% higher than those obtained from Kozeny–Carman, both formulations preserve exactly the same hydraulic ranking of the samples. This agreement indicates that the two models provide a consistent interpretation of the relative hydraulic performance of the synthetic cores despite differences in their empirical coefficients.

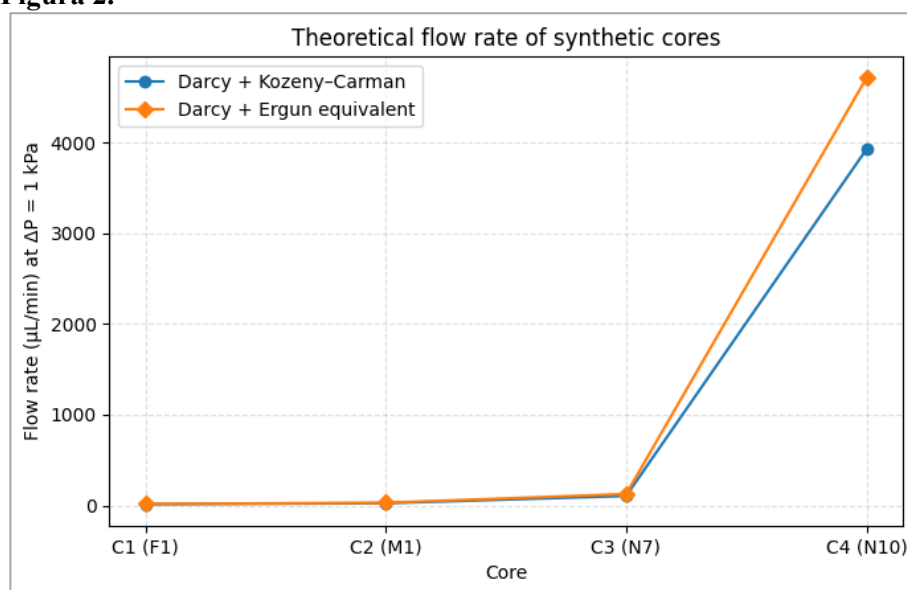
Figure 1 illustrates the permeability predicted by both models. The logarithmic scale highlights the nonlinear increase in permeability and demonstrates that the hydraulic response is dominated by structural parameters rather than by small variations in porosity alone.

Darcy flow predictions

The permeability values obtained from the structural models were incorporated into Darcy's law to estimate the corresponding flow rates under a reference pressure drop of 1 kPa. The predicted flow rates are presented in Table 3 and graphically summarized in Figure 2.

The results reveal an extreme sensitivity of flow rate to permeability. While samples C1 and C2 exhibit flow rates on the order of 10^{-7} m³/s, sample C4 reaches values approaching 10^{-4} m³/s. Consequently, relatively small structural differences generate substantial changes in hydraulic performance.

Figure 2.



Predicted flow rates obtained from Darcy's law using permeability estimates from Kozeny–Carman and Ergun formulations. Flow rates were calculated under a constant pressure gradient of $6.67 \times 10^3 \text{ Pa} \cdot \text{m}^{-1}$. The results show a progressive increase in flow rate from C1 to C4, consistent with the predicted permeability values. Differences between the two permeability models remain small, indicating that both approaches provide similar hydraulic predictions for the analyzed porous media.

The flow rate predicted for C4 is approximately 37 times larger than that of C3 and more than 270 times larger than that of C1. These differences reflect the strong influence of pore connectivity and grain size on flow capacity. From an engineering perspective, this behavior suggests that synthetic porous materials can be tailored to achieve very different hydraulic responses through controlled modification of particle size and porosity.

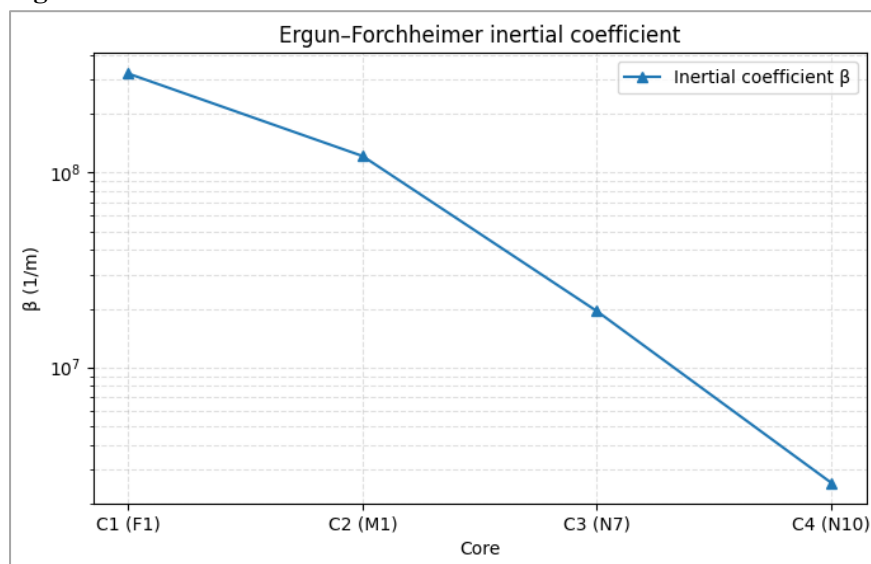
The trends observed in Figure 2 are consistent with those obtained from the permeability analysis, confirming that permeability acts as the dominant parameter controlling macroscopic flow behavior

Inertial effects and nonlinear flow interpretation

The inertial coefficients estimated from the Ergun–Forchheimer formulation are listed in Table 2 and illustrated in Figure 3. A pronounced decrease in β is observed as porosity and grain diameter increase. Sample C1 exhibits the highest inertial coefficient, whereas sample C4 presents values approximately two orders of magnitude lower. This behavior indicates that denser media composed of smaller particles impose greater resistance to fluid acceleration and therefore exhibit stronger inertial effects. Conversely, larger pore channels and increased pore connectivity reduce the importance of inertial losses.

To further evaluate the relative importance of viscous and inertial mechanisms, Figure 4 compares the corresponding pressure-gradient contributions. Under the reference flow conditions considered in this study, the viscous term exceeds the inertial contribution by several orders of magnitude in all samples. Consequently, the predicted flow remains within the Darcy regime despite the inclusion of nonlinear effects. Nevertheless, the progressive increase in the inertial contribution observed from C1 to C4 suggests that highly permeable materials may eventually approach a transitional regime at sufficiently high velocities. Therefore, the Forchheimer–Ergun framework provides a useful predictive tool for identifying the onset of non-Darcy behavior in future experimental studies.

Figura 3.



Inertial coefficient (β_E) estimated from the Ergun–Forchheimer formulation for the four synthetic cores. The inertial coefficient decreases as permeability increases, reflecting the reduced hydraulic resistance associated with larger pore spaces and grain diameters. Core C1 exhibits the highest inertial coefficient, whereas C4 presents the lowest value, indicating that highly permeable samples require a smaller inertial correction under equivalent flow conditions.

Comparison with Natural Porous Materials

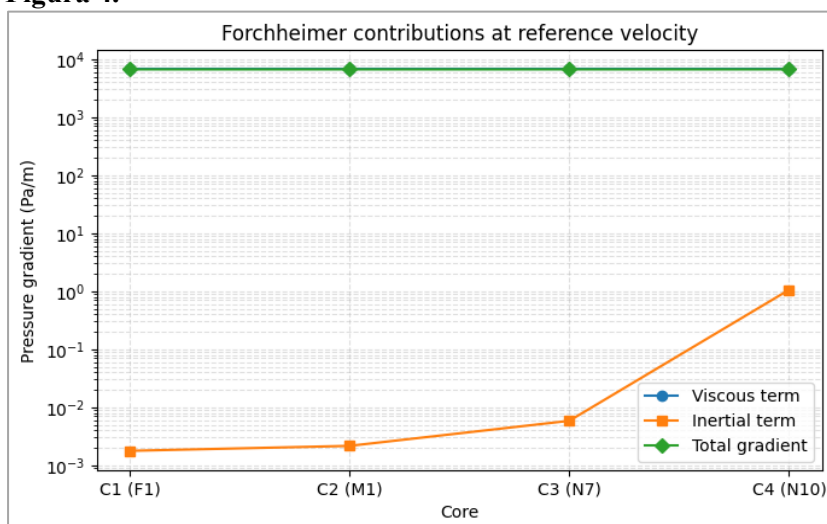
The permeability values predicted using the Kozeny–Carman and Ergun formulations provide a useful basis for positioning the manufactured synthetic cores within the broader spectrum of porous materials reported in the literature. Although the cores were fabricated from controlled granular mixtures, their hydraulic behavior can be compared with that of natural rocks, unconsolidated sediments, and engineered filtration media.

Sensitivity analysis

A parametric sensitivity analysis was performed to quantify the relative influence of porosity and grain diameter on the permeability predicted by the Kozeny–Carman and Ergun models. This analysis was introduced because both formulations depend on the structural term $(d_g^2 \phi^3 / (1 - \phi)^2)$, suggesting that permeability may respond nonlinearly to changes in pore structure.

First, porosity was varied while grain diameter was kept constant. The results show that permeability increases nonlinearly with porosity, especially as the pore volume fraction becomes larger. This behavior is consistent with the cubic dependence of permeability on porosity in both the Kozeny–Carman and Ergun formulations. However, the increase is gradual when compared with the effect produced by variations in grain diameter.

Figura 4.



Relative contributions of viscous and inertial pressure losses predicted by the Forchheimer–Ergun equation. The viscous term dominates the pressure drop in all samples, accounting for nearly the entire hydraulic resistance. The inertial contribution remains several orders of magnitude smaller than the viscous component, reaching a maximum value of approximately $1.06 \text{ Pa} \cdot \text{m}^{-1}$ in core C4 compared with a viscous contribution of $6.67 \times 10^3 \text{ Pa} \cdot \text{m}^{-1}$. These results indicate that all experiments remain within the Darcy flow regime under the imposed pressure gradient.

Second, grain diameter was varied while porosity was kept constant. In this case, permeability increased more rapidly because both models contain a quadratic dependence on particle diameter. This confirms that grain size is the dominant structural parameter controlling permeability in the synthetic cores. Therefore, even moderate increases in grain diameter can generate substantial increases in hydraulic conductivity and predicted flow rate.

To further evaluate the combined effect of both parameters, a response surface ($k=f(\phi, d_g)$) was constructed. The contour map shows that the highest permeability values occur when high porosity and large grain diameter are combined. Conversely, low porosity and small grain diameter produce compact structures with low hydraulic capacity. This confirms that permeability is controlled by the interaction between pore volume and particle-scale geometry.

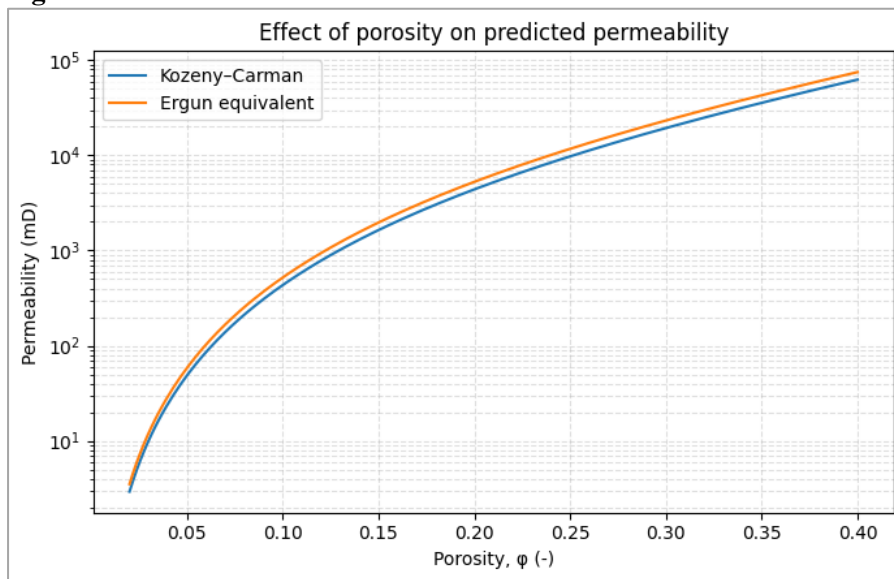
The relative sensitivity coefficients confirm that both porosity and grain diameter exert a strong influence on permeability. The response surfaces further show that the largest permeability increases occur when both parameters are simultaneously increased, highlighting the coupled nature of hydraulic transport in synthetic porous media. The sensitivity analysis demonstrated that permeability is strongly influenced by both porosity and grain diameter. The highest permeability values were obtained when both parameters increased simultaneously, confirming that hydraulic performance results from their combined structural effect on pore geometry and flow pathways.

The sensitivity analysis provides quantitative support for the trends observed in the permeability models. Figure 5 shows that permeability increases nonlinearly with porosity, following the $\phi^3/(1 - \phi)^2$ dependence present in both the Kozeny–Carman and Ergun formulations. Although increasing porosity significantly enhances fluid transport, the resulting permeability variations remain moderate when compared with those produced by changes in grain diameter.

A stronger effect is observed in Figure 6, where permeability increases rapidly as grain diameter increases. This behavior reflects the quadratic dependence on particle size ($k \propto d_g^2$), indicating that grain diameter exerts a dominant control on hydraulic performance. Consequently, relatively small changes in particle size produce permeability variations spanning several orders of magnitude.

The combined influence of porosity and grain diameter is illustrated in Figure 7. The response surface reveals that maximum permeability occurs when both parameters are simultaneously increased, whereas low porosity and small grain diameter generate compact structures with limited hydraulic capacity. The contour distribution further indicates that permeability gradients are steeper along the grain-diameter direction than along the porosity direction, providing visual evidence that grain size is the most influential parameter within the analyzed range.

Figure 5.



Effect of porosity on predicted permeability. Permeability predicted by the Kozeny–Carman and Ergun models as a function of porosity for a fixed grain diameter. The nonlinear increase reflects the contribution of the term $\phi^3/(1 - \phi)^2$.

Overall, the sensitivity analysis confirms the working hypothesis proposed in this study: although permeability depends on both porosity and pore structure, grain diameter represents the primary controlling factor governing the hydraulic response of the fabricated synthetic porous cores.

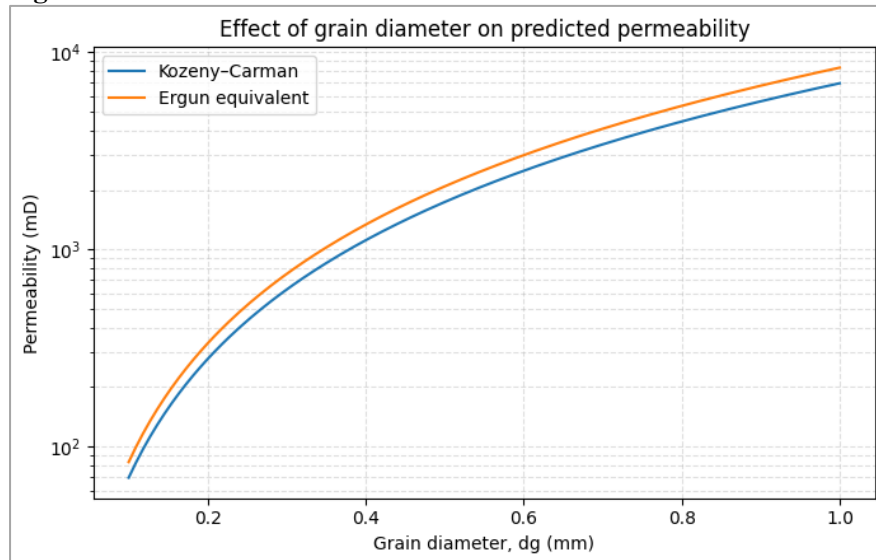
The agreement between the analytical sensitivity analysis and the permeability response surfaces demonstrates that the theoretical framework is internally consistent and capable of capturing the dominant physical mechanisms controlling flow through synthetic granular porous media.

Quantitative sensitivity analysis

To quantify the relative influence of porosity and grain diameter on permeability, dimensionless sensitivity coefficients were evaluated using the Kozeny–Carman formulation. The relative sensitivity

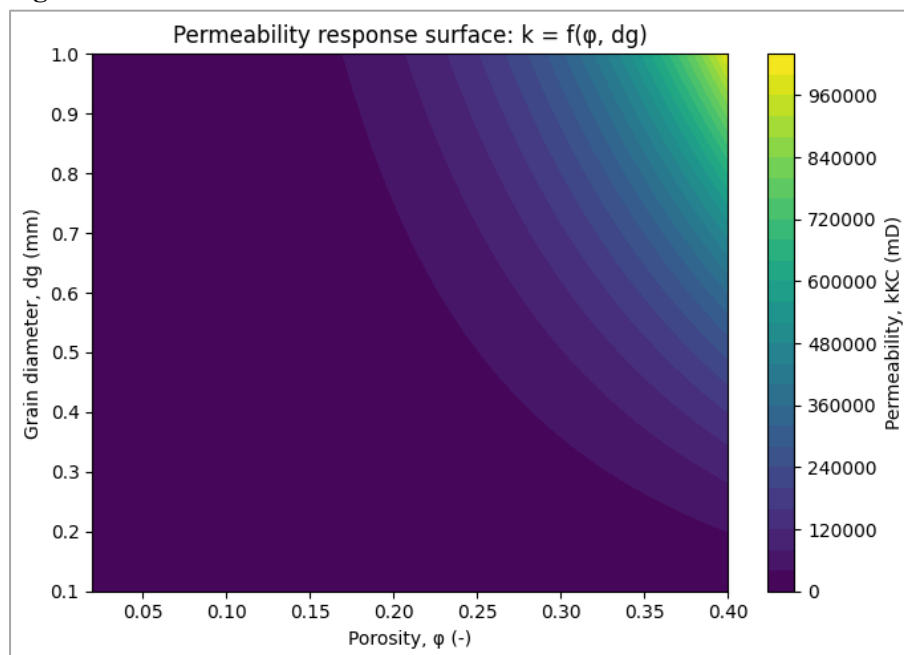
of permeability to a parameter x is defined as $S_x = \frac{\partial k}{\partial x} \frac{x}{k}$. For grain diameter, the permeability expression contains a quadratic dependence, yielding $S_{dg} = 2$. This result indicates that a 1% increase in grain diameter produces approximately a 2% increase in permeability.

Figure 6.



Effect of grain diameter on predicted permeability. Permeability predicted by the Kozeny–Carman and Ergun models as a function of grain diameter for a fixed porosity. The stronger increase confirms the quadratic dependence of permeability on particle diameter.

Figure 7.



Permeability response surface. Contour map of predicted permeability as a function of porosity and grain diameter. The highest permeability values occur when large grain diameter and high porosity are combined.

For porosity, differentiation of the Kozeny–Carman equation gives $S\phi = 3 + 2\phi/(1-\phi)$. For the representative porosity range of the fabricated cores ($\phi = 0.026\text{--}0.101$), the sensitivity coefficient varies between approximately 3.05 and 3.22. Therefore, permeability is highly sensitive to porosity variations within the analyzed interval.

The sensitivity analysis demonstrates that both porosity and grain diameter strongly influence permeability. The observed increase in permeability from C1 to C4 results from the combined effect of increasing pore volume and increasing grain size. Consequently, permeability enhancement in synthetic porous media should be interpreted as a coupled structural effect rather than the result of a single controlling variable.

These findings are consistent with the response surfaces shown in Figures 5–7, where the highest permeability values occur when both porosity and grain diameter are simultaneously increased.

Predicted permeabilities: natural cores and synthetic cores

The predicted permeabilities span approximately three orders of magnitude, ranging from about 10^{-14} m² for cores C1 and C2 to about 10^{-12} m² for core C4. Such values are consistent with those commonly reported for permeable sedimentary rocks and granular porous materials. Cores C1 and C2 exhibit permeabilities comparable to those of low- to moderately permeable sandstones, while core C3 falls within the range typically associated with highly permeable sandstones and compact granular sediments. In contrast, core C4 reaches permeability values characteristic of coarse granular media and highly permeable filtration materials.

The comparison also highlights the influence of grain diameter on hydraulic performance. Although cores C3 and C4 have relatively similar porosities, the substantially larger grain diameter of C4 results in a permeability nearly two orders of magnitude greater. This observation is consistent with both Kozeny–Carman and Ergun predictions, which indicate that permeability scales with the square of the characteristic grain size.

From an engineering perspective, the analyzed cores reproduce hydraulic conditions relevant to several natural and industrial porous systems. Consequently, the manufactured specimens may serve as representative analogues for laboratory studies involving fluid transport through sedimentary formations, granular filtration media, and packed-bed systems. Their permeability range bridges the

transition between consolidated porous rocks and highly permeable granular materials, making them suitable for controlled investigations of flow processes in porous media. Table 5 summarizes the approximate permeability ranges reported for selected porous materials and compares them with the values predicted for the synthetic cores investigated in this study.

Table 5.

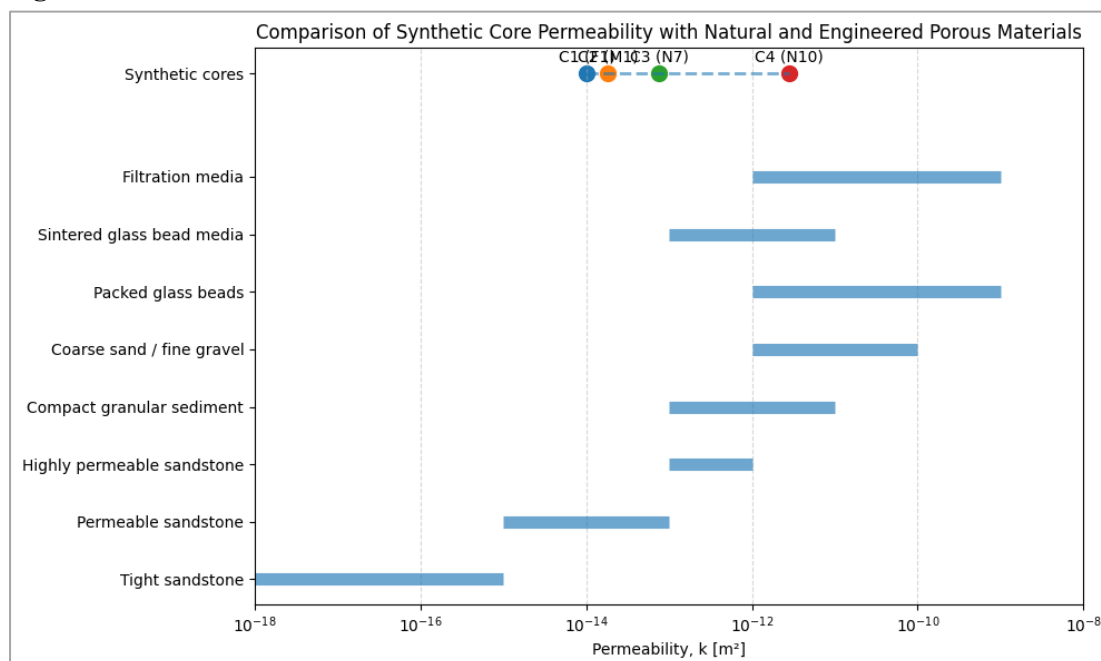
Material	Typical Permeability (m ²)	Equivalent Core
Tight sandstone	$10^{-18} - 10^{-15}$	None
Permeable sandstone	$10^{-15} - 10^{-13}$	C1, C2
Highly permeable sandstone	$10^{-13} - 10^{-12}$	C3
Compact granular sediment	$10^{-13} - 10^{-11}$	C3
Coarse sand / fine gravel	$10^{-12} - 10^{-10}$	C4
Packed glass beads	$10^{-12} - 10^{-9}$	C4
Sintered glass bead media	$10^{-13} - 10^{-11}$	C3–C4
Filtration media	$10^{-12} - 10^{-9}$	C4

Typical permeability ranges reported for natural rocks, granular sediments, packed glass beads, sintered porous media and filtration materials. The predicted permeability values of the synthetic cores are included to provide a physically meaningful hydraulic classification of the manufactured specimens.

Figure 5 compares the predicted permeability of the synthetic cores with typical permeability ranges reported for a variety of natural and engineered porous materials. The results indicate that cores C1, C2, and C3 exhibit permeabilities on the order of 10^{-14} – 10^{-13} m², placing them within the range commonly associated with permeable sandstones and compact granular sediments. In contrast, core C4 reaches a permeability on the order of 10^{-12} m², approaching the hydraulic behavior of coarse granular media, packed glass beads, and filtration materials.

This comparison demonstrates that the manufactured specimens reproduce hydraulic conditions representative of a broad spectrum of real porous media. Consequently, the synthetic cores provide a physically meaningful framework for interpreting the experimental results and support their use as laboratory analogues of natural and engineered porous systems.

Figure 5.



Comparison between the predicted permeability of the synthetic cores and typical permeability ranges reported for natural rocks, granular sediments, packed glass beads, sintered porous media, and filtration materials. The synthetic cores span from the range of permeable sandstones to highly permeable granular and filtration media.

CONCLUSIONS

This work presented a theoretical characterization of permeability in synthetic porous cores fabricated from glass beads using four complementary flow models: Darcy, Kozeny–Carman, Forchheimer and Ergun. Together, these formulations provide a multiscale framework that links pore-scale structural properties with macroscopic hydraulic behavior and allows permeability, flow rate and inertial effects to be evaluated under controlled conditions.

The permeability values predicted by the Kozeny–Carman and Ergun formulations ranged from 9.39 to 2583.40 mD and from 11.26 to 3100.08 mD, respectively. Although the Ergun formulation systematically produced slightly higher permeability values, both models yielded the same hydraulic ranking of the synthetic cores, indicating that they consistently capture the combined influence of porosity and grain diameter on hydraulic behavior. This agreement strengthens the reliability of the theoretical interpretation and supports the use of both formulations for comparative permeability assessment.

The results demonstrate that permeability is highly sensitive to structural parameters. Core C4, which combined the largest grain diameter and highest porosity, exhibited permeability values more than two orders of magnitude greater than those of the least permeable samples. The sensitivity analysis demonstrated that permeability is strongly influenced by both porosity and grain diameter. The highest permeability values were obtained when both parameters increased simultaneously, confirming that hydraulic performance results from their combined structural effect on pore geometry and flow pathways. The permeability response surfaces further revealed that neither parameter alone is sufficient to explain the observed hydraulic behavior, emphasizing the coupled nature of fluid transport in synthetic porous media.

Analysis of the Forchheimer–Ergun formulation showed that viscous forces dominate the hydraulic response under the reference operating conditions considered in this study. Reynolds numbers and inertial-to-viscous force ratios remained low, indicating that the analyzed flow conditions lie predominantly within the Darcy regime, although the most permeable samples exhibited a weak tendency toward viscous–inertial transition.

Comparison with permeability ranges reported for natural rocks, granular sediments, packed glass beads and filtration media showed that the fabricated synthetic cores reproduce hydraulic conditions representative of a broad spectrum of porous materials. The lower-permeability specimens are comparable to permeable sandstones and compact granular sediments, whereas the most permeable core approaches the hydraulic behavior of coarse granular media and filtration materials. This result supports the use of synthetic cores as controlled laboratory analogues for investigating flow and transport processes in natural and engineered porous systems.

Overall, the study demonstrates that theoretical permeability models provide a consistent and physically meaningful framework for evaluating synthetic porous materials and for guiding the design of future filtration, water-treatment and porous-media research applications. Furthermore, the integration of theoretical modeling, parametric simulation and sensitivity analysis provides a reproducible methodology for assessing the hydraulic performance of synthetic porous structures when direct permeability measurements are unavailable or uncertain.

COMMENTS

The present work is intentionally theoretical and predictive in nature. The permeability, flow rate and inertial effects reported here were estimated from measured structural parameters and established porous-media models rather than from direct hydraulic permeability experiments. Consequently, the results should be interpreted as theoretical predictions that provide a physically grounded baseline for future experimental validation.

One important outcome of this study is the demonstrated consistency among the Darcy, Kozeny–Carman, Forchheimer and Ergun formulations when applied to synthetic porous cores fabricated from glass beads. Despite differences in empirical coefficients, the models produced comparable permeability trends and identical hydraulic rankings, suggesting that the coupled effects of porosity and grain diameter are robustly captured by the theoretical framework.

The comparison with natural porous materials further indicates that the fabricated cores occupy permeability ranges relevant to sedimentary rocks, granular sediments and filtration media. This expands their potential usefulness beyond permeability studies and suggests possible applications in laboratory-scale investigations of filtration, water purification, groundwater flow and porous-media transport phenomena.

Future work should focus on direct permeability measurements using controlled hydraulic experiments. Experimental pressure–flow data would allow quantitative validation of the theoretical predictions, calibration of inertial coefficients and assessment of the applicability limits of each model. Additional characterization techniques, such as micro-computed tomography and pore-network analysis, could also provide a more detailed description of pore connectivity, tortuosity and pore-throat geometry, enabling more realistic permeability predictions and model refinement.

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