

Integrated analysis of pore size, shape, and position on mesoscale compressive strength of cementitious materials: Numerical modelling and statistical regression

Research Article

Grzegorz Piotr Kaczmarczyk, Marek Cała*

Faculty of Civil Engineering and Resource Management, AGH University of Krakow, Al. Mickiewicza 30, 30-059, Krakow, Poland

Received 21 April 2025; Accepted 28 March 2026

Abstract: Cement-based materials often suffer reduced compressive strength due to internal porosity, yet the specific roles of pore size, shape, and spatial distribution remain inadequately quantified. This study investigates the effect of pore geometry and position on the mesoscale compressive strength of a cement-clay mixture. High-resolution X-ray computed tomography (CT) captured three-dimensional pore structure and total porosity in cured specimens. The reconstructed microstructure was used in numerical models in FLAC3D, where a damage-plasticity concrete constitutive model was calibrated against *in situ* CT-monitored compression tests and validated with a second specimen. A series of parametric simulations were then conducted, systematically varying pore radius (1–2 mm), sphericity (0.79–1.00), and vertical location. The results show that increasing total porosity leads to a pronounced decrease in peak compressive strength (a strong inverse correlation, with exponential trends outperforming linear fits). However, strength in mesoscale should not be predicted by porosity alone: variations in pore size, shape, and position caused significant deviations from the single-parameter trend. To quantify the combined influence of pore-related features, a multiple linear regression model was developed using porosity, pore sphericity and pore position as predictors. The multi-parameter model achieved a high coefficient of determination ($R^2 = 0.80$) and a low prediction error ($MSE = 0.34 \text{ MPa}^2$), representing more than a threefold improvement in accuracy compared to porosity-only correlations. Standardised regression coefficients indicate that porosity is the dominant factor controlling compressive strength, followed by pore position and pore sphericity, all of which are statistically significant. The results demonstrate that pore geometry and spatial distribution critically influence the load-bearing capacity of cementitious mixtures. The proposed integration of CT imaging, physically calibrated numerical modelling, and statistical regression provides a robust framework for quantitative assessment of microstructure–performance relationships at the mesoscale.

Keywords: Pores • Sphericity • Mesoscale • Statistical regression

1. Introduction

Due to their widespread use, cement-based materials rank among the most essential construction materials and play a key role in ensuring the durability and safety of engineering structures. Compressive strength is one of the primary parameters used to evaluate their quality, and its reduction can lead to serious operational consequences. The scientific literature emphasises the influence of pore

structure, which significantly determines the mechanical properties of concrete [1,2]. It is well known that increased porosity in cementitious materials leads to a decrease in their mechanical strength [3]. Reducing the solid phase content decreases the effective load-bearing cross-section and disrupts the continuity of force transmission paths. In the case of cement-stabilised soils, decreasing porosity leads to significant strength gains by improving interparticle contact and increasing frictional resistance [4]. Conversely, increasing total porosity weakens the material. For instance, each 1% increase in air content in concrete

* E-mail: cala@agh.edu.pl

can noticeably reduce strength, particularly compressive strength, often following an exponential decay relationship [3]. The larger the value of a homogeneous stress field, the greater the stress concentrations become, and consequently, the more severe the damage caused by pores. This is why, for example, a 1% increase in porosity leads to a more significant decrease in compressive strength than in flexural strength or other mechanical properties [3].

The total porosity of concrete results from three components [5]: the porosity of the aggregate, the porosity of the cement paste, and the porosity of the interfacial transition zone between the aggregate and the paste. The most detrimental to strength are pores with diameters greater than 10 μm . Additionally, both irregularly distributed small pores and large pores exceeding 300 μm in diameter negatively affect the material's mechanical properties [5]. A classification of pores based on their size and origin is presented in Table 1.

There are several methods to reduce porosity in hardened cementitious mixtures. The most common approach involves lowering the water-to-cement (w/c) ratio [7–10]. However, excessively low w/c ratios may lead to micro-cracking. Nevertheless, low values are effective in minimising porosity and improving strength [11]. Studies indicate that a w/c ratio of 0.3 provides the best balance between porosity and mechanical strength [9,10,12]. Porosity can also be reduced by incorporating admixtures and filler materials [13,14]. It has been demonstrated that silica fume and meta-kaolin reduce porosity through pozzolanic reactions, which lead to the formation of a denser cement matrix [15]. Nanomaterials have also been shown to decrease porosity [16,17]. Air voids may also originate from inappropriate aggregate selection, which significantly influences the final porosity of the mixture [18]. Aggregates with poorly graded particle sizes promote the formation of larger air voids, negatively affecting the mechanical properties and permeability of concrete [19].

It can be unequivocally stated that porosity influences the failure mechanism in cementitious materials. These mechanisms, observed during experimental investigations,

remain a subject of interest for contemporary researchers. Despite decades of study, the description of failure mechanisms in cement-based materials continues to evolve, particularly due to the development of advanced technologies such as computed tomography (CT), which enables 3D observation of sample failure [20]. Three-dimensional data of the sample also serve as input (geometry) for numerical analysis in computational models [21]. The mesoscale represents a critical intermediate scale between micro- and macro-level analyses. According to the literature [22], simulations that account for variations within the matrix and aggregate fulfil the defining criteria of the mesoscale domain. Modern computational resources allow for highly accurate reconstruction of specimen geometry at the mesoscale.

This article focuses on analysing the influence of porosity on cementitious mixtures' compressive strength. The study aimed to investigate the influence of several parameters – namely pore size, shape, and position – on the compressive strength of the sample. The analysis was conducted at the mesoscale. Literature [23] indicates that macroscopic parameters are derived from fundamentally different material characteristics at the mesoscale. Accordingly, the first step involved uniaxial compression testing performed within a computed tomography scanner. At selected load levels, tomographic scans were conducted to capture the internal damage evolution. The tomographic data enabled reconstruction of the specimen geometry, including defects in the form of pores. These data were subsequently used to calibrate the material properties. The calibrated material model was then applied in simulations involving single pores with varying geometries and spatial distributions

2. Materials and methods

2.1 Material and its properties

The analysis used a mixture of clay, CEM I cement (Górażdże 42.5 R), and water. The tested soil was

Name	Size	Origin
Air pores	>10 μm	Intentionally or unintentionally entrained air inclusions and porous aggregate material
Large capillary pores	0.05–10 μm	Formed due to the evaporation of excess mixing water from the cement paste and typical porous structures in dense aggregates
Small capillary pores	10–50 nm	Resulting from excess water in the paste and microcrack-like porous structures in the aggregate
Gel pores	<10 nm	Approximately 28% of the volume of hydrated cement consists of micropores (1.5–4 nm), small capillary pores, and pores in the interfacial transition zone

Table 1. Types of pores present in cementitious mixtures [6].

Source: Based on [5].

predominantly composed of silt (Si), accounting for 68.8% of the total particle distribution (particle size between 0.002 and 0.063 mm). Clay particles (Cl), defined as particles smaller than 0.002 mm, constituted 28.73% of the material, while sand (Sa) content, with particle sizes ranging from 0.063 to 2 mm, was minimal at only 2.47%. This composition indicates a fine-grained soil with a dominant silt fraction and a relatively high clay content. Each batch consisted of 1,000 g of water, 900 g of cement, and 1,350 g of clay. The resulting water-to-cement (w/c) ratio of 1.1 is typical for injection works in geotechnical engineering, such as jet grouting [24]. The mixing process was carried out by the PN-EN 196-1 standard [25]. The prepared material was placed into syringes with a diameter of 10 mm. After a curing period of 28 days, the syringes were cut open and sectioned to obtain test specimens with a height of 10 mm (± 0.2 mm). The samples were examined using a GE Phoenix M300 computed tomography scanner and a DEBEN CT5000TEC loading stage. A high-resolution scan was performed with an accuracy of 10 μm , which enables detailed evaluation of the internal structure [26]. Tomographic data were used to assess porosity through segmentation algorithms [27], which are particularly effective in detecting air pores. Image analysis of the tomographic data was conducted using VGStudio 3.5 software. Porosity analysis was also performed in the same software. The detection was carried out according to the VGDefx. Image analysis parameters and filtering criteria were adjusted individually based on the absorption histograms. These data also served as the basis for reconstructing the actual geometry of the analysed sample [20]. A numerical model was generated in FLAC3D 9.0, consisting of elements with a size of 50 μm . The material behaviour was described using the ‘concrete’ model [28,29]. This concrete model is a plastic-damage formulation based on the concepts of fracture-energy-driven damage evolution and modulus degradation, as defined in continuum damage mechanics. The numerical model was calibrated using damage patterns observed during *in situ* compression tests inside the CT scanner. A detailed description of the calibration process is presented in a separate paper [30]. The calibration involved adjusting the stress–strain curve to closely match the behaviour observed in the physical sample. Subsequently, energy accumulation parameters were refined to ensure that the simulated damage pattern corresponded with the one recorded in the CT chamber. Digital Volume Correlation was also employed in the displacement analysis. Figure 1a–c shows the sample geometry, a cross-section of the failed sample, and the result of the calibrated numerical simulation. An isometric view of the analysed sample, along with the porosity analysis, is shown in Figure 1d. The pore colours

indicate variations in their sizes. A single elongated pore has a diameter exceeding 5 mm. Subsequently, Figure 1e presents the distribution of the analysed pores according to their diameters. The vast majority of pores are within the range of $d > 100 \mu\text{m}$. All pores identified in the analysis have diameters greater than 50 μm .

The calibrated results were validated against the failure mechanism of a second specimen from the same material batch. With the calibrated material parameters, the damage pattern observed in shear strain maps for the second numerical model showed strong agreement with the experimental observations. The material parameters used in the analysis are summarised in Table 2, and the stress–strain relationship $\sigma(\epsilon)$ from both the experiment and the simulation is presented below. In the numerical calculations, the model accounted for the following parameters: Young’s modulus (E), fracture energy in uniaxial compression/tension (G_c , G_t), uniaxial initial yield strength compression/tensile (f_{c0} , f_{t0}), or maximum uniaxial yield strength compression/tensile (f_{cm} , f_{tm}). Mesoscale parameters differ significantly from those obtained directly through experimental measurements. All of these parameters were calibrated as shown in [30].

The graph shown in Figure 2 presents the $\sigma(\epsilon)$ relationship for both the experimental results and the calibrated numerical analysis. The simulation results are depicted with a dotted line. In the range of small strains (up to 0.1%), discrepancies are observed, associated with the settlement of the actual samples during testing. A nonlinear stress increase occurs at the initial loading stage, suggesting the closure of initial pores and microcracks within the cemented soil structure. The material exhibits predominantly elastic behaviour during this phase, with gradually increasing stiffness.

In the quasi-linear phase ($0.01 < \epsilon < 0.03$), stress increases linearly, indicating the development of elastic deformations. The value of σ_{max} (approximately 14–15 MPa for sample 6 and 12–13 MPa for sample 5) corresponds to the maximum load-bearing capacity of the material, beyond which degradation processes commence. In this phase, the microstructure begins to experience intense cracking and localised failure. The post-critical phase, occurring for $\epsilon > 0.05$, follows the peak stress. After reaching σ_{max} , the stress decreases, indicating damage and disintegration of the cemented soil matrix. The experimental data reveal a more abrupt stress drop, suggesting brittle fracture and loss of structural continuity. In contrast, the numerical simulation shows a more gradual stress decline, resulting from using a plastic-damage material model that does not fully capture the sudden failure mechanisms of the real material. Another factor influencing the difference between experimental and numerical behaviour is the necessity to halt the loading process for CT scanning. The strain

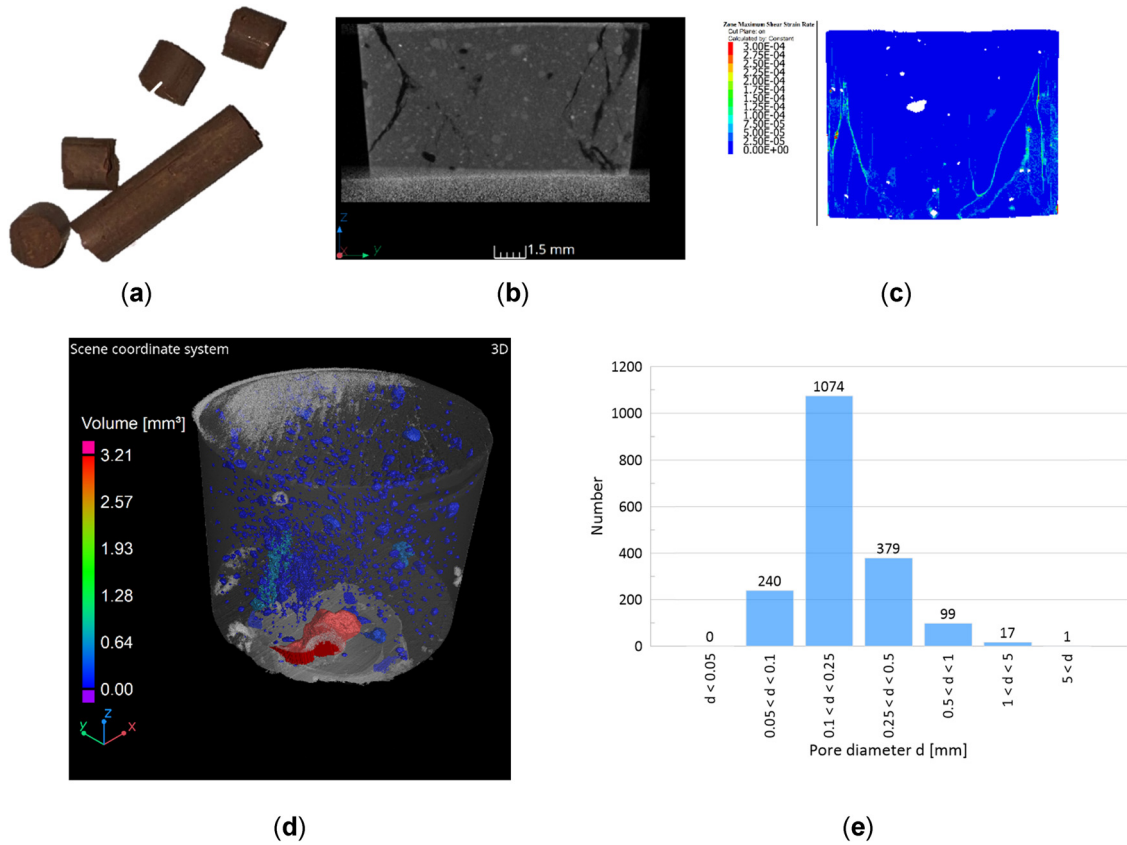


Figure 1. Material used in the study: (a) test specimen; (b) vertical CT cross-section of the failed specimen; (c) result of the calibrated numerical analysis; (d) isometric view; (e) distribution of pores.

Source: Author's contribution.

increment was not continuous at a constant rate but was interrupted at four discrete points to perform tomographic scans (under constant load without unloading), which may have influenced the experimental response.

The experimental and numerical data exhibit a typical pattern for compression tests: an initial phase of stress increase, reaching a maximum, followed by a decline associated with material degradation. The simulation curves (dotted lines) are generally smoother than the experimental curves (solid lines), which may be attributed to numerical averaging within the model. The numerical model is based on a continuum approach. The simulations predict higher maximum stress values than experimentally, particularly

for sample 6. In the case of sample 5 (thin dotted vs. thin solid line), the maximum values are closer, although the simulation still slightly overestimates the stress. After the peak stress, the real cemented soil exhibits a more abrupt degradation, suggesting that the numerical model may lack the complete representation of localised cracking phenomena.

Numerical model

The study involved performing numerical analyses on models matching the dimensions of the specimens used for model calibration. In FLAC3D, 20 models were generated – one solid reference model and nineteen models containing pores. The geometric parameters of these models are summarised in Table 3. The models are labelled

E [GPa]	f_{c0} [MPa]	f_{cm} [MPa]	G_c [N/m]	f_{t0} [MPa]	f_{tm} [MPa]	G_t [N/m]
0.32	18.2	30.4	35,600	3.7	3.7	202

Table 2. Numerical parameters for the material.

Source: Author's contribution.

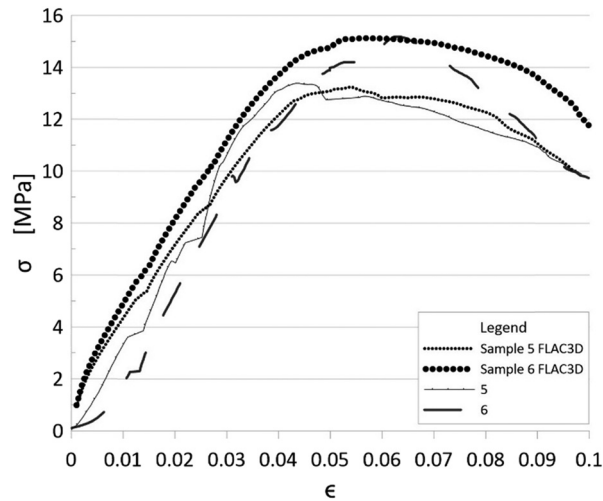


Figure 2. Uniaxial compression. Stress–strain $\sigma(\epsilon)$ curves for the tested samples and the corresponding simulation results.

Source: Author's contribution.

with a number (pore size, shape) and a letter (position). Sample 0 served as the reference specimen, against which subsequent models could be compared. The analyses focused on the influence of pore size (with radius ranging from 1 to 2 mm) and sphericity (ranging from 0.79 to 1.00). Sphericity is a dimensionless parameter that quantifies how closely the shape of an object approaches that of a perfect sphere. The value of sphericity ranges from 0 to 1, where 1 represents a perfect sphere. Objects with lower sphericity are more elongated, flattened, or irregular. Sphericity is an essential parameter in material science, geotechnics, and concrete research because it affects packing density, mechanical behaviour, and the development of stress concentrations around inclusions or pores. Changes in sphericity were achieved by scaling the pore dimensions along two axes. Scaling one horizontal axis by a factor of 0.66 and the other by 1.5 (while keeping the third axis unchanged) reduced the sphericity to 0.91 while maintaining the initial pore volume. A similar method was used to obtain a sphericity of 0.79. The numerical models can be grouped into several categories. Simulations 1–3 include spherical pores of varying sizes. Models 4 and 5 represent the smallest pores with different sphericities. In pairs 6 and 7, 8 and 9, the pore volume and the degree of sphericity vary. Figure 3 shows the geometries used in the simulations. Figure 3a illustrates three different pore shapes, highlighting the impact of sphericity changes.

The individual pores were positioned at specific locations within the sample. Position A corresponds to the placement where the pore's geometrical centre is located at the centre of the specimen, which under ideal conditions corresponds to the zone of maximum shear stress

concentration. The height of the pore centre in position A is 5 mm. Position B is located below the specimen centre, with the pore centre at a height of 4 mm. Position C places the pore centre at 3 mm. Figure 3b presents an example of pore positioning within the sample.

The numerical model was composed of roughly 10 million cubic elements, each with a side length of 50 μm . To simulate a rigid, non-deformable loading surface, the top layer was constrained with zero-velocity boundary conditions in all spatial directions. The bottom layer was subjected to a constant vertical velocity of 0.05 μm per cycle, while horizontal movements were fully restricted. Numerical stabilisation was performed after every 200 cycles, corresponding to a total displacement of 10 μm .

3. Results and discussion

The key numerical results of the conducted numerical simulations are summarised in Table 4. A detailed discussion of these results and their mechanical interpretation is provided in the following subsections.

3.1 Effect of shape

The effect of pore shape was studied for position C (pore centre height at 3 mm). This analysis location was selected because it is below the sample centre, where maximum shear stress concentrations occur under peak loading conditions. The analysis was carried out for three pore sizes and three sphericity values.

No	Base radius [mm]	Scale <i>X</i>	Scale <i>Y</i>	Scale <i>Z</i>	Sphericity	Porosity [%]	Position	Comment
0	0	—	—	—	—	0	—	Solid model without pores (reference)
1	1	1	1	1	1	0.37	A,B,C	Model containing spherical pores of varying size
2	1.5	1	1	1	1	1.25	A,B,C	
3	2	1	1	1	1	2.97	A,B,C	
4	1	1.5	0.66	1	0.91	0.37	C	Model with the smallest pores of varying sphericity, horizontally elongated
5	1	2	0.5	1	0.79	0.37	C	
6	1.5	1.5	0.66	1	0.92	1.25	C	Model with medium-sized pores of varying sphericity, horizontally elongated
7	1.5	2	0.5	1	0.79	1.25	C	
8	2	1.5	0.66	1	0.91	2.97	A,B,C	Model with the most prominent pores of varying sphericity, horizontally elongated
9	2	2	0.5	1	0.79	2.97	A,B,C	

Table 3. Description of numerical models.

Source: Author's contribution.

The graphs show differences in the simulation results for samples with the smallest pore diameter (Figure 4a) that are not initially visible. As the strain increases, differences between the reference sample and the samples containing pores become more apparent. All samples with pores exhibit lower stress levels compared to Sample 0. Within the group of pores with a radius of 1 mm, the differences caused by pore shape remain quite subtle – the results for sphericity 1.0 (Sample 1C) and 0.91 (Sample 4C) are very similar. In contrast, Sample 5 (sphericity 0.79) shows slightly lower stress values.

Maximum stresses are reached in the 5–6.5% strain range before degradation effects dominate. The reference

sample maintains the highest stress level, while the presence of pores reduces the load-carrying capacity. Comparing the samples with a 1 mm radius, it is observed that Sample 1C (perfectly spherical) generally reaches slightly higher stress levels than the samples with lower sphericity. Samples 4C and 5C exhibit very similar behaviour, although Sample 5 (sphericity, 0.79) occasionally achieves marginally lower stress values, which may indicate higher stress concentrations due to the irregular pore shape.

As shown in Figure 4b, all specimens – the reference and those with a 1.5-mm pore – show similar stress values at very low strains. As the strain increases, the reference

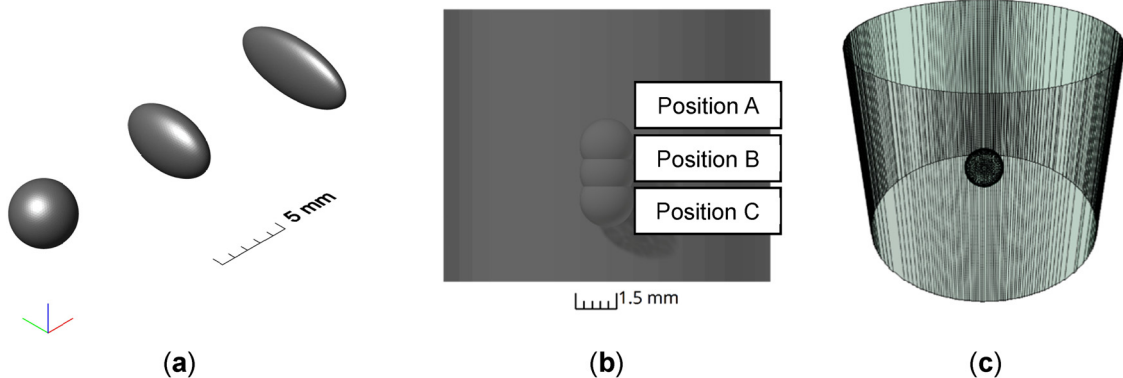


Figure 3. Numerical models: (a) pores with constant volume and varying sphericity, from left to right: 1.0, 0.91, 0.79 – isometric view; (b) three pores of identical diameter shown at positions A, B, and C; (c) model's geometry view – pore no. 1, position C, FLAC3D. Source: Author's contribution.

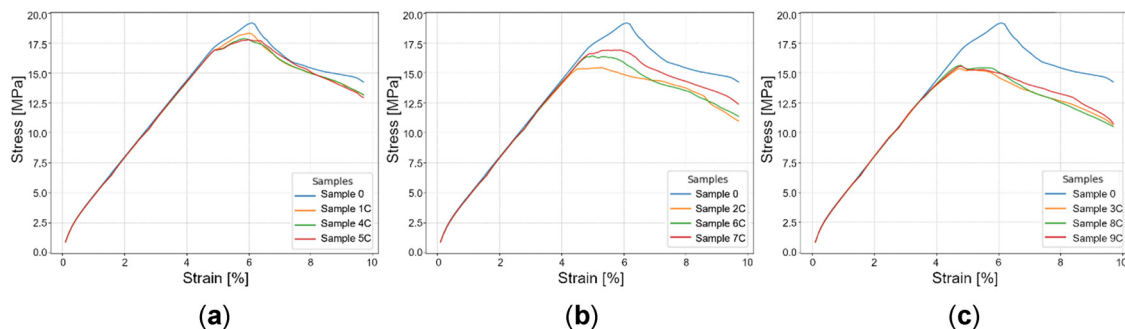
	Porosity [%]	Vertical coordinate of the pore centroid [mm]	Sphericity [–]	Peak compressive stress [MPa]	Axial strain at peak stress [%]
1A	0.37	5	1	15.79	4.9
1B	0.37	4	1	15.95	4.9
1C	0.37	3	1	18.30	6.0
2A	1.25	5	1	14.70	4.8
2B	1.25	4	1	14.44	4.9
2C	1.25	3	1	15.40	5.3
3A	2.97	5	1	13.75	4.6
3B	2.97	4	1	13.97	4.9
3C	2.97	3	1	15.32	4.7
4C	0.37	3	0.91	17.84	5.8
5C	0.37	3	0.79	17.75	6.0
6C	1.25	3	0.98	16.40	5.0
7C	1.25	3	0.79	16.89	5.9
8A	2.97	5	0.91	14.25	4.7
8B	2.97	4	0.91	14.38	4.7
8C	2.97	3	0.91	15.60	4.8
9A	2.97	5	0.79	15.33	4.9
9B	2.97	4	0.79	14.30	4.9
9C	2.97	3	0.79	15.55	4.8

Table 4. Results summary.

Source: Author's contribution.

specimen's stress remains noticeably higher. For example, at a strain of 3%, Sample 0 reaches approximately 11.14 MPa, while the 1.5 mm specimens show lower stresses (around 10.99 MPa for Sample 2, with comparable values for Samples 6 C and 7 C). At very low strains, all specimens – the reference and those with a 1.5-mm pore – show similar stress values. At a strain of 5%, Sample 0 exhibits a stress of roughly 17.36, whereas the 1.5 mm specimens show markedly reduced stresses – approximately

15.37 MPa for Sample 2, 16.40 MPa for Sample 6C, and 16.58 MPa for Sample 7C. While one might initially expect the ideally spherical pore (Sample 2C, sphericity = 1) to produce the least stress reduction, the data indicate that for a pore of 1.5 mm, the sample with the lowest sphericity (Sample 7, sphericity = 0.79) maintains slightly higher stress values at higher strains compared to its more spherical counterpart. For the 1.5 mm pore size, the irregularity of the pore (lower sphericity) appears to modify the local

**Figure 4.** Stress–strain curves with varying sphericity (a) pore radius: 1 mm; (b) pore radius: 1.5 mm; and (c) pore radius: 2 mm.

Source: Author's contribution.

stress distribution such that Sample 7C sustains higher stresses at elevated strains than Sample 2C. Nonetheless, all pore-containing specimens are still significantly below the performance of the pore-free reference.

The samples with a 2 mm pore located at position C are shown in Figure 4c. All specimens – the pore-free reference and those containing a 2 mm pore – exhibit similar stress values at low strains. Although the presence of the pore remains the dominant factor reducing mechanical performance, subtle effects related to pore shape are observable. The ideally spherical pore (Sample 3C) generally corresponds to a lower stress response at higher strain levels. Specimens with lower sphericity (Samples 8C and 9C) occasionally record slightly higher stresses, indicating a complex interaction between pore shape and stress distribution under large deformations.

Compared to the reference sample without pores, the specimens with a 1-mm pore radius exhibit lower stress values at a given strain level. This reduction results from the presence of the pore, which induces local stress concentrations. These findings demonstrate that, although the impact of changing sphericity at a constant 1 mm radius is not appreciable, there is a clear tendency for more irregular pore shapes to decrease the load-bearing capacity further. In practice, pore shape cannot be directly prescribed, particularly in injection-based cementing technologies; however, experimental studies on grouted granular media demonstrate that injection parameters and grout properties can significantly modify pore structure and effective porosity by filling existing voids and altering the pore size distribution. As a result, technological control primarily affects the void system indirectly through changes in porosity and microstructural homogenisation rather than through direct geometric control of individual pores [31]. While a pore of 1.5 mm in size compromises the material's overall stiffness and strength compared to a pore-free specimen, the irregularity of the pore (as evidenced by a lower sphericity) may mitigate the reduction in stress-bearing capacity at higher strains. This behaviour contrasts with the observations for smaller pores (e.g., 1 mm), where a more spherical shape tends to preserve stiffness better under higher strain. These nuances highlight the importance of considering pore size and shape when evaluating cement grout's mechanical performance. In some strain ranges, Sample 8C and Sample 9C exhibit slightly higher stress values than Sample 3C. This suggests that a deviation from perfect sphericity may alter the stress distribution for larger pores to partially compensate for the reduced load-bearing capacity. However, it should be emphasised that the variation in strength for the specimens with the largest pore did not exceed 4% of the

maximum strength. It is important to note that the analysis was performed only for a single pore within a mesoscale specimen.

3.2 Effect of pore position

To investigate the effect of vertical pore placement on the mechanical behaviour of cemented soils, uniaxial compression simulations were performed on specimens with a single spherical pore of radius 1, 1.5, or 2 mm. For each configuration, the pore was located at three different heights: mid-height (5 mm from the base, denoted as A), slightly lower (4 mm, B), and near the bottom of the specimen (3 mm, C). Stress–strain responses were compared to identify the influence of pore position on global material strength. The stress–strain relationships are presented in Figure 5a.

The results consistently indicate that specimens with pores closer to the sample's base (position C) exhibit higher peak stresses and greater residual load-bearing capacity than those with centrally located defects (position A). This trend becomes more pronounced at larger strains, beyond the linear elastic level. The highest degradation in mechanical response was observed when the pore was placed near the cones of maximum shear stress (positions A and B).

This phenomenon can be linked to the well-established stress distribution in uniaxial compression tests, where the central region of the specimen is known to accumulate the highest shear stresses. The presence of a defect in this critical zone leads to earlier initiation of plastic deformation and microcracking, accelerating the overall material degradation. Conversely, pores near the boundaries experience lower local shear stress intensity, and their impact on global failure mechanisms is less severe. These findings underscore the importance of pore size and geometry and their positioning relative to internal stress fields, particularly in heterogeneous materials such as cemented soils.

Based on the results of numerical and geometrical analyses, it is shown that a pore whose volume does not intersect the shear stress concentration cone (as in position C) exerts a significantly smaller influence than a pore located at or intersecting the boundaries of these high-stress zones. Figure 5b–d presents vertical stress distribution maps for a 1 mm pore positioned at locations A–C, along a vertical cross-section through the centre of the specimen. The corresponding shear strain distributions are shown in Figure 5e–g. At a strain level of $\epsilon = 5\%$, the most remarkable asymmetry in vertical stress is observed

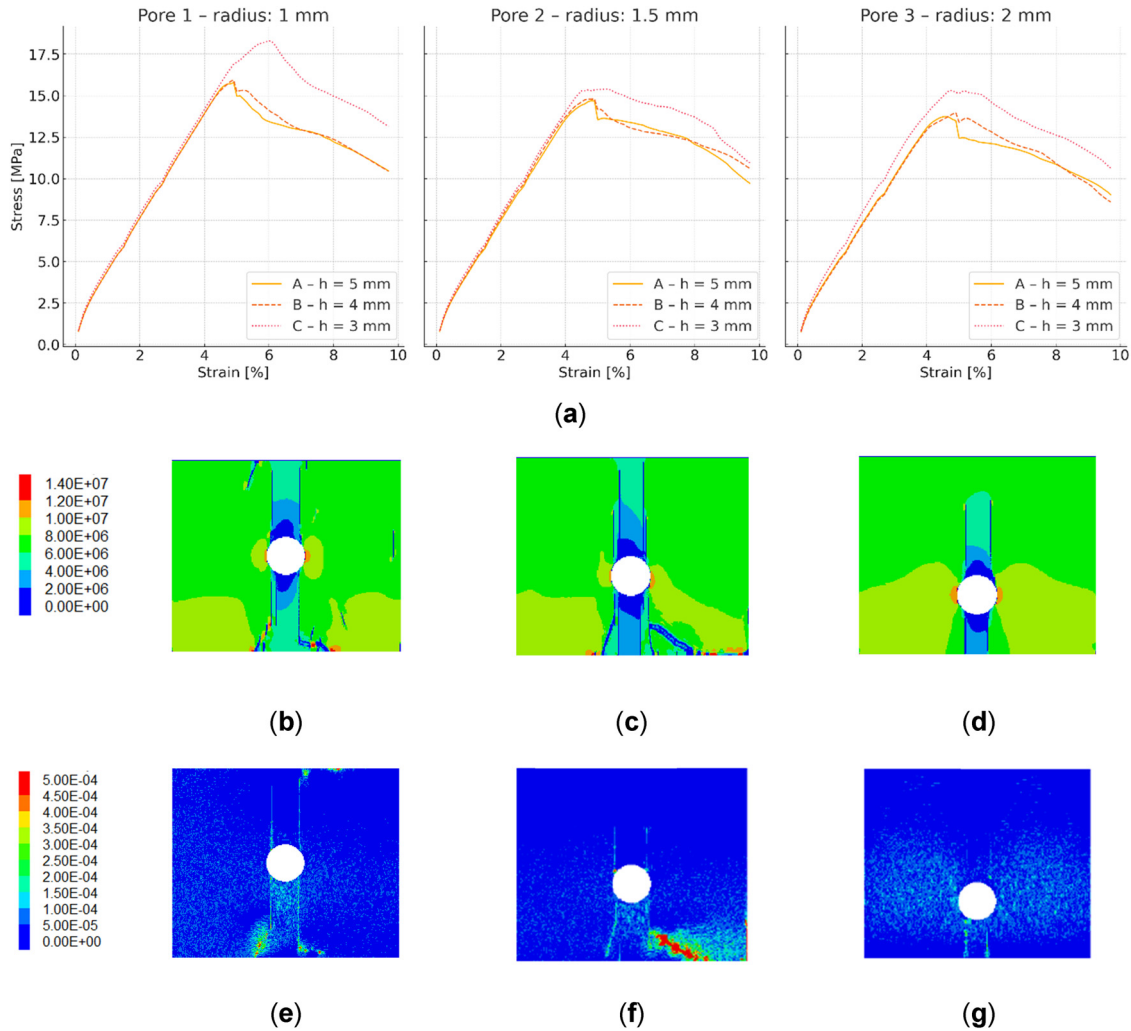


Figure 5. Results for the effect of pore position: (a) stress–strain curves for different pore locations; (b) vertical stress distribution map for position A; (c) vertical stress distribution map for position B; (d) vertical stress distribution map for position C; (e) shear strain distribution map for position A; (f) shear strain distribution map for position B; and (g) shear strain distribution map for position C. Source: Author's contribution.

for position B. For this configuration, the numerical analysis indicated the earliest onset of cracking.

3.3 Effect of porosity

Figure 6 illustrates the influence of total porosity on the peak compressive strength of cemented soil specimens. The peak strength generally decreases with increasing porosity, which aligns with theoretical expectations. The reference sample with 0% porosity achieved the highest strength (19.15 MPa). At a total porosity of just 1%, the strength dropped to a range of 16–18.3 MPa, representing a maximum reduction of more than 11%.

With further increases in porosity, the strength followed a downward trend – for example, at approximately 3% porosity, the average strength was around 14.3 MPa. The most porous specimens (3–4.5%) exhibited the lowest strength values, in the 13–15 MPa range, which is approximately 20–30% lower than the solid model. This inverse relationship is consistent with the well-known mechanism of strength reduction in cementitious materials due to a decrease in the load-bearing phase [4].

However, it is essential to note that this dataset's relationship between strength and porosity is not perfectly monotonic due to variability among the specimens. Some individual samples may even suggest a trend opposite to that reported in the literature. For instance, a specimen

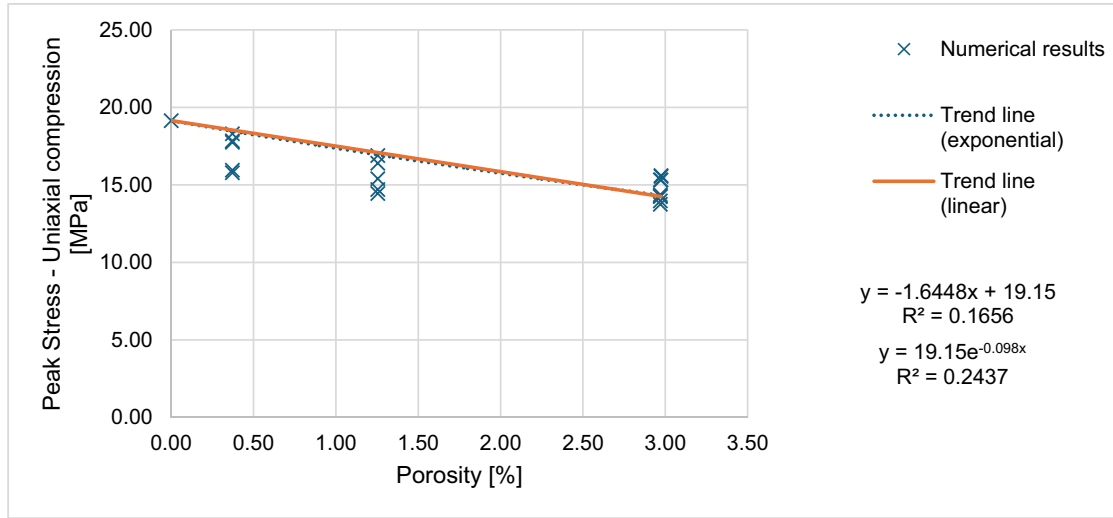


Figure 6. Relationship between uniaxial compressive strength and total porosity.

Source: Author's contribution.

with 2.97% porosity reached a peak strength of approximately 15.6 MPa, whereas specimens with 1.25% porosity exhibited lower peak stresses (~14.44 MPa). Therefore, in mesoscale studies, it is essential to provide detailed information on the shape and position of pores, as these factors can significantly influence the mechanical response.

The deviations shown in Figure 6 result in significant data dispersion. Two trend lines were added to the plot: linear and exponential. Both were constrained to satisfy a boundary condition: at 0% porosity, the trend line was required to pass through the value of 19.15 MPa, corresponding to the peak compressive strength of the solid (pore-free) specimen. Based on the coefficient of determination (R^2) and following the verbal interpretation for linear correlations by Sobczyk [32], a strong correlation is indicated between porosity and maximum compressive strength. The mean squared error (MSE) was also computed for linear and exponential fits, yielding values of 1.88 and 1.70 MPa², respectively.

The numerical results demonstrate that variations in pore shape and pore position, in addition to total porosity, significantly influence the final mesoscale response of the specimens. This indicates that porosity alone is insufficient for a reliable prediction of compressive strength and that additional geometric descriptors of pores must be considered. To quantify the combined effect of these parameters in a statistically consistent and fully interpretable manner, a multiple linear regression model was adopted.

Compressive strength f_c was treated as the dependent variable, while porosity n , pore sphericity S , and pore position p served as independent predictors. The regression analysis was performed on the complete dataset

($n = 19$). The resulting model achieved a high coefficient of determination $R^2 = 0.80$ and an adjusted coefficient $R^2_{adj} = 0.77$, indicating very good agreement between the numerical simulations and the regression-based prediction despite the limited number of samples.

The final regression equation can be written as:

$$f_c = 23.46 - 0.803 n - 4.228 S - 0.660 p,$$

where f_c is expressed in MPa, n denotes porosity, S the pore sphericity, and p the pore position index.

All three predictors were found to be statistically significant at the 0.05 level. Porosity exhibits the strongest and most robust influence on compressive strength ($\beta = -0.803$, $p = 5.0 \times 10^{-5}$), confirming that increasing void content systematically reduces the load-bearing capacity of the cemented soil matrix. This observation is in full agreement with classical micromechanical interpretations, according to which increasing porosity leads to enhanced stress concentration and earlier initiation of damage.

Pore sphericity is also statistically significant ($\beta = -4.228$, $p = 0.034$), demonstrating that pore shape measurably affects the macroscopic strength response. Within the analysed geometric configuration, the results indicate that horizontally elongated pores lead to systematic changes in strength compared to nearly spherical voids. Although the influence of sphericity is weaker than that of porosity, it remains non-negligible and highlights the importance of pore geometry at the mesoscale.

The effect of pore position is likewise statistically significant ($\beta = -0.660$, $p = 0.0035$), confirming that the

vertical location of a dominant defect within the specimen substantially influences compressive strength. Pores located closer to the lower part of the specimen were found to be less detrimental than those positioned higher. This observation is consistent with the spatial distribution of stress and deviatoric strain in the numerical models and supports the conclusions drawn in the previous subsection regarding the role of defect location. A summary of the regression parameters describing the mechanical influence of pore-related features on compressive strength is provided in Table 5.

Since the predictors are expressed in different physical units and have different numerical ranges, their relative importance was additionally assessed using standardised regression coefficients. The standardised values indicate that porosity has the strongest relative influence on compressive strength ($\beta^* = -0.69$), followed by pore position ($\beta^* = -0.42$) and pore sphericity ($\beta^* = -0.28$). This ranking confirms that porosity is the primary mesoscale control on compressive strength, while pore position and shape provide additional, independent contributions to the observed variability.

Overall, the regression-based multi-parameter model demonstrates that compressive strength of cemented soil specimens is governed by the combined interaction of porosity, pore shape, and pore position. The high coefficient of determination and the statistical significance of all three predictors confirm that a simple and fully interpretable linear model is sufficient to capture the dominant physical trends present in the analysed dataset.

The comparison of prediction errors demonstrates (Table 6) a clear advantage of the multi-parameter regression approach over single-variable trend-line models. The single-parameter linear and exponential trend-line fits yield relatively high prediction errors ($MSE = 1.88 \text{ MPa}^2$ and $MSE = 1.70 \text{ MPa}^2$, respectively), indicating limited predictive capability when porosity alone is considered. In contrast, the multiple linear regression model, which simultaneously accounts for porosity, pore sphericity, and pore position, achieves a substantially lower prediction error ($MSE = 0.34 \text{ MPa}^2$). This represents more than a threefold reduction in error compared to the single-parameter models and confirms that compressive strength is governed by the combined interaction of several geometric features rather than porosity alone.

4. Conclusions

The numerical mesoscale model (FLAC3D with a concrete damage-plasticity law) was calibrated and validated

Parameter	Regression coefficient β [MPa/unit]	Std. error	t-Value	p-Value	Standardised β^*	Mechanical interpretation
Porosity	-0.803	0.143	-5.61	5.0×10^{-5}	-0.69	Dominant factor controlling strength. Increasing porosity strongly reduces compressive strength due to increased void volume and stress concentration
Pore sphericity	-4.228	1.816	-2.33	0.034	-0.28	Statistically significant but weaker geometric effect. Horizontal elongation of pores modifies local stress redistribution and affects strength at the mesoscale
Pore position	-0.660	0.191	-3.46	0.0035	-0.42	Second most influential parameter. Vertical relocation of a dominant pore may change strength by ~1.3 MPa over two position units. Reflects interaction with specimen-scale stress field

Table 5. Statistical parameters of the multiple linear regression model describing the mesoscale influence of pore geometry and position on compressive strength. Source: Author's contribution.

Parameter	Trend line (linear)	Trend line (exponential)	Multiple linear regression (three predictors)
MSE [MPa ²]	1.88	1.70	0.34

Table 6. Mean squared error, $n = 19$.

Source: Author's contribution.

against experimental data. It replicated the observed failure patterns and stress–strain responses from CT-monitored compression tests, confirming that the simulation approach can reliably capture the influence of pore features on compressive strength.

Total porosity showed a strong inverse correlation with the compressive strength of the cement-based mixture. Many publications [16,17,33,34] highlight the relationship between porosity and the strength obtained in laboratory tests. The analyses indicate that total porosity and the shape and distribution of pores within the examined material are significant, especially in mesoscale analyses. Pore size was found to be the most influential single factor on strength. Larger pores significantly lowered the peak strength of specimens due to greater stress concentrations, whereas smaller pores had a less deleterious effect and allowed higher strength retention. Pore shape, characterised by sphericity, had a discernible but lesser impact on strength than pore size. More irregular (lower sphericity) pores caused slight reductions in strength relative to nearly spherical pores. This effect was modest, indicating that pore shape alone plays a secondary role within the tested range. The spatial position of pores, particularly their vertical location, affected the compressive strength outcomes. Pores near the sample's mid-height (the region of highest shear stress) induced more severe strength loss than those near the base. This highlights that void placement relative to the internal stress distribution is critical to failure initiation.

Incorporating multiple pore characteristics into a predictive framework substantially improved the accuracy of compressive strength estimation. The multiple linear regression model, which simultaneously accounts for porosity, pore sphericity, and pore position, reduced the prediction error by more than threefold compared to porosity-only correlations. While single-parameter linear and exponential trend-line models yielded relatively high errors (MSE = 1.88 and 1.70 MPa², respectively), the multi-parameter regression achieved a markedly lower prediction error (MSE = 0.34 MPa²). This clearly demonstrates the benefit of jointly considering pore geometry and defect location when forecasting mechanical behaviour.

The regression analysis further enabled a quantitative assessment of the relative importance of individual pore-related features. Standardised regression coefficients indicate that porosity is the dominant factor controlling compressive strength ($\beta^* = -0.69$), followed by pore position ($\beta^* = -0.42$), while pore sphericity exhibits the weakest, yet still statistically significant, influence ($\beta^* = -0.28$). These statistically robust results confirm that compressive strength is governed by the combined interaction of pore volume, spatial defect distribution, and pore geometry, rather than by porosity alone.

Funding information

Authors state no funding involved.

Author contributions

Grzegorz Piotr Kaczmarczyk: writing – original draft, visualization, validation, software, project administration, methodology, investigation, formal analysis, data curation, conceptualization. Marek Cała: writing – review & editing, supervision, funding acquisition.

Conflict of interest statement

Authors state no conflict of interest.

Data availability statement

Data will be made available on request.

References

- [1] Kępnia, M., Chyliński, F., Górecka, E., & Goljan, A. (2025). The influence of water pretreated recycled aggregate on the required time of concrete care. *Archives of Civil Engineering*, 71, 295–310. doi: 10.24425/ace.2025.153335.
- [2] Petrella, A., Todaro, F., Yadav, P., Gubitosa, J., & Notarnicola, M. (2025). Physical and mechanical properties of cement mortars with recycled polyethylene terephthalate: Influence of grain size and composition. *Materials*, 18(6), 1378. doi: 10.3390/ma18061378.

- [3] Popovics, S. (1989). A hypothesis concerning the effects of macro-porosity on mechanical properties of concrete. In *Fracture of concrete and rock* (pp. 170–174). Springer. doi: 10.1007/978-1-4612-3578-1_17.
- [4] Baldovino, J. A., Millan-Paramo, C., & Saba, M. (2022). Porosity-to-cement index controlling the strength and microstructure of sustainable crushed material-cemented soil blends. *Buildings*, 12(11), 1966. doi: 10.3390/buildings12111966.
- [5] Babińska, J. (2011). The study of porosity in the evaluation of freeze–thaw durability of air-entrained concretes. *Prace Instytutu Techniki Budowlanej*, 40(4), 3–15.
- [6] Rusin, Z. (2002). *Technology of frost-resistant concretes* (1st ed.). Polski Cement.
- [7] Liu, Q. (2024). Experimental study on factors influencing the permeable concrete performance on the road surface. *Ceramics–Silikaty*, 68, 242–251. doi: 10.13168/cs.2024.0024.
- [8] Shahzar, M., Kalita, N. M., Azin, R., Osfour, S., Sharma, S., & Saxena, A. (2024). Advanced solutions for oil-well cementing in high-pressure high-temperature oil wells using nano-gilsonite. *Energy Fuels*, 38(16), 15182–15193. doi: 10.1021/acs.energyfuels.4c02492.
- [9] Siva, D., Kumar, R. S., & Dakshinamurthy, N. R. (2025). Influence of recycled aggregates on mechanical and permeability properties of pervious concrete. *Indian Journal of Science and Technology*, 18(7), 559–570. doi: 10.17485/IJST/v18i7.3953.
- [10] Wang, S., Fu, X., He, Z., & Wang, W. (2024). Influence of water to cement ratio on mechanical strengths and microstructure of cellulose ethers modified portland cement-calcium sulfoaluminate cement composite system. *Journal of Thermal Analysis and Calorimetry*, 150(21), 1–21. doi: 10.1007/s10973-025-14724-5.
- [11] Rahul, R., & Ravi Kumar, M. S. (2025). Experimental study of the effect of fine aggregate in pervious concrete. *Materiali in Tehnologije*, 59(1), 31–37. doi: 10.17222/mit.2024.1295.
- [12] Liang, Y., Liu, G., Chen, H., Chen, J., Zha, L., Ortiz de Zarate, F. I., & Rashad, A. M. (2025). Regulatory mechanism of the microstructure, water absorption, and release properties of internal curing phosphogypsum-based aggregates by silica fume. *Construction and Building Materials*, 463, 139968. doi: 10.1016/j.conbuildmat.2025.139968.
- [13] Kumar, R., Mohd Yaseen, A. Y. B., Shafiq, N., & Jalal, A. (2017). Influence of metakaolin, fly ash and nano silica on mechanical and durability properties of concrete. *Key Engineering Materials*, 744, 8–14. doi: 10.4028/www.scientific.net/KEM.744.8.
- [14] Zhang, H., Zhang, Q., Zhang, M., Tang, S., Pei, Y., Skoczylas, F., et al. (2024). Effect of fly ash and metakaolin on the mechanical properties and microstructure of magnesium ammonium phosphate cement paste. *Construction and Building Materials*, 424, 135871. doi: 10.1016/j.conbuildmat.2024.135871.
- [15] Morsy, M. S., & Shebl, S. S. (2007). Effect of silica fume and metakaoline pozzolana on the performance of blended cement pastes against fire. *Ceramics–Silikaty*, 51(1), 40–44.
- [16] Tian, L., Liu, T., Fu, H., Wang, P., Taqi, M., Li, W., Cui, L., & Wang, Y. (2025). Electrochemical extraction of chloride in OPC-CSA composite conductive mortar with nano- Al_2O_3 . *Journal of Building Engineering*, 105, 112432. doi: 10.1016/j.jobbe.2025.112432.
- [17] Bheel, N., Chohan, I. M., Alraeeini, A. S., Alwetaishi, M., Waheeb, S. A., Alkhatabi, L., & Benjeddou, O. (2025). Optimization of durability characteristics of engineered cementitious composites combined with titanium dioxide as a nanomaterial applying RSM modelling. *Scientific Reports*, 15(1), 9428. doi: 10.1038/s41598-025-94382-7.
- [18] Alsayed, S. H., & Amjad, M. A. (1996). Strength, water absorption and porosity of concrete incorporating natural and crushed aggregate. *Journal of King Saud University Engineering Sciences*, 8(1), 109–119. doi: 10.1016/S1018-3639(18)30642-1.
- [19] Sahdeo, S. K., Ransinchung, G. D., Rahul, K. L., & Debbarma, S. (2020). Effect of mix proportion on the structural and functional properties of pervious concrete paving mixtures. *Construction and Building Materials*, 255, 119260. doi: 10.1016/j.conbuildmat.2020.119260.
- [20] Kaczmarczyk, G. P., & Cała, M. (2023). Possible application of computed tomography for numerical simulation of the damage mechanism of cementitious materials – a method review. *Buildings*, 13(3), 587. doi: 10.3390/buildings13030587.
- [21] Kinasz, R., Bilozir, V., Shmyh, R., & Vysochenko, A. (2019). Suspensibility of steel fibre reinforced concrete values with external ribbed armature. *IOP Conference Series: Materials Science and Engineering*, 471(5), 052047. doi: 10.1088/1757-899X/471/5/052047.
- [22] Du, X., & Jin, L. (2021). Concrete on the meso-level. In *Size effect in concrete materials and structures* (pp. 17–25). Springer. doi: 10.1007/978-981-33-4943-8_2.
- [23] Kim, J.-S., Kim, J. H., & Han, T.-S. (2019). Microstructure characterization of cement paste

- from micro-CT and correlations with mechanical properties evaluated from virtual and real experiments. *Materials Characterization*, 155, 109807. doi: 10.1016/j.matchar.2019.109807.
- [24] Spagnoli, G., & Oreste, P. (2025). Statistical interpretation of jet grouting field data regarding its strength and stiffness. *Geotechnical and Geological Engineering*, 43(1), 44. doi: 10.1007/s10706-024-03008-8.
- [25] Polski Komitet Normalizacyjny. (2016). *PN-EN 196-1:2016, Metody badania cementu - Część 1: Oznaczanie wytrzymałości*. Polski Komitet Normalizacyjny, Warszawa.
- [26] Kaczmarczyk, G. P., Wałach, D., Natividade-Jesus, E., & Ferreira, R. (2022). Change of the structural properties of high-performance concretes subjected to thermal effects. *Materials*, 15(16), 5753. doi: 10.3390/ma15165753.
- [27] Radmacher, W., Head, M. J., Uchman, A., Mikołajczak, M., Lempart-Drozd, M., Kaczmarczyk, G. P., & Wałach, D. (2023). The Neogene–Quaternary boundary at its type locality, Monte San Nicola, Sicily, southern Italy: X-ray computed tomography and ichnofabric signals of the sapropelic Nicola bed. *Marine and Petroleum Geology*, 158, 106552. doi: 10.1016/j.marpetgeo.2023.106552.
- [28] Lee, J., & Fenves, G. L. (1998). Plastic-damage model for cyclic loading of concrete structures. *Journal of Engineering Mechanics*, 124(8), 892–900. doi: 10.1061/(ASCE)0733-9399(1998)124:8(892).
- [29] Lubliner, J., Oliver, J., Oller, S., & Oñate, E. (1989). A plastic-damage model for concrete. *International Journal of Solids and Structures*, 25(3), 299–326. doi: 10.1016/0020-7683(89)90050-4.
- [30] Kaczmarczyk, G. P., & Cała, M. (2025). Adoption of tomographic analysis and digital volume correlation as a support in calibrating numerical models of cement-based materials. *Construction and Building Materials*, 489, 142369. doi: 10.1016/j.conbuildmat.2025.142369.
- [31] Saiyouri, N., Alaiwa, A. A., & Hicher, P. Y. (2011). Permeability and porosity improvement of grouted sand. *European Journal of Environmental and Civil Engineering*, 15(3), 313–333. doi: 10.1080/19648189.2011.9693329.
- [32] Sobczyk, M. (2006). *Statystyka: aspekty praktyczne i teoretyczne*. Lublin: Wydawnictwo UMCS.
- [33] Jiang, Z., Lu, K., Limdevit, M., Fu, C., Ling, Y., & Dong, B. (2025). Influence of durability properties on life-cycle carbon reduction of low-carbon mortar with similar compressive strength. *Case Studies in Construction Materials*, 22, e04558. doi: 10.1016/j.cscm.2025.e04558.
- [34] Zhang, Q., & Fan, K. (2025). Effect of molar ratio on mechanical properties and water resistance of citric acid modified magnesium sulfate cement. *Archives of Civil Engineering*, 71, 19–35. doi: 10.24425/ace.2025.153318.