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Porous Lattice Structure Optimization in 3D Printed Insole Design

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Abstract

This work realises the total parametric design of the insole through the topological structural design of the lattice units, which helps to meet the pressure requirements of different locations and increase the comfort and personalisation of insoles. Prior research has primarily concentrated on creating planar porous structures and basic geometric insole structures; intricate three-dimensional lattice structure optimisation has been systematically neglected. To close this gap, the research examines three common porous lattice structural units for analysis: equilateral triangular, square, and hexagonal units. It does this by using 3D printing technology to produce customised insoles. In addition, variance analysis is carried out, and the orthogonal experimental design method is used to examine the significant impact of structural design factors on the compressive performance of the porous lattice structure. The lattice's structural neutral size, unit size, and rod diameter are chosen to influence the elastic modulus. With a 22% reduction in maximum plantar pressure and an 18% reduction in average pressure compared to the uniform solid structure, research reveals a considerable improvement in plantar pressure distribution with the lattice insole structure created in this study. In the meantime, the porous lattice structure's overall weight is 15% less than that of the solid structure, which successfully reduces the insole's burden while still fulfilling the standards for mechanical performance. This study offers a fresh technological perspective on creating customised, comfortable insoles.

Keywords: Personalized Insoles; Lattice Structure; Plantar Pressure; 3D Printing

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1 Introduction

Wearing comfort and foot health are greatly impacted by insoles, which serve as a vital interface between the human body and footwear [1]. Reasonably designed insole constructions can reduce fatigue, pain, and other foot discomfort, enhance plantar pressure distribution, and guard against foot injuries and associated illnesses [2]. Plantar pressure distribution is a crucial metric for assessing how comfortable insoles are. Personalised footbed design is becoming a significant area of research because it is challenging to fully suit the needs of every individual due to the wide variations in foot form and pressure distribution. True customisation is impossible with the intricate, inefficient manufacturing methods of creating traditional bespoke insoles. Recent developments in CAD, 3D printing, and 3D scanning provide fresh methods for creating customised insoles. 3D scanning can collect foot data individually. Parametric design can be aided by computer-aided design (CAD), and complicated insoles can be effectively manufactured with 3D printing [4].

This work investigates insole parametric design using a topological lattice structure. Orthogonal experiment analysis examines the impact of key lattice characteristics on compressive performance, such as neutral size, unit size, and rod diameter. This offers a conceptual framework for later customised insole design. Wearing comfort and foot health are greatly impacted by insoles, which serve as the vital interface between the human body and footwear and are of utmost importance to the textile and clothing industries [1]. In a market where demand for personalised and customised goods is rising, insole design and production have emerged as key areas of study.

Rationally designed footbed constructions can reduce tiredness, pain, and other foot discomfort, enhance plantar pressure distribution, and guard against foot injuries and associated illnesses [2]. Plantar pressure distribution is a crucial metric for assessing how comfortable insoles are. Personalised insole design is becoming a significant research topic in the textile and apparel sector, as it is challenging to fully suit the needs of every individual because of the wide variations in foot form and pressure distribution.

The growing demand for personalised and comfortable footwear is predicted to propel the global 3D printed insole market, which is projected to expand at a Compound Annual Growth Rate (CAGR) of 20.4% between 2022 and 2030, according to a recent industry analysis [3, 4]. True customisation cannot be achieved with the intricate, inefficient manufacturing techniques of creating traditional bespoke insoles. New methods for custom insole design in the textile and clothing industries are made possible by recent developments in 3D scanning, CAD, and 3D printing. 3D scanning can collect foot data individually. Parametric design can be aided by computer-aided design (CAD), and complicated insoles can be effectively manufactured with 3D printing [5].

This offers a theoretical foundation for designing and producing individualized insoles utilizing 3D printing technology. The parametric design of insoles through topological lattice structure is explored in this study, which is a promising approach for personalised insole development in the textile and apparel industry, in contrast to previous studies that have primarily focused on planar porous structures and simple geometric insole designs. The impact of key lattice factors on compressive performance is examined through orthogonal experiment analysis, including rod diameter, neutral size, and unit size. This offers a theoretical foundation for the design and production of individualised insoles utilising 3D printing technology.

2 Method

2.1 Lattice Structure Design

Insole design requires balancing compressive strength and cushioning performance. Insoles must withstand vertical compression from body gravitational loads and horizontal impact deformation. Hollow structures provide elasticity and cushioning to absorb and dissipate impact forces. As shown in the research workflow diagram (Fig. 1), this study explores the parametric design of insoles through topological lattice structure.

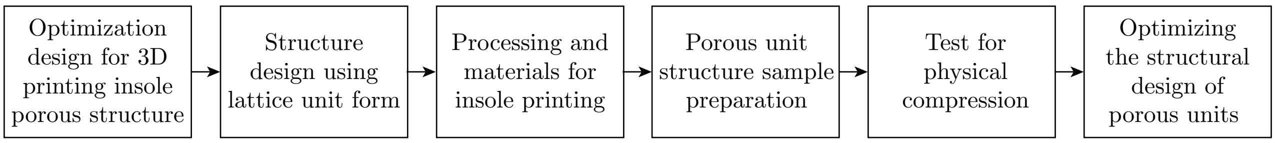


Fig. 1: Porous structure modeling research process diagram

Existing research has shown that porous structures with different honeycomb shapes (such as square, hexagonal, and triangular) will affect the effective linear elastic characteristics of the material [6]. Torquato et al. found that porous materials with different honeycomb shapes significantly differ in mechanical properties, such as elastic modulus and Poisson's ratio [7]. Therefore, this study selected three common porous structural units for design, including face-centred cubic, hexagonal honeycomb, and triangular honeycomb structures (as shown in Fig. 2), to explore the influence of different structures on insole performance.

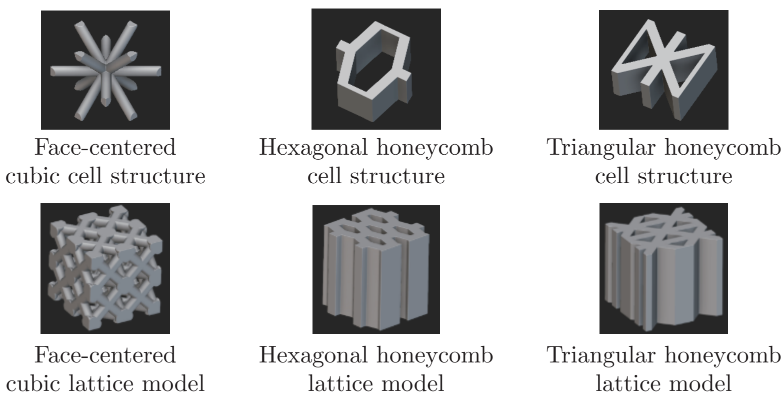


Fig. 2: Porous structure modeling

When determining the lattice structure and dimensions, the designers must balance two key considerations: the structural design requirements and manufacturability.

On the one hand, smaller unit sizes can increase the overall stiffness and load-bearing capacity, which is beneficial for meeting the insole's mechanical performance requirements. However, an overly dense structure may reduce the cushioning performance and affect the final elastic behaviour of the product. On the other hand, larger unit sizes may decrease the supporting capacity and pose challenges for the subsequent 3D printing process, making it difficult to fabricate.

In addition to unit size, the surface porosity and pore morphology are crucial factors that influence the mechanical properties of the lattice structure. The porosity directly affects the effective load-bearing area of the material, potentially reducing overall strength and stiffness as it increases. Pore size and shape also play significant roles in stress distribution; larger pores may become stress concentration points, increasing the crack initiation and propagation risk. However, appropriately distributed micropores could enhance material toughness by impeding crack propagation.

Therefore, to determine the optimal structural parameters, a balance must be struck between these various demands. This optimisation process needs to consider unit size, porosity, pore size distribution, and pore morphology to achieve the desired mechanical properties while maintaining manufacturability.

Based on the preliminary 3D printing trials of the lattice structures, the range of printing process parameters, and the analysis of surface pore characteristics, this study ultimately selected the hexagonal honeycomb structure as the porous lattice design for the insole. This structure can balance mechanical performance and manufacturability, providing the technical foundation for designing smart insoles that meet ergonomic requirements. The chosen design allows for control of porosity within an optimal range, promotes uniform pore distribution, and maintains an average pore size that enhances mechanical properties without compromising the structure's functionality.

2.2 Selection of 3D Printing Materials and Process

Personalised 3D printing of insoles is the core content of this research, so selecting an appropriate printing method is crucial. Factors such as printing cost, accuracy, material, and time must be comprehensively considered. High printing costs will affect the market promotion of 3D printed insoles, while insufficient printing accuracy will cause quality issues on the product surface. Meanwhile, the selected printing material must match the performance requirements of the insoles. Additionally, longer printing times can lead to an unsatisfactory consumer customisation experience.

This study adopted the Rayshape Shape 1HD 3D printer developed by Suzhou Laisai Smart Technology Co., Ltd. (as shown in Fig. 3). This printer uses DLP (Digital Light Processing) ultraviolet light curing technology, achieving layer-by-layer solidification by irradiating the liquid photosensitive resin with 405 nm blue light. This technology has the advantages of high printing accuracy, relatively low cost, and fast printing speed, making it well-suited for the manufacturing of personalised gradient modulus insoles.

Fig. 3: Rayshape Shape 1 HD 3D printer

In the 3D printing customisation of insoles, the selected printing material is one of the key factors. According to market research and research needs, this study chose the Resione F series liquid flexible photosensitive resin material F80 series [8]. F80 is a softer elastic resin that can maintain good flexibility even at lower temperatures, meeting the flexibility requirements of insoles. In the specific printing process, the layer thickness determines the vertical resolution of the model. Too large will result in rough surfaces, and too small will reduce printing efficiency; the control of the exposure time directly affects the curing degree of each layer and needs to be optimised according to the material characteristics. At the same time, reasonable model placement and support structure design are important factors to ensure printing quality and efficiency, which must be considered comprehensively. After the experiments, the final printing parameters were: bottom layer lift height of 8 mm, bottom layer exposure time of 18.0 s, single layer exposure time of 1.8s, and exposure light intensity of 60%.

2.3 Lattice Structure Physical Compression Performance Design Scheme

This study selected three key design variables for the hexagonal honeycomb lattice structure: cubic unit size, internal structure size, and connecting rod diameter. When setting 3D printing process parameters, it is essential to carefully consider how each parameter affects the final print quality. Print speed directly influences the accuracy of material deposition and interlayer bonding strength, with slower speeds generally improving precision but extending print time. Extrusion temperature determines the material flow and solidification rate; excessive temperatures can lead to over-flow and reduced accuracy, while insufficient temperatures may result in inadequate layer adhesion. Layer thickness affects surface precision and print duration, with thinner layers enhancing accuracy at the cost of increased print time. Infill density impacts structural strength and weight, requiring a balance between strength and material usage. Print bed temperature influences first-layer adhesion and overall warping, with appropriate temperatures improving print success rates. Fine-tuning these parameters makes it possible to optimise production efficiency while ensuring print quality, providing a reliable manufacturing foundation for hexagonal honeycomb lattice structures. This systematic parameter optimisation process not only ensures the quality of the final product but also enhances the reproducibility and controllability of the manufacturing process. An orthogonal table L9 (3^4) three-factor three-level experimental design scheme was used. Orthogonal experimental design can effectively reduce the number of experiments and consider each factor's influence on the response index. The levels of cubic unit size were set to 3.5, 4.5, and 5.5 mm; the levels of internal structure size were set to 2.0, 3.0, and 4.0 mm; the levels of connecting rod diameter were set to 0.6, 0.8, and 1.0 mm. The levels of the orthogonal experimental factors are shown in Table 1.

Table 1: The level table of orthogonal experimental parameter changes for the lattice structure

No.	Cubic size (mm)	Cell size (mm)	Struts diameter (mm)
Level 1	−1 (3.5)	0 (2.0)	1 (0.6)
Level 2	−1 (4.5)	0 (3.0)	1 (0.8)
Level 3	−1 (5.5)	0 (4.0)	1 (1.0)

As shown in Table 2, the L9 (3^4) orthogonal experimental table covers nine schemes with different level combinations of the three design variables. This can systematically examine the influence of different porous lattice structure parameters on mechanical properties. A compute-aided design program produced matching 3D computer-aided models based on the orthogonal

Table 2: Elastic modulus of hexagonal honeycomb porous lattice structure samples under compression

No.	Cubic size (mm)	Cell size (mm)	Struts diameter (mm)	Compression elastic modulus (MPa)
1	3.5	2	0.6	3.880
2	3.5	3	0.8	2.709
3	3.5	4	1.0	2.156
4	4.5	2	0.8	3.720
5	4.5	3	1.0	2.104
6	4.5	4	0.6	0.882
7	5.5	2	1.0	3.664
8	5.5	3	0.6	1.923
9	5.5	4	0.8	1.392

experimental design approach. These models showed variations in the lattice cubic size (3.5-5.5 mm), internal structure size (2.0-4.0 mm), and connecting rod diameter (0.6-1.0 mm). Those above flexible photosensitive resin substance and printing technique were used to create all the models. This methodical sample preparation procedure guarantees each sample's uniformity and repeatability.

2.4 Lattice Structure Physical Compression Performance Testing

2.4.1 Sample Preparation

According to the orthogonal experimental design scheme of the hexagonal honeycomb porous lattice structure, this study prepared 9 samples with the structural size parameters shown in Table 2. All samples were made using Resione F80 photosensitive resin material and prepared using a Rayshape Shape 1HD 3D printer. See Fig. 4.

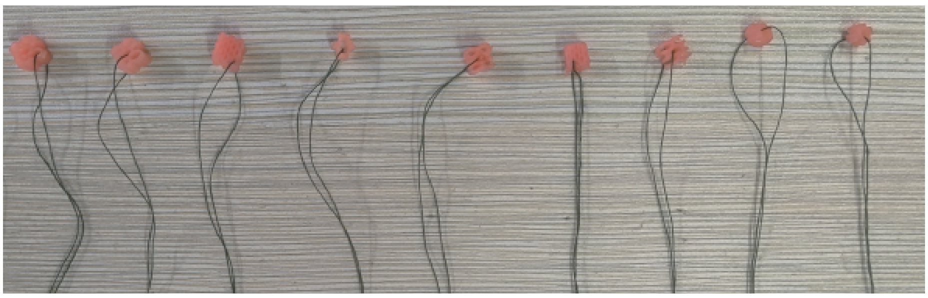


Fig. 4: Hexagonal honeycomb porous lattice structure sample

2.4.2 Experimental Equipment

The compression experiment was carried out on an electronic universal testing machine UTM5205X, as shown in Fig. 5. The range of this equipment is 50 kN, with a displacement resolution of 0.001 mm. The prepared nine different sizes of hexagonal honeycomb porous lattice structure samples were placed on the loading platform of the testing machine, ensuring that the upper and lower surfaces of the sample were level and perpendicular to the loading direction and in close contact with the loading platform.

Fig. 5: UTM5205X electronic universal testing machine

The experiment followed the GB/T 1041-2008/ISO 604:2002 "Plastics - Determination of Compression Properties" standard. The displacement control mode was used, and a uniaxial compression load was applied at a constant loading rate of 4 mm/min until the sample showed significant plastic deformation. During the test, the testing machine will record the compression load and displacement data in real-time, providing a basis for subsequent stress-strain analysis [9].

3 Results and Discussion

Through analysis of the experimental data, we determined the connection between stress and strain for various porous lattice architectures under compression force. Elastic modulus and other important mechanical indicators may be further computed when combined with the samples' geometric size characteristics, as Table 2 illustrates.

3.1 Analysis of Variance

Table 3 shows the variance analysis results for the structural factors tested. The analysis results are shown in the table. The sum of squares results shows that the order of influence magnitude on the elastic modulus is B > A > C. Therefore, when designing the lattice structure, more attention should be paid to factor B [10].

By fitting and regressing the three structural design elements that substantially impacted the elastic modulus, a quantifiable link between the specimen's compressive elastic modulus and the design of the hexagonal honeycomb porous lattice structure was established. The regression equation was found to have statistically significant meaning by the model validity test, and the effective prediction model passed the significance test with an F-value of 56.32 and a p-value less than 0.05. The likelihood of the f-value happening is only 1.75% because of noise. Table 3 displays the variance analysis of the successful prediction model.

The R-squared, or coefficient of determination, is a crucial metric for assessing a prediction model's quality. The degree of data fitting increases with the R-squared's proximity to 1, indicating a larger predictive power of the model. It is widely acknowledged that a model is seen to have a good practical reference value when the R-squared is higher than 0.7. The prediction above

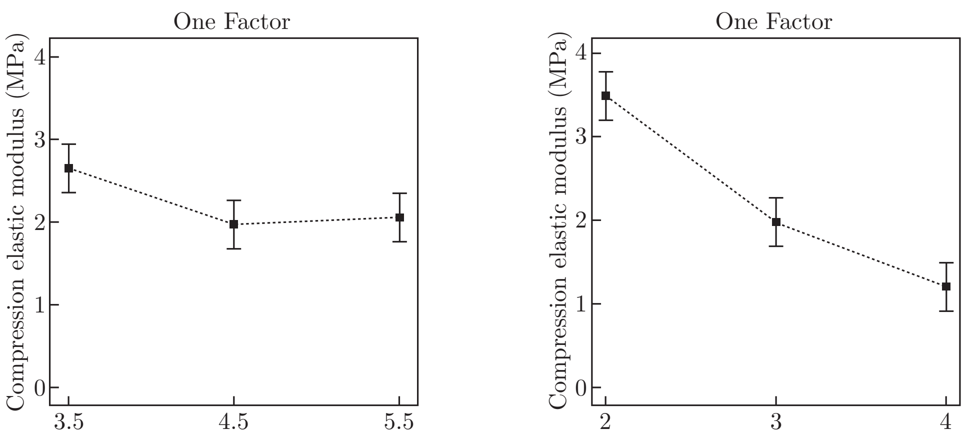
Table 3: Variance analysis of factors affecting the compressive elastic modulus of hexagonal honeycomb porous lattice structure specimens

Source	Sum of squares	Degrees of freedom	Mean square	F value	P value	Remarks
Model	9.19	6	1.53	56.32	0.02	Significant
A	0.82	2	0.41	15.02	0.06	–
B	8.06	2	4.03	148.16	0.01	–
C	0.32	2	0.16	5.79	0.15	–
Residual	0.05	2	0.03	–	–	–
Cor Total	9.24	8	–	–	–	–
R^2			0.99			
Adj R^2			0.98			
Press			1.10			

model has an R-squared value of 0.99, which is significantly higher than the reference standard of 0.7 and shows high goodness of fit and excellent explanatory power for changes in the dependent variable.

3.2 Impact of Every Factor on Overall Performance

The experimental findings of each component at various levels are plotted as a curve, as shown in Fig. 6(a). The test findings indicate that the compressive elastic modulus achieves its greatest value at 3.5 mm, the lattice's cubic dimension. This might result from the structure's relative stability and reduced stress concentration effect at this scale, both of which help to increase the structure's total load-bearing capacity. The compressive elastic modulus drops to its lowest point, a 30% reduction, when the cubic size is expanded to 4.5 mm. This is mainly explained by greater sizes being linked to poorer structural stability.



(a) Compressive elastic modulus vs. cubic size (b) Compressive elastic modulus vs. cell size

Fig. 6: Influence of different cubic sizes and cell sizes of the lattice on the compressive elastic modulus

When the cubic size is increased to 5.5 mm, the material displays an intermediate compressive elastic modulus. At this scale, lowering the concentration of stress helps improve the structure's overall load-bearing capacity. In summary, the cubic dimension strongly influences the compressive elastic modulus of the hexagonal honeycomb porous lattice structure. In particular, the highest performance is shown by a cubic dimension of 3.5 mm. In contrast, the worst performance is shown by a size of 4.5 mm, most likely due to reduced structural stability. An intermediate performance is obtained with a cubic size of 5.5 mm, which benefits from lessened stress concentration and helps to maintain a balanced load-bearing capacity.

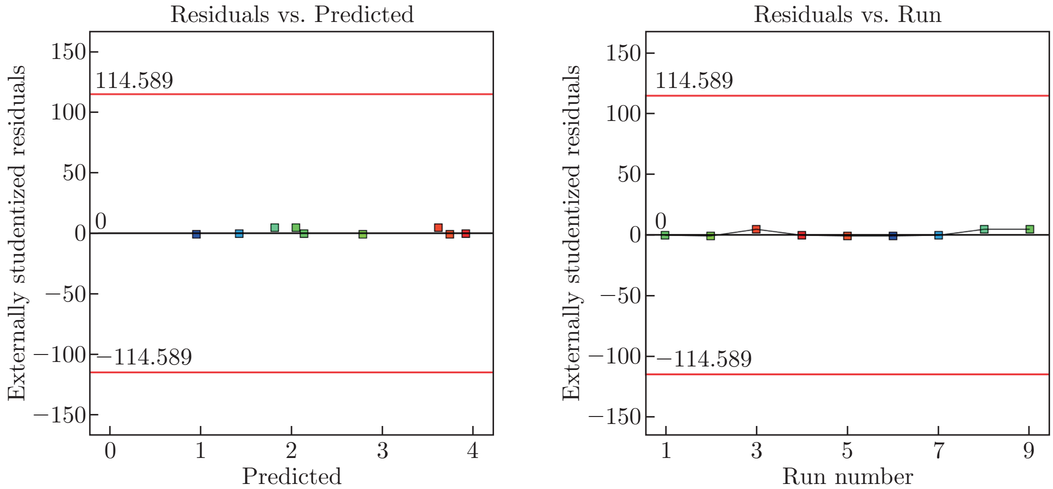
Based on the influence curve of different unit sizes on the experimental results, as shown in Fig. 6(b), the results show that when the unit size is set to 2 millimetres, the compressive elastic modulus peaks due to a stronger interlocking effect among the units which enables more efficient stress transmission across the entire structure enhancing overall stiffness and load-bearing capacity. The unit size increases to 4 millimetres, the compressive elastic modulus drops to its lowest point. This is because the interaction between units weakens at this larger size, leading to ineffective stress distribution within the structure, causing stress concentration and increased local deformation, thus reducing stiffness and load-bearing capacity. At a unit size of 3 millimetres, the compressive elastic modulus is intermediate. This size allows for moderate interaction and stress transfer between units, avoiding the limitations of very small sizes and preventing significant stress concentration issues. Therefore, the elastic modulus reflects a balanced structural performance. The experimental data trends reveal a clear pattern where the compressive elastic modulus initially rises sharply and then falls as the unit size moves from 2 millimetres to 4 millimetres, creating a bell-shaped curve. This suggests an optimal unit size maximises the structure's mechanical properties, with deviations from this size leading to less optimal performance. In summary, the hexagonal honeycomb porous lattice structure has unit size significantly impacts its compressive elastic modulus, with 2 mm being the best, 4 mm being the worst, and 3 mm being in between.

3.3 Residual Analysis

In addition to R-squared, the quality of this prediction model can be comprehensively evaluated from multiple aspects, such as residual analysis and stability. From the scatter plot of the residual values and the predicted values, it can be observed that the residual values do not exhibit a clear functional relationship with the predicted values but rather a relatively random scatter distribution, as shown in Fig. 7.

This suggests that the model's predictions do not exhibit any overt systematic bias. Additionally, the absence of a "funnel" shape in the distribution suggests that the model meets the homoscedasticity condition and that the prediction accuracy is constant across a range of expected values. The established mathematical model can adequately fit the observed data when considering all indicators, and the forecast accuracy is satisfactory. This confirms the model's flexibility and dependability even more.

The supporting and cushioning qualities of these materials may be completely utilised by the well-considered three-dimensional structural design, improving overall comfort, lowering pressure during wear, and offering improved foot protection and support. In the meantime, the three-dimensional design can also increase the insole's general stability, assisting in keeping the feet in the right position and enhancing balance while exercising. Additionally, the sensible three-



(a) Analysis of externally studentised residuals vs. predicted values

(b) Analysis of externally studentised residuals vs. experimental numbers

Fig. 7: Residual analysis of predicted values and experimental numbers

dimensional load distribution can distribute the stress on the feet more efficiently, preventing localised concentrated pressure and lowering user fatigue. Furthermore, by encouraging the feet's natural movement within the shoe, the three-dimensional construction can raise foot muscle activation and enhance the wearing experience. Lastly, by increasing the materials' overall structural strength and toughness, the three-dimensional moulding technique may prolong the insole's life and create pleasant and long-lasting foot protective gear.

4 Conclusions

The compressive elastic modulus of a hexagonal honeycomb porous lattice structure was investigated experimentally in this work, with particular attention paid to three key design parameters: strut diameter, unit size, and cubic size. The study aimed to comprehend the influence and interdependencies of these design elements on the compressive elastic modulus using physical testing of the porous lattice samples. The results produced included the following:

(1) It was found that cubic size and unit size had the most impact on the compressive elastic modulus among the three criteria examined, with cubic size having a stronger effect. This emphasises that cubic size selection and optimization must come first when creating high-performance porous lattice systems.

(2) The investigation found that strut diameter had the least influence, so it was removed from further analysis using bilinear regression analysis. To show the connection between cubic size, unit size, and compressive elastic modulus, a prediction model was created. With its precise description of the quantitative connection between these factors, this model offers a helpful foundation for further design work.

(3) Recognising the model's limits is essential. The model may have limited use since it removes strut diameter and oversimplifies the intricate interactions inside the hexagonal honeycomb porous lattice structure. Its prediction accuracy might be jeopardised when used in situations other than those evaluated. To improve the model's resilience and expand its utility, future studies should

incorporate more precise geometrical elements and material parameters, such as strut diameter, and employ sophisticated computer simulations and further experimental validations.

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