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Article

Method of Forming Road Surface Replicas Using 3D Printing Technology

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Abstract: Rolling resistance is a critical factor that influences vehicle energy consumption, emissions, and overall performance. It directly impacts fuel efficiency, tire longevity, and driving dynamics. Traditional rolling resistance tests are conducted on smooth steel drums, which fail to replicate real-world road surface textures, potentially skewing results. This article presents the process of designing surface replicas using 3D printing technology, which consisted of selecting the internal structure, material, and print parameters of the surface sample. In order to verify the designed structures, an original mechanical strength test was performed. The test was based on pressing the tire onto the test sample with an appropriate force that corresponded to typical conditions during rolling resistance measurements. The test results included surface texture profiles before and after the application of load, which were then superimposed to detect any possible sample deformation. The obtained strength test results confirmed the validity of using 3D printing technology in the process of obtaining road surface replicas.

Keywords: tire; road pavement; texture; rolling resistance; 3D printing; measurements

Citation: Owczarzak, W.; Sommer, S.; Ronowski, G. Method of Forming Road Surface Replicas Using 3D Printing Technology. *Coatings* **2024**, *14*, 1455. https://doi.org/10.3390/coatings14111455

Academic Editors: Valeria Vignali, Hao Jin, Jiwang Jiang, Hui Li, Xing Cai and Li Ai

Received: 5 September 2024
Revised: 9 November 2024
Accepted: 13 November 2024
Published: 15 November 2024

1. Introduction

The rolling resistance of car tires is one of the most significant parameters describing the interaction between the tire and the road surface. It directly affects the energy consumption of the moving vehicle, the emission of toxic compounds into the atmosphere (such as NH_3, CO_2, or NO_2), as well as its performance, such as maximum speed, acceleration, and maximum range. What is more, a high rolling resistance value also increases the tire temperature, which accelerates the aging process and reduces its mechanical strength. Rolling resistance is one of the primary resistances to motion (along with air resistance, incline resistance, and inertia). Depending on the driving conditions, reducing rolling resistance by 10% may lead to a 2%–4% decrease in fuel consumption. The rolling resistance of car tires results directly from energy losses that occur during cyclic deformation of the tire structure during pressures occurring on the track of its contact with the road. Tire deflection requires some work that must be supplied to the system from the vehicle side. The materials used to produce tires are characterized by significant hysteresis, which means that the amount of energy used to deform the tire is greater than the amount of energy released when the tire returns to its original shape. The vast majority of the energy lost by the vehicle as a result of rolling resistance is converted into heat. The remaining, much smaller part of the energy is converted into acoustic energy, permanent deformation of the road surface, and tire abrasion [1–4].

The rolling resistance of a car tire is determined by factors such as [2]:

1. Tire construction (width, height, tread pattern and depth, number of cord layers, belt material, type of rubber compound).
2. Traffic conditions, i.e., wheel load, inflation, tire temperature, rolling direction, rolling speed.

3. Road surface, i.e., its type, texture, stiffness, and technical condition.

This article focuses on the last of these: the influence of texture. The figure below shows the texture sub-ranges along with their influence on the tire-road interaction (Figure 1).

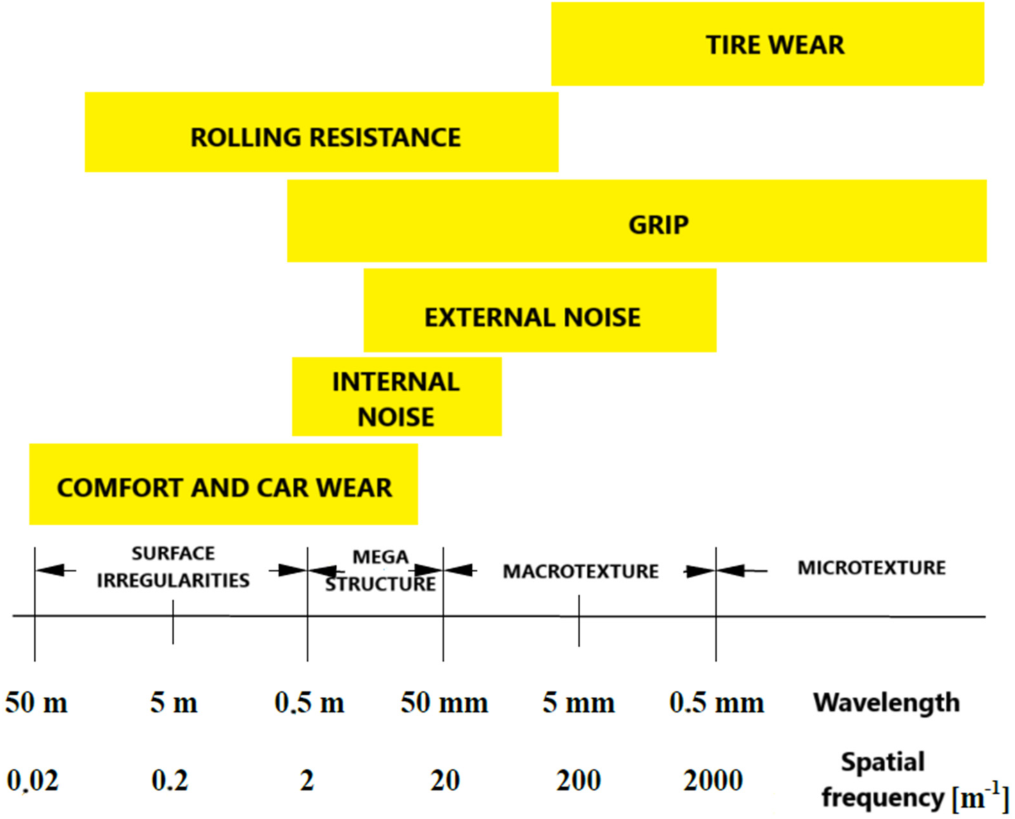

Figure 1. Texture ranges and their impact on tire-road interaction [5].

The texture of the road surface significantly affects the deformation of the tire tread elements, and therefore contributes to the increase in rolling resistance. Deformations also occur on the surface side, but due to the fact that the mechanical impedance of the surface is much greater than that of the tire, the deformations of the former are much smaller. Many previous studies have tried to describe the interactions between the tire and the road surface [6–8]. When talking about the influence of surface texture on rolling resistance, we cannot forget about the phenomenon of so-called enveloping. Too little elasticity of the tread elements does not allow them to be deformed to accurately reflect the shape of the surface. Contact with the surface is limited only to the highest parts of the surface (aggregate peaks). The tire tread is pressed and deflected by the highest points of the surface, but due to the stiffness of the rubber compound and the belt, its elements do not penetrate into the surface texture recesses but create “bridges” between adjacent peaks. As a result, air pockets and channels are formed on the contact patch of the tire with the surface. In the figure below we can see how two different texture profiles A and B deflect the tire in the same way, but the air pockets and channels differ to a large extent (Figure 2) [9].

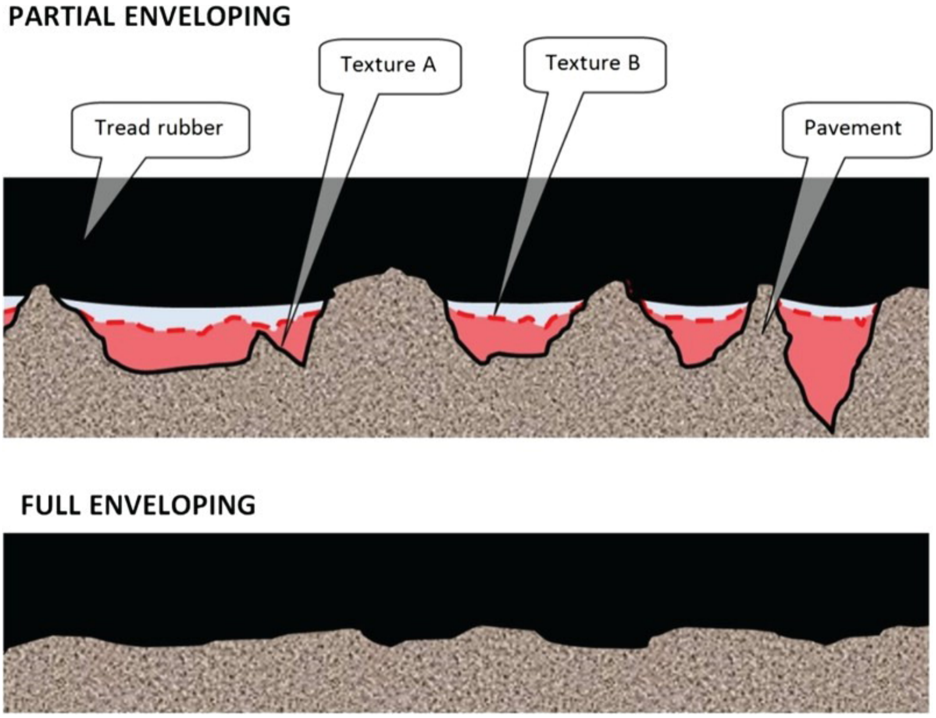

Figure 2. Interface between tire and road surface for pavements with different texture [9].

Rolling resistance can be reduced by improving tire production technologies and road surfaces. In order to achieve this, it is essential to conduct measurements that verify the effectiveness of the solutions applied in this regard. Rolling resistance is measured using both road and laboratory methods [10]. When reviewing contemporary literature, one can also find attempts to simulate the rolling resistance of car tires using computer simulations [11,12]. Tire manufacturers highly prefer laboratory testing methods, which allow tire testing regardless of weather conditions and enable greater accuracy and repeatability of results. Currently applicable standards, such as ISO 28580 (2018) and SAE J2452 (2017), require that standard tests be conducted on tire testing machines equipped with smooth steel drums, which is called the torque method (Figure 3) [13–16]. The main reasons for using steel drums are the difficulties in replicating the texture of typical road surfaces on the drums and the challenge of ensuring that all testing devices used for standardized tests have identically textured drums. It is well known that road surface texture strongly affects tire rolling resistance, this means that tests conducted on smooth steel drums do not yield results that accurately correspond to real road conditions. Rolling resistance coefficients (CRR) measured during laboratory tests are lower due to the lack of tread element deformation caused by the road surface texture [9]. In order to maintain the advantages of laboratory testing while ensuring a high level of representativeness in the results the drums are equipped with replicas of road surfaces that have the same texture as the surfaces on which vehicles actually drive.

Currently, replicas are produced using the casting method (replicas are made with the help of casting molds using materials such as epoxy resins and fiberglass). Based on our own experience and a review of the literature [6–8] on the influence of road surface texture on rolling resistance results, there is a strong need to improve the method of manufacturing road surface replicas. In contrast to the currently used technology, the use of 3D printing will allow for filling the research gap in the form of creating the possibility of designing original surface textures (current technology allows for the creation of surface replicas with existing textures). In addition to the possibility of rapid prototyping of surface textures in terms of their impact on rolling resistance, it will also allow for a more thorough exploration of the previously mentioned enveloping phenomenon (creating replicas with a similar texture, differing in profile depth). This will also allow for an extension of the range of measurement conditions. The smaller mass of the replicas will allow for the drum to accelerate to higher speeds (lower centrifugal force), or it will improve the fit of the replica segments to each other, which will allow them to be used for accurate measurements of car tire noise (no acoustic interference when the tire drives over the replica joints). The research presented in the article is an introduction to the development of a method for forming road surface replicas using 3D printing technology. The research objective was to determine the internal structure and printing parameters so that the replicas would meet the measurement conditions occurring during tests on drum stands.

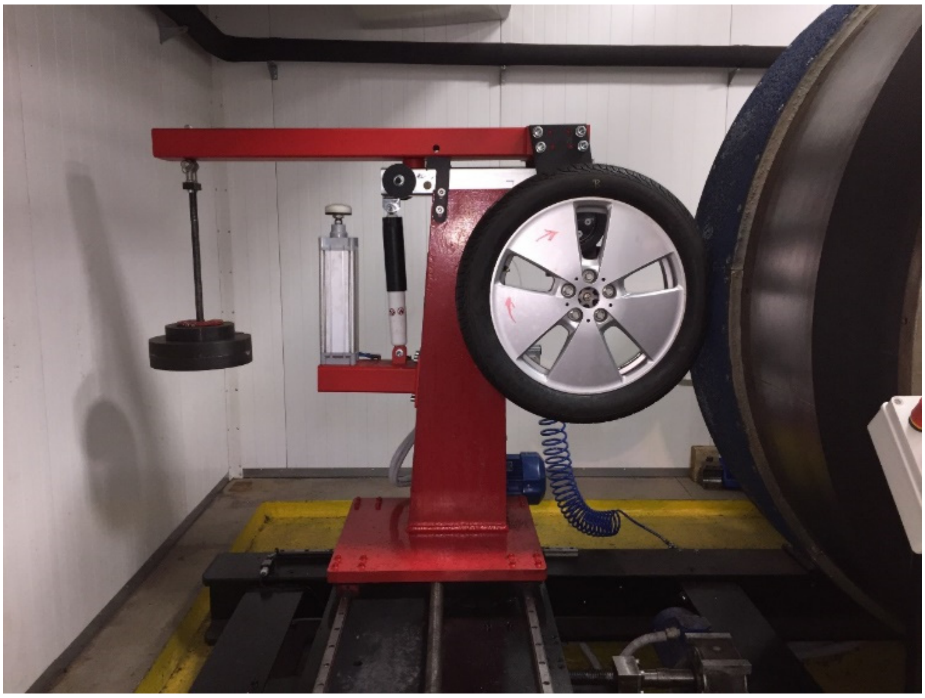

Figure 3. A running machine, which belongs to the equipment of the Mechanical Vehicles and Military Techniques Department of the Gdańsk University of Technology, drum with a diameter of 2 m.

2. Materials and Methods

The Gdańsk University of Technology has the world's only laboratory that uses replicas of actual road surfaces, made from reinforced laminates, which are produced using epoxy resins while preserving the original surface texture (Figure 4). Tests conducted on these replicas are more reliable compared to those performed on steel surfaces, as they better reflect the real operating conditions of vehicles. The results of rolling resistance and noise measurements on these replicas are consistent with those obtained on actual road surfaces under real traffic conditions. Road surface replicas adapted for mounting on tire testing machine drums must meet several requirements. The first is mechanical strength, which ensures safe installation on rapidly rotating drums. The centrifugal force generated during drum rotation would destroy almost any road surface material used for wearing courses. The road surface replica and its mounting system must withstand both the centrifugal force and the localized pressure of the tires on the surface. The second requirement is that the replicas shall accurately reflect the texture of the road surface, which they imitate.

Figure 4. Road surface replica (PERS surface).

The simplified diagram of the production of this type of road surface replica is presented below:

1. First, a layer of silicone rubber is poured onto the original surface, which after hardening will constitute a negative representation of the road surface (Figure 5). This layer is additionally reinforced with a glass fiber mat.

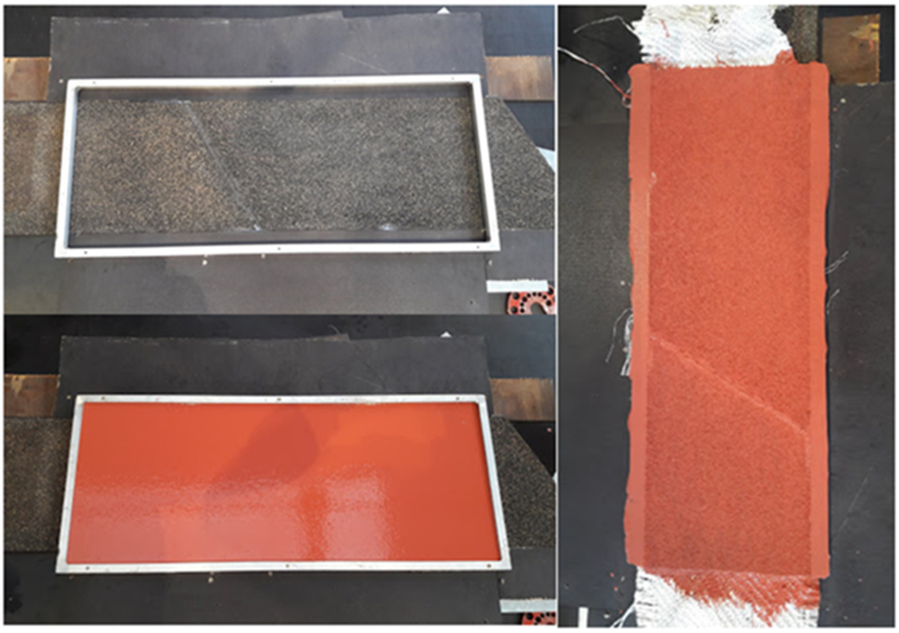

Figure 5. The process of creating an elastic layer that is a negative representation of the road surface.

2. The obtained elastic coating is next placed in the concave half of the mold (Figure 4). In the same part of the mold, gelcoat layers (the outer layer of the replica) and epoxy resin equalization layers are applied successively.
3. In the second part of the mold, layers of glass fiber immersed in epoxy resin are applied.
4. In the final phase, both parts of the mold are joined and the empty space between them is filled with epoxy casting resin. It is worth noting that the finished replica in the form of a shell is only a part of the entire surface on which the tested car wheel rolls (Figure 6). Usually, three to eight shells are attached to the drum track.

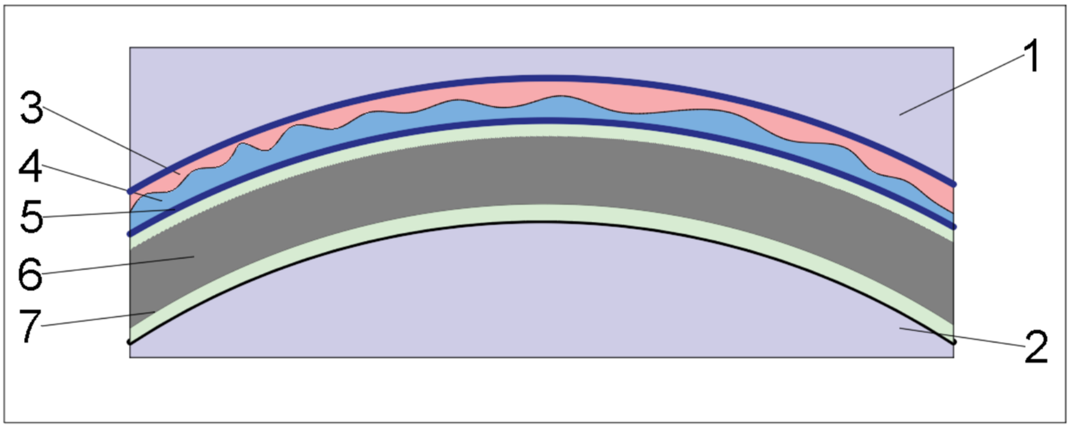

Figure 6. Diagram showing the method of forming a replica of a road surface for running machines with an external drum (1, 2—mold halves; 3—elastic coating constituting a negative reproduction of the road surface; 4—top layer of the replica (gelcoat layer mixed with finely cut glass fiber); 5—leveling layer of epoxy resin; 6—layer of epoxy casting resin; 7—layer consisting of glass fiber mats immersed in epoxy resin).

The results obtained on the replicas are fully satisfactory, but the process of their production has many drawbacks, hence the need to test a new technology for their production. The main disadvantages are high time consumption, laborious processing of replica segments in order to fit them to the drum surface, and the production process itself generates a lot of chemical waste requiring disposal. Due to the growing interest in tire and automotive industry concerns in research on surface replicas, there was a need to improve the method of their production. The research presented later in the article also aims to determine whether 3D printing technology will shorten the time needed to produce replicas, reduce costs, and reduce hazardous chemical waste. This method will also simplify the modification of existing road surface textures or enable the creation of new road surface textures. The process of developing a road surface replica using 3D printing technology is shown in the flowchart below (see Figure 7).

In order to develop a method for forming full-size replicas of road surfaces for covering the external tread of the wheel drum using 3D printing technology, it was necessary to select the internal structure and the appropriate material (filament).

For this purpose, predefined fill geometries from the library of the 3D printer software were used, and several types of fill were chosen.

Description of the different types of fill for the replicas:

- Geometry called "grid", which is based on a square filling with a filling level from 5 to 15% (see Figure 8). The internal structure of the "grid" type in 3D printing is one of the popular methods of filling the print. It consists of regular connections in the form of a grid, creating spatial cells. The supporting nodes are the points of intersection of the grid lines. In the classic "grid" filling, the nodes are evenly distributed, creating a symmetrical, mesh structure, resembling a rectangular or square system.
- Geometry called "concentric", with a filling level from 5 to 15% (see Figure 9). The "concentric" fill in 3D printing differs from the "grid" structure primarily in the way the fill lines are arranged. Instead of creating grid-like, rectangular patterns, the fill lines are arranged concentrically (around the object) in concentric layers that reproduce the external shape of the model. The "concentric" fill does not have the typical supporting nodes of the "grid" structure because the fill lines are arranged in layers in a continuous manner, without regular intersection points. In practice, supporting nodes could only appear in places where successive circles, ellipses, or other curves end.

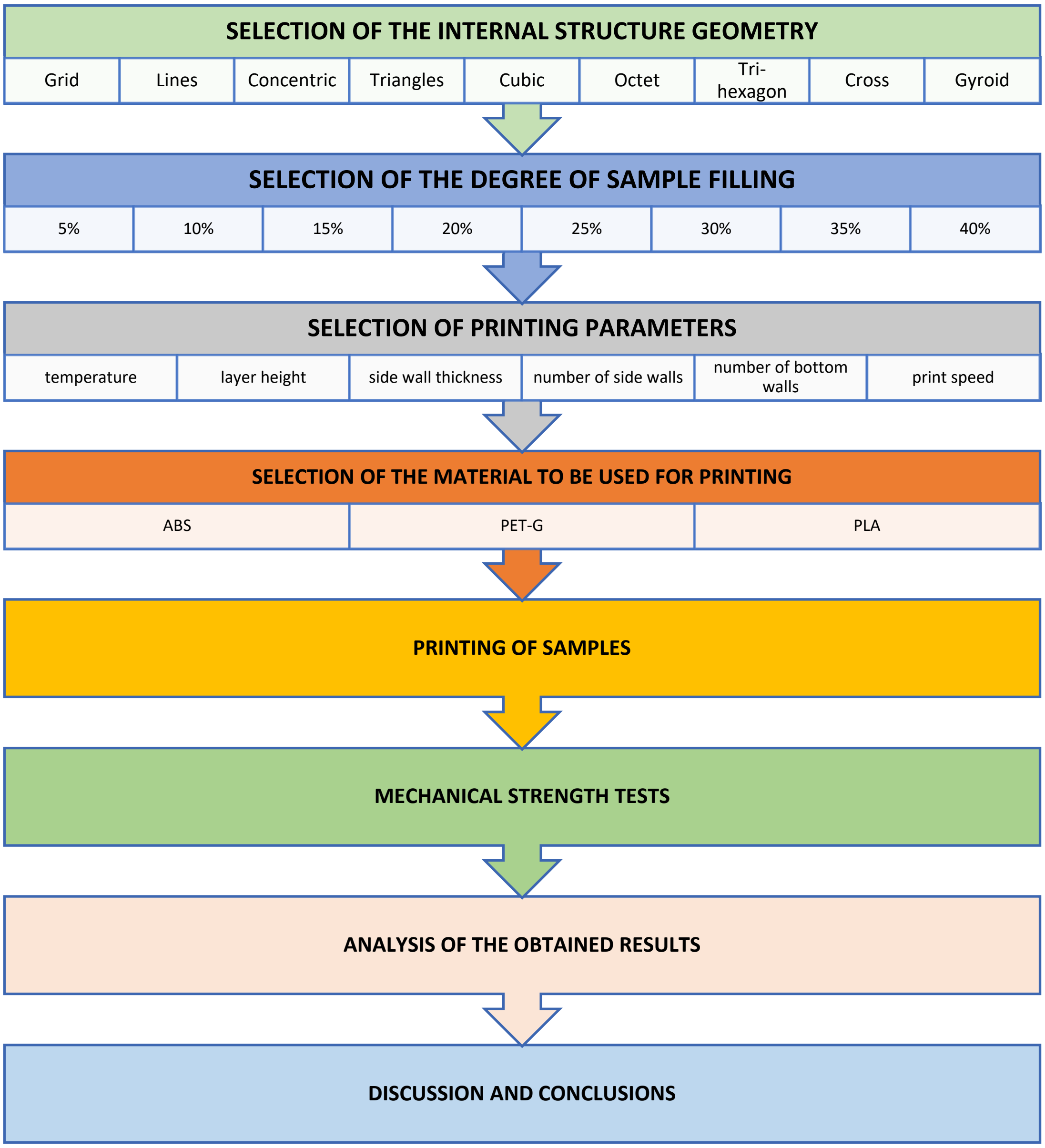

Figure 7. Flowchart showing the research stages.

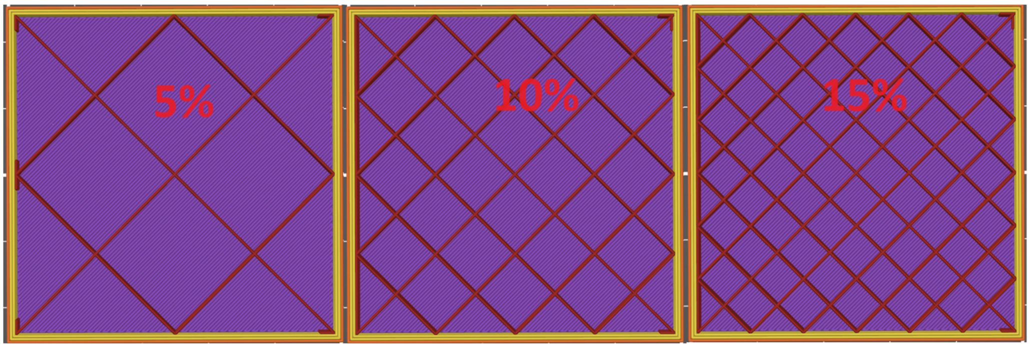

Figure 8. "Grid" geometry of pavement replica fillings (5%, 10%, and 15% of infill density).

Figure 9. "Concentric" geometry of pavement replica fillings (5%, 10%, and 15% of infill density).

- Geometry called "triangles", with a filling level from 5 to 15% (see Figure 10). In a cross section, the "triangles" structure presents regular, equilateral triangles. In the "triangles" structure, the supporting nodes are located at the points of intersection of the lines forming the triangles.

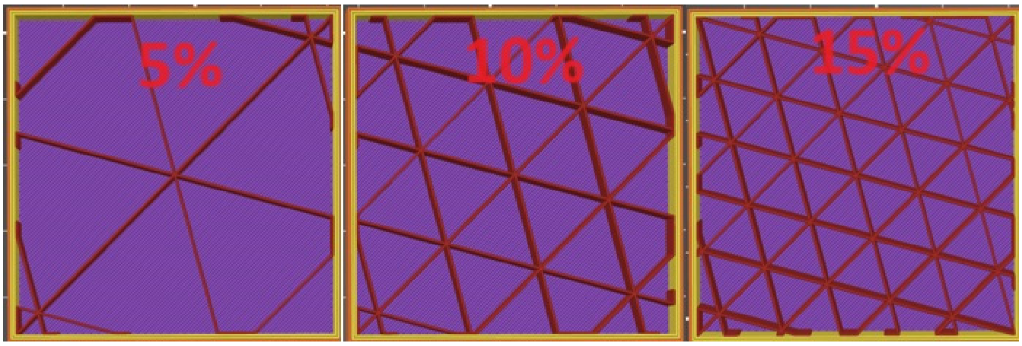

Figure 10. "Triangles" geometry of pavement replica fillings (5%, 10%, and 15% of infill density).

- Geometry called "tri-hexagon", with a filling level from 5 to 15% (see Figure 11). The "tri-hexagon" structure in 3D printing is more complex than simple infills because it combines two different shapes—triangles and hexagons. The supporting nodes in the "tri-hexagon" structure are located at the places where the lines that make up both triangles and hexagons meet.

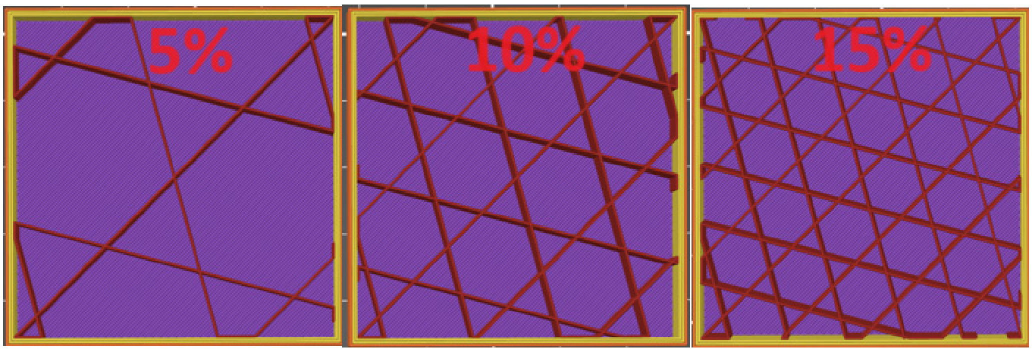

Figure 11. "Trihexagon" geometry of pavement replica fillings (5%, 10%, and 15% of infill density).

- Geometry called "cross", with a filling level from 5 to 15% (see Figure 12). The "cross" infill in 3D printing is based on a system of lines that create a cross pattern. The "cross" infill does not have typical load-bearing nodes. The lines are arranged perpendicularly, but do not create nodal points, as in the case of more complex structures, e.g., "triangles" or "tri-hexagon". The strength of the infill comes rather from the overall geometric stability of the lines, which distributes forces over the entire surface of the model, without concentrating them in single points.

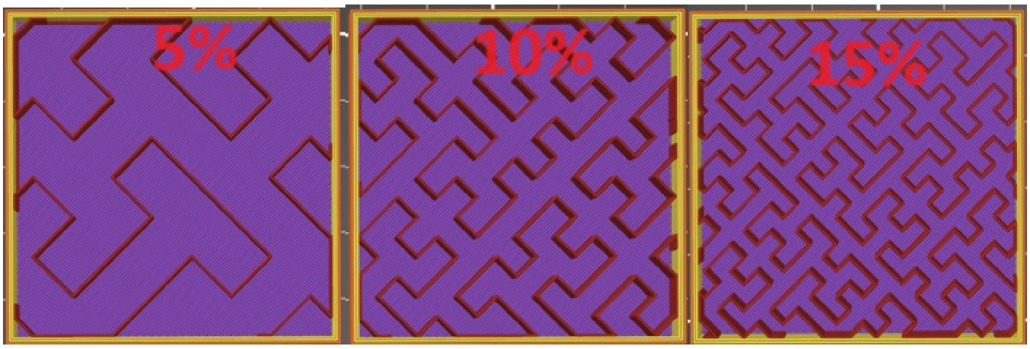

Figure 12. "Cross" geometry of pavement replica fillings (5%, 10%, and 15% of infill density).

Below is a description of the common features of all models:

- Each replica was printed using layers with a height of 0.15 mm. The print layer height was selected based on previous experience. A thicker layer (0.20 mm) would create a "stepped" top layer, which would result in differences in the texture of the original and the replica. On the other hand, a thinner layer would significantly extend the printing time, which is one of the parameters that requires optimization in the currently used method of replica production.
- The bottom and top layers of the replicas consisted of a solid fill with a thickness of 1.05 mm.
- The peripheral layer consisted of a triple wall with a thickness of 1.05 mm.

The exterior of the replica is a road surface texture. To develop a method for forming such replicas, the decision was made to replicate the rough APS4 surface (see Figure 13). Due to the protruding aggregate elements, this surface is prone to mechanical damage [17]. Therefore, it was assumed that if the internal structure and suitable material could be developed for this type of road surface, the other types would also meet the required standards. The geometries of the APS4 surface texture were obtained using a 3D scanner.

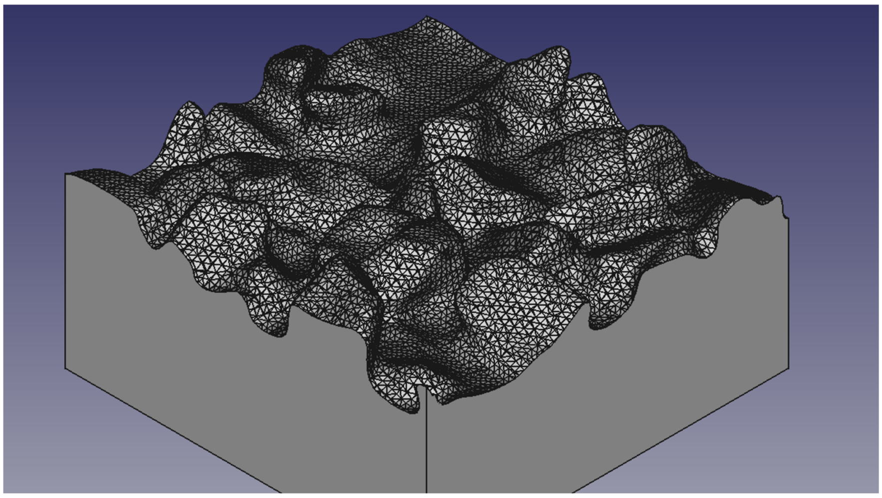

Figure 13. APS4 surface 3D model.

To create a replica it was decided to use the material PET-G [18]. This choice was dictated by high mechanical strength and a correspondingly high softening temperature of 82 °C [19]. Under standard test conditions, the surface temperature does not exceed 50 °C [4]. To verify the design assumptions, samples of dimensions 50 × 50 × 20 mm were printed. These samples were used for strength testing to determine if the designed replica met the requirements for rolling resistance testing on wheel drums machines. The road surface samples were subjected to a proprietary compression strength test. Due to the specific interaction between the tire and the road surface (the elastic deformation of tread elements over surface roughness), a traditional strength test using a testing machine was not chosen. Instead, it was decided to use an original method, which consisted of pressing a sample of the surface with a tire (smooth slick tread). The tests were performed starting from a load of 3 $\mathrm{kg/cm^2}$ (standard load in passenger car tires), ending with 8 $\mathrm{k/cm^2}$ (load in trucks) [2]. It was decided to measure only the compressive strength because during the actual measurement of rolling resistance the wheel rolls freely. During the measurement there is no braking or driving torque (it occurs only during the acceleration and braking of the drum, but the times of these processes have been selected so that the generated torques are small). The test was performed on a drum wheel machine, which is used in the torque method mentioned in the introduction (see Figure 14). To better understand the idea of carrying out rolling resistance tests using the torque method, its description is given below. It is based on the use of wheel drum machines, where rolling resistance is measured by measuring the torque on the drum drive shaft. When determining rolling resistance, the running machine's own resistances are taken into account, which are determined by measuring the torque driving the drum, on which the wheel rolls pressed with a force of only 100 N (the rolling resistance during such a test is negligible and is less than 0.5 N). The advantage of this method is its accuracy and low sensitivity to deviations or shifts in the line of action of the radial force loading the wheel from the straight line normal to the drum surface and passing through the center of the tested wheel. The rolling resistance force and the rolling resistance coefficient are determined based on the following Formula (1).

$$f_t = \frac{\frac{M - M_{SKIM}}{R_b} \cdot [1 + k(T - T_o)] \cdot \left(1 + \frac{r}{R_b}\right)}{N} \tag{1}$$

where

M—moment of force measured on the shaft of the running machine drum [Nm]
M_{SKIM}—moment of force of the running machine's own resistances [Nm]
R_b—radius of the running machine drum [m]
r—radius of the tested wheel [m]
k—empirical coefficient
T—ambient temperature during rolling resistance tests [°C]
T_o—reference temperature 25 °C
N—force normal to the drum surface [N]

In order to determine the deformation of the samples, a laser profilometer was used. The surface profile was measured before and after the compression, and the area between these profiles was compared (see Figure 15).

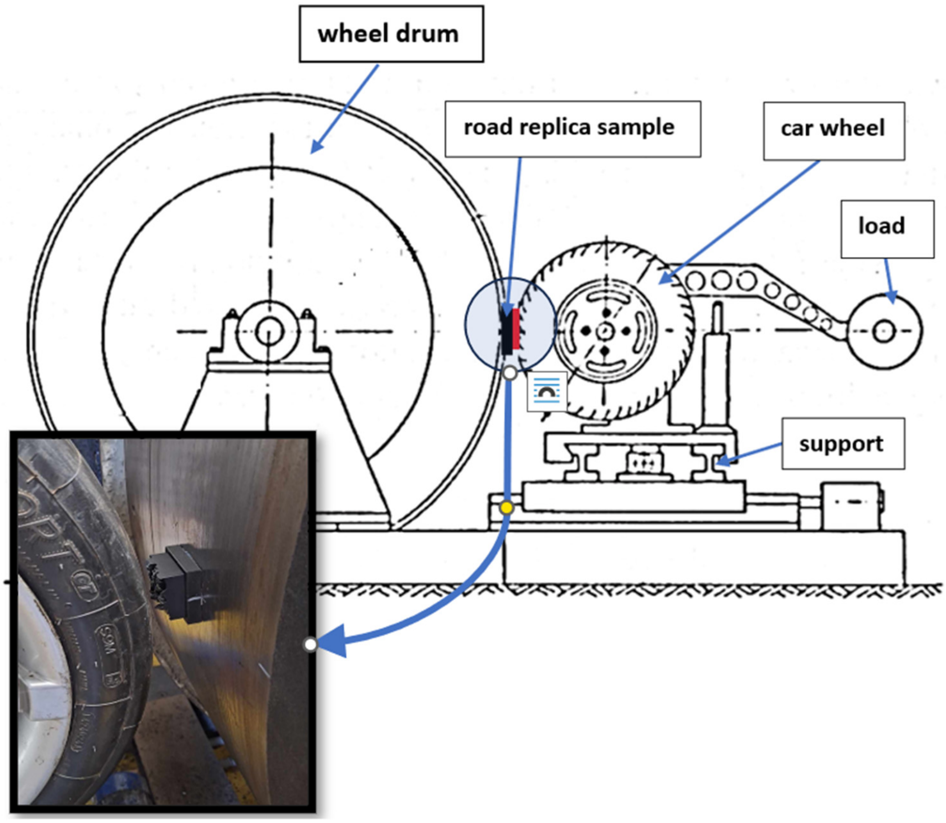

Figure 14. A stand for carrying out strength tests.

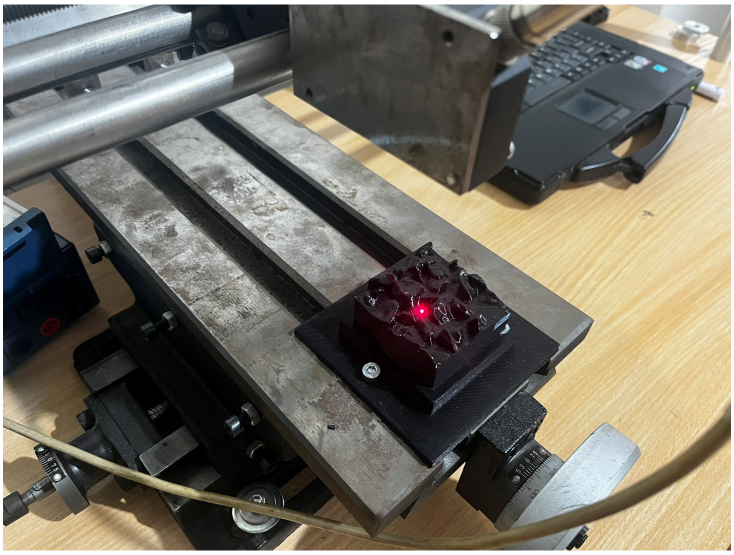

Figure 15. Road replica sample scanned by laser profilometer.

3. Results

The results obtained using the research method described above are presented in figures below in the form of superimposed surface texture profiles.

3.1. Replicas with Internal Structures of the "Grid", "Trihexagon" and "Cross" Types

Road replicas with internal structures of the "grid", "trihexagon" and "cross" types proved to be fully mechanically resistant to the loads occurring during the test. Even the lowest filling level of 5% was completely sufficient. As can be seen in the graphs below, the surface profiles obtained after each load match the profile obtained before the measurements (Figure 16). This proves that there was no mechanical damage to the tested replicas.

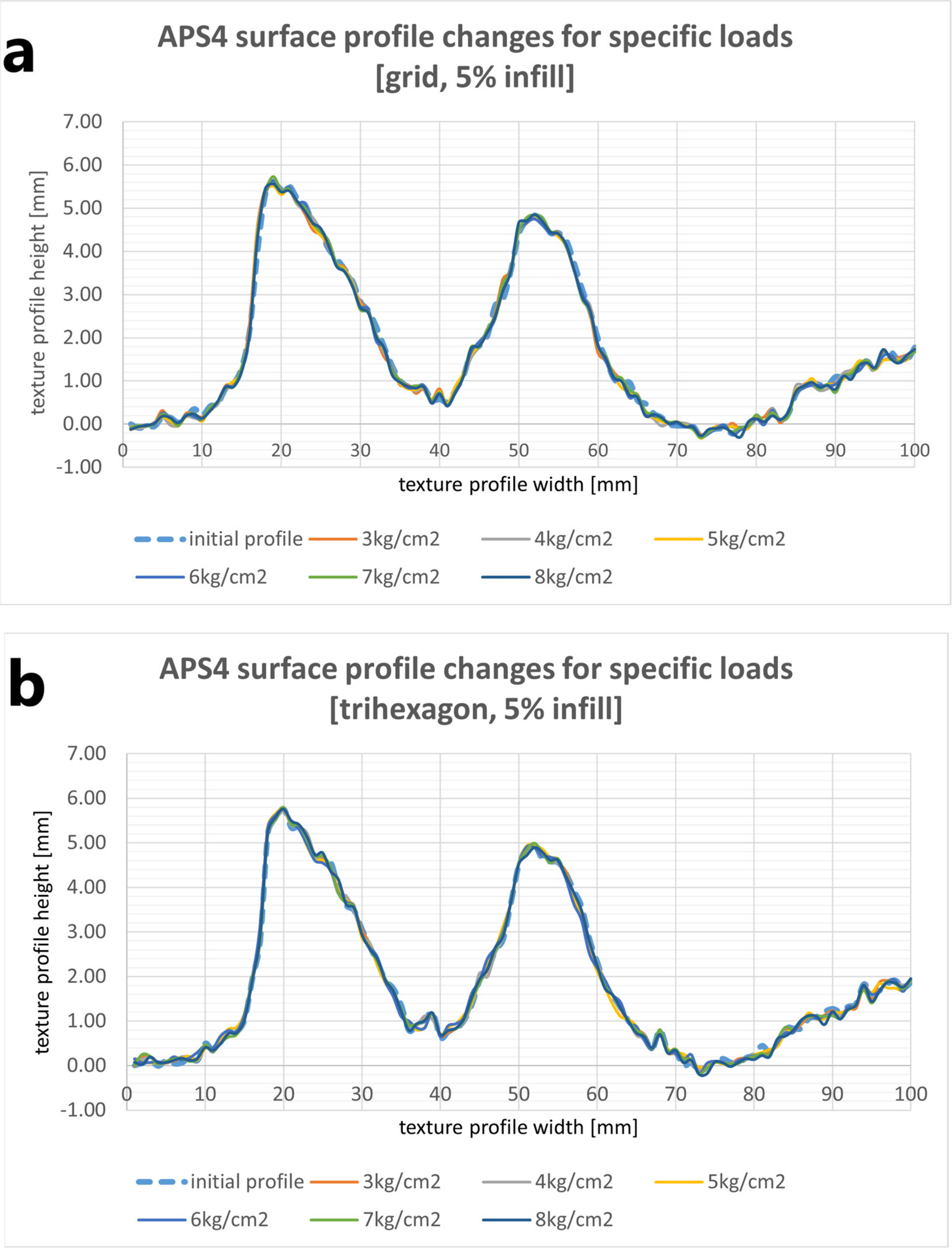

Figure 16. *Cont.*

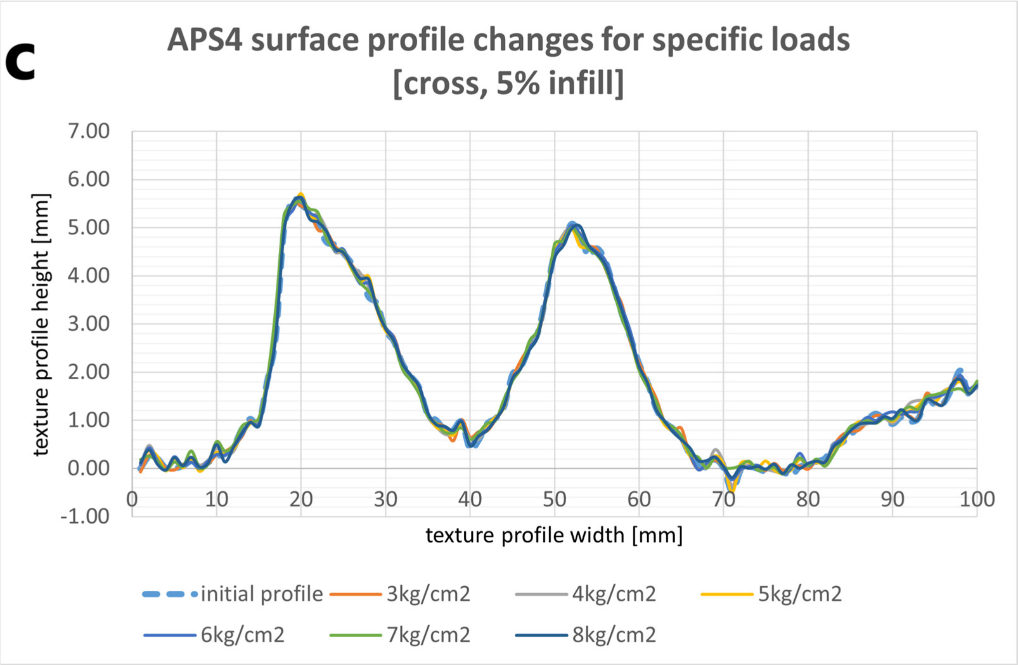

Figure 16. Graphs showing the strength test results for individual samples: (**a**) Grid; (**b**) Trihexagon; (**c**) Cross.

3.2. *Replica with Internal Structure of the "Concentic" Type*

For a 5% fill level, the profiles are superimposed as follows (Figure 17). The protruding "peaks" (texture profile width 22 mm and 55 mm) of the texture and "valleys" (texture profile width 0–15 mm) show material deformation. Material deformation had already occurred at a load of 3 kg/cm^2. The deformations were small (the largest reached 0.6 mm), but in the case of road surface replicas no deformations are not allowed. Replicas must maintain texture continuity and stiffness throughout their period of use.

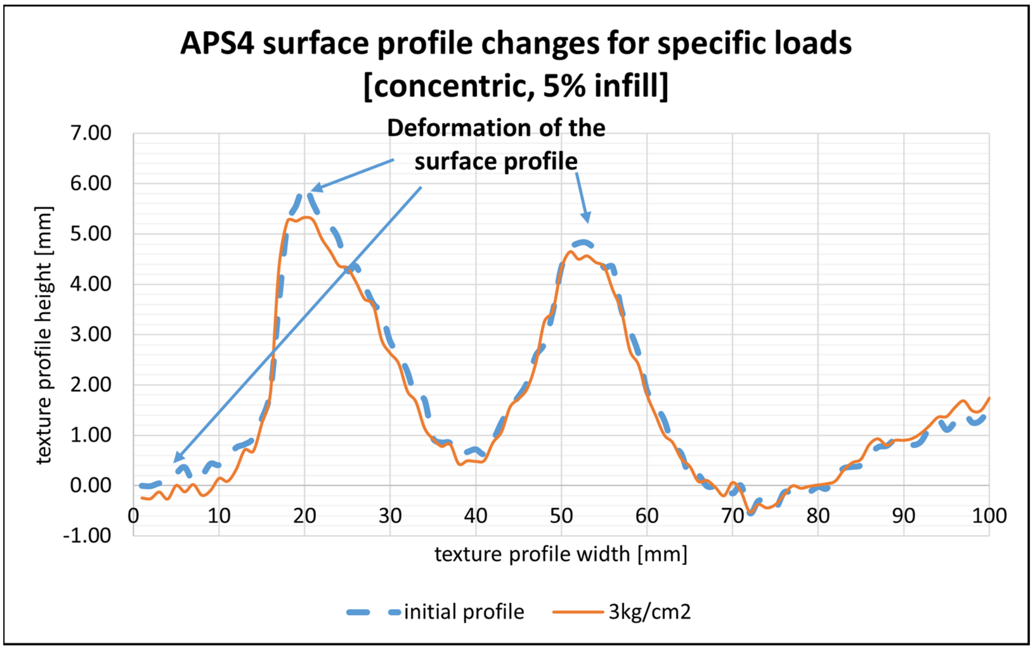

Figure 17. APS4 surface profile changes for specific loads (concentric, 5% infill).

Next, a sample with a 10% fill level was tested. As can be seen, the damage is much smaller, with only one peak deformation (texture profile width 50–55 mm, deformation reach 0.4 mm) at a load of 6 kg/cm^2 (Figure 18). As in the previous case, this is unacceptable.

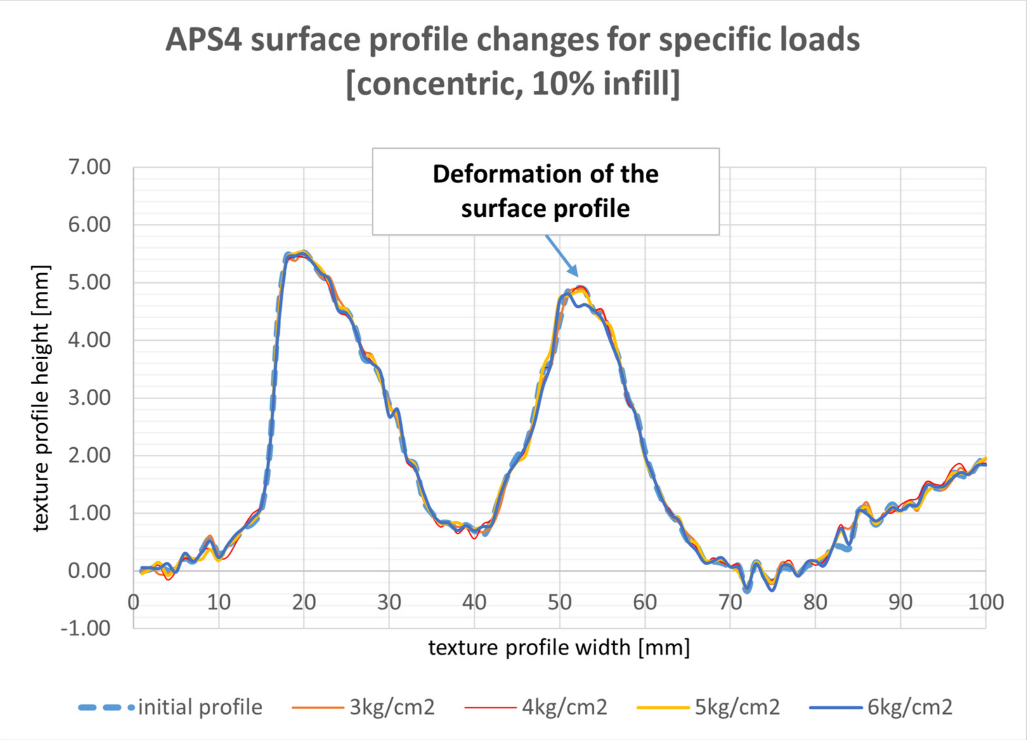

Figure 18. APS4 surface profile changes for specific loads (concentric, 10% infill).

Only a filling degree of 15% ensured the appropriate strength of the tested sample (Figure 19). For all loads, the surface texture profiles match the initial profile.

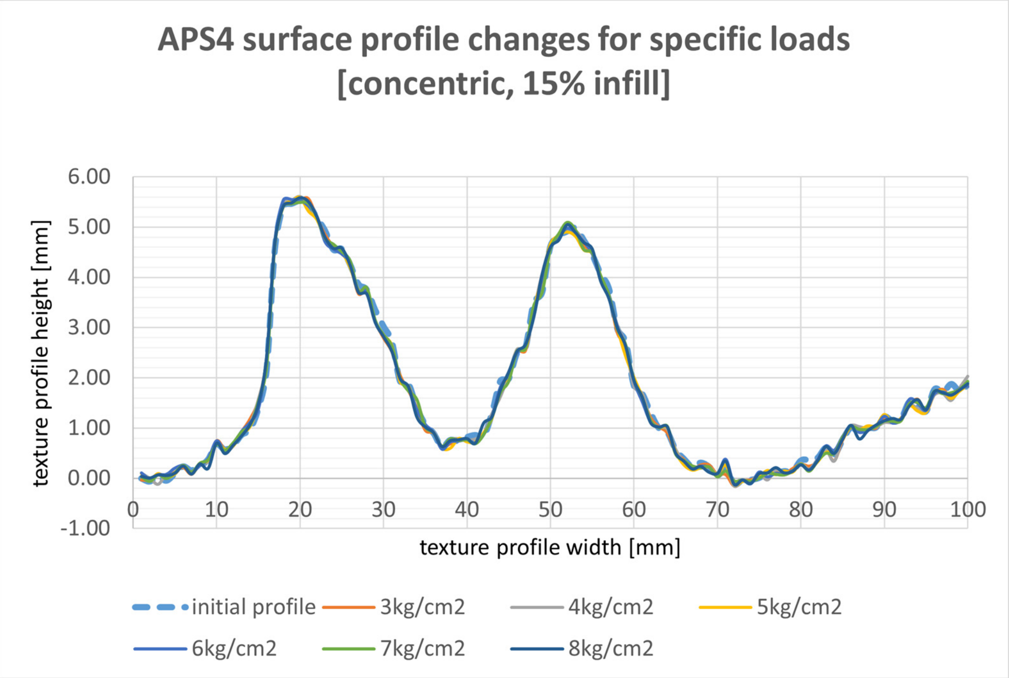

Figure 19. APS4 surface profile changes for specific loads (concentric, 15% infill).

3.3. Replica with Internal Structure of "Triangle" Type

In this type of internal structure, the filling level of 5% was insufficient. In the drawing below (Figure 20), when the tire was pressed with a weight of 6 kg/cm^2, the "peaks" of the replica were deformed, and the internal structure was crushed (deformlations visible at widths of 10 mm, 20 mm, and 84 mm). With a filling level of 10%, this problem no longer occurred (Figure 21).

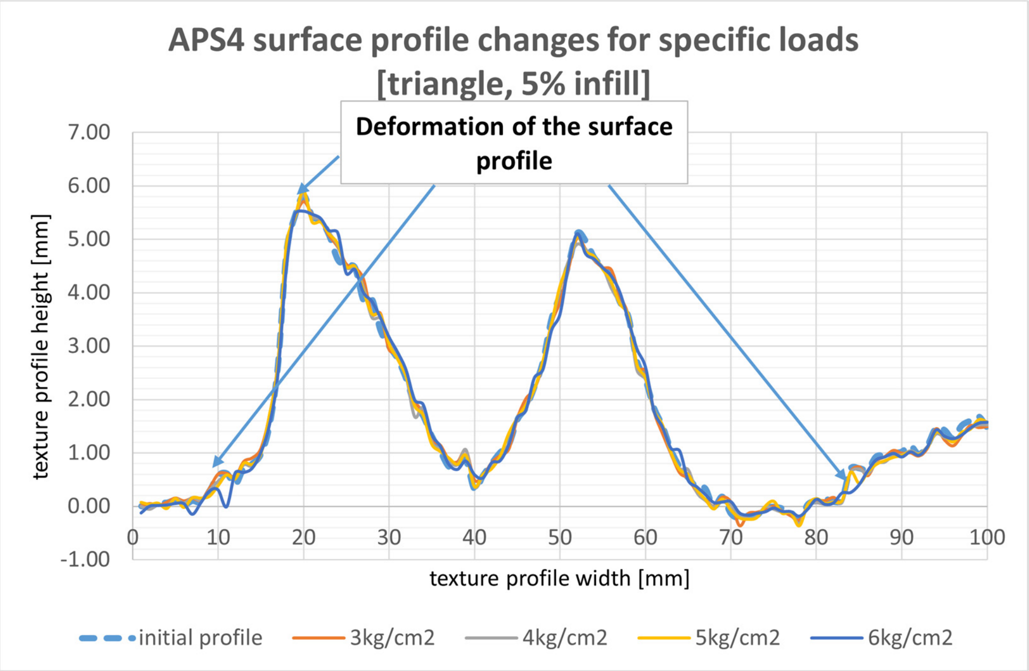

Figure 20. APS4 surface profile changes for specific loads (triangle, 5% infill).

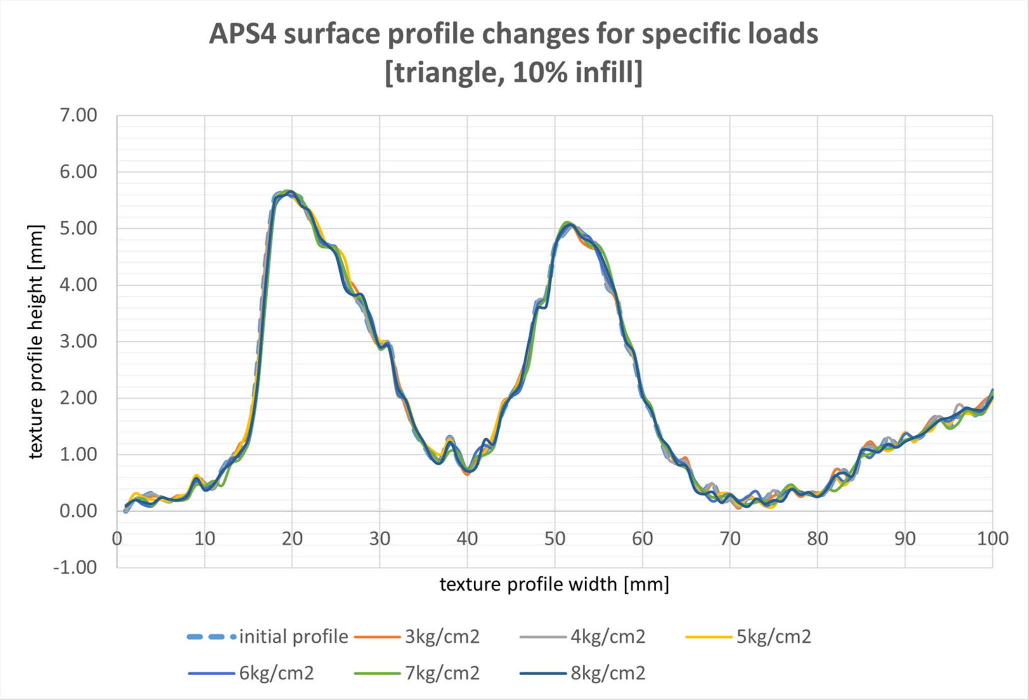

Figure 21. APS4 surface profile changes for specific loads (triangle, 10% infill).

3.4. Printing Time and Amount of Filament Used

Next, two other criteria were used to select the most advantageous internal structure: print time and amount of filament used. The table below presents parameters for samples that met the strength requirements (Table 1). The difference between the longest (Concentric) and shortest (Trihexagon) printing times was 44%. The difference in filament consumption was 25% (difference between Concentric and Grid).

Table 1. Summary of printing time and filament consumption for individual fill types.

Filling Type	Printing Time [Min]	Amount of Used Material [g]
Grid [5%]	78	17.83
Trihexagon [5%]	52	18.21
Cross [5%]	53	18.26
Concentric [15%]	92	23.55
Triangle [10%]	53	20.6

4. Discussion

At this stage of research, the aim was to select an internal structure that would provide satisfactory load-bearing capacity using the least amount of material and the shortest printing time. The results presented above indicate that the maximum infill level, which provides mechanical strength in the tire-to-road contact is 15% (taking into account all types of infill). However, for three types of infill geometry: "Grid", "Trihexagon", and "Cross", 5% infill was sufficient. Therefore, further analysis was limited to these three filling types (material consumption criterion).

When analyzing replicas for print time, the difference between the shortest ("Trihexagon") and longest ("Grid") time was 33%. When considering the same three types of filling in terms of material consumption, the differences between the lowest ("Grid") and the highest ("Cross") were only 2.35%. These were small differences; therefore it was decided that the parameter determining the choice of structure would be the printing time. It might seem that 26 min is not a big difference. However, it should be remembered that the target is to print a full-size replica of the surface to cover the outer track of the drum wheel machine. The estimated size of such a replica is 38 × 78 × 2 cm, and eight segments need to be printed to cover the entire circumference of the drum. Taking into account all of the abovementioned criteria, the optimal solution seems to be the use of the "Tri-hexagon" filling, due to its sufficient mechanical strength and the fastest printing time, as well as its material consumption.

To further verify the usefulness of the proposed method, it is planned to print larger samples of different types of road surfaces, characterized by a high and low rolling resistance coefficient. These samples would be used to perform tests using the so-called oscillation method. The method is based on indirect measurement of energy losses occurring as a result of cyclic pressing of the tire against the surface, forced by free fall causing oscillations of the system containing mass, elasticity, and damping [20]. This test will be used to determine the influence of the filament material used (its stiffness) and layer height (texture accuracy) on the obtained results of energy losses during oscillations, which are directly correlated with the rolling resistance of the tire on a given surface.

5. Conclusions

The research results presented in this article initially indicate the possibility of using 3D printing technology to produce surface replicas used to measure rolling resistance. Comparing the above research results with previous experiences on surface replicas obtained using the traditional method (casting from resin, reinforced with glass fiber), one can conclude that the use of 3D printing technology will allow for:

- Simplification and reduction in the time needed to obtain a road surface matrix by performing an accurate scan of its texture. Currently, the matrix is obtained by making a rubber cast of the actual road surface section, which is then glued to a casting mold. This operation is problematic due to the several-hour process of rubber gelation, and the entire procedure takes place in traffic conditions (it rarely happens that the road section is closed). The use of a high-resolution 3D handheld scanner would shorten the time needed to obtain a surface texture scan to several minutes, and thus increase the comfort and safety of people performing the entire procedure.

- Reduction in replica production time. Currently, using the casting method, the process of making a full replica takes approximately 100 days. This time consists of obtaining a rubber matrix of the road surface, preparing a casting mold, laminating and casting the replica, allowing the resins to harden, machining the front and side surfaces of the replica segments so that they will fit the drum circumference, and drilling holes for mounting screws. The method proposed in the application would enable printing of ready replica segments in an estimated time of 35 days (replicas could be printed around the clock). The appropriate design of the replica segments would eliminate the time-consuming processing in order to fit them to the drum surface.
- Reducing the costs of producing road surface replicas. Currently, the cost of producing a replica using the casting method is approximately $4000 (gross). This consists of making a casting mold, making a surface texture matrix cast using silicone rubber, and the purchase of resins, separator, gelcoat, glass fiber mats, mounting screws etc. The estimated cost of printing a replica is approximately $1000 (purchase of filament and electricity consumption). Of course, the proposed method requires the purchase of a 3D printer and a portable 3D scanner; however, this is a one-time purchase that would pay off in the case of producing a large number of replicas.
- Expanding the research area. Current replicas are based on textures of existing surfaces. Three-dimensional printing technology allows for modifying or designing completely new road surface textures using CAD software. This enables rapid prototyping of new types of road surfaces and testing them for rolling resistance and noise. Printed replicas would also be lighter, which allows for testing tires at higher speeds, fitting into the current measurement trend (the value of the centrifugal force acting on the segments attached to the drum surface would decrease). The replica segments would fit together better, and as a result smaller gaps would be achieved in the surface texture between adjacent segments, having a positive impact on the rolling resistance and noise of car tires (in the case of poorly fitted segments, the tire driving over the gaps between them generates noise in the form of a "knock").

Author Contributions: Conceptualization, W.O., S.S. and G.R.; measurements, S.S.; validation, G.R.; formal analysis, W.O.; writing, W.O.; visualization, W.O.; supervision, W.O.; funding acquisition, W.O. All authors have read and agreed to the published version of the manuscript.

Funding: Financial support of these studies from Gdańsk University of Technology by the DEC-037406 grant under the ARGENTUM TRIGGERING RESEARCH GRANTS—'Excellence Initiative—Research University' program is gratefully acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to plans related to patenting the presented solution.

Acknowledgments: The authors would like to acknowledge Kornel Piłat for his contribution to measurements and evaluations.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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