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# 1 Optimization of Adhesion Properties of PLA on Cork Substrate via FDM : 2 A Taguchi Experiment Design

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## 8 **Abstract**

9  
10 This study investigates the optimization of interfacial adhesion between polylactic acid (PLA)  
11 and cork substrates using fused deposition modeling (FDM), a topic scarcely explored in the  
12 literature. The research question seeks to identify FDM parameters that most strongly influence  
13 adhesion strength and microstructural porosity in PLA–cork laminated structures. Cork, a  
14 lightweight, elastic, and sustainable material, was selected as a novel substrate for functional,  
15 laminated structures. A Taguchi L36 fractional factorial design was employed to systematically  
16 evaluate six process parameters—build orientation, infill density, layer height, printing speed,  
17 contour lines, and bed temperature—and their effects on adhesion and porosity. Mechanical  
18 shear tests revealed a maximum adhesion strength of 1.39 N/mm under optimal conditions.  
19 Taguchi analysis indicated build orientation and infill density to be the most influential factors  
20 ( $\Delta = 0.2591$  and  $0.2484$ , respectively). Microstructural analysis showed that increasing infill  
21 density and adding contour lines reduced total porosity from ~25% to ~13%, enhancing  
22 interfacial bonding. Regression and signal-to-noise analyses quantifying the synergistic effects  
23 of key parameters, providing a predictive framework for optimizing adhesion. The findings  
24 demonstrate the value of integrating FDM technology with natural cork to produce sustainable,  
25 high-performance laminated structures. This approach addresses the need for better materials  
26 in applications that demand excellent layer adhesion, which is the main study's central  
27 contribution.

28  
29 **Keywords :** Fused Deposition Modeling (FDM) ; Laminated structures ; Cork substrate  
30 adhesion; Printing parameters optimization; Taguchi Design

## 31 **1. Introduction**

32 Various technologies have been explored for integrating functional materials onto flexible,  
33 unconventional substrates such as textiles, polymers, or natural materials like cork.  
34 Conventional methods such as surface mounting and lamination are well-established in the  
35 manufacturing, electronics, and textile industries [1,2]. Additionally, techniques such as screen  
36 and inkjet printing have been widely used to fabricate smart and functional surfaces, especially  
37 in the field of wearable electronics, enabling the deposition of conductive or active materials in  
38 multilayer configurations [3–5]. The advantages of these methods include low-cost processing,  
39 compatibility with non-planar surfaces, and scalability. However, they also present limitations,  
40 such as the need for post-curing, limited 3D structural capability, and restricted material  
41 versatility [6,7].

42 In response, to these challenges, Fused Deposition Modeling (FDM) has emerged as a  
43 promising additive manufacturing method that allows the direct deposition of molten  
44 thermoplastic filaments—such as polylactic acid (PLA)—onto diverse substrates with precise  
45 control over geometry, material distribution, and layer orientation. This approach provides a  
46 unique method for fabricating functional, laminated structures on unconventional natural  
47 substrates such as cork, enabling direct study of interfacial adhesion mechanisms and  
48 mechanical performance under controlled conditions.

49 The mechanical and functional properties of PLA components produced by FDM are strongly  
50 influenced by printing parameters such as nozzle temperature, build orientation, the number of  
51 contours (perimeters), layer thickness, and bed temperature [1]. Thus, optimizing these  
52 parameters can improve tensile strength, interlayer adhesion, and surface quality. For instance,  
53 Khalifah et al. [8] demonstrated that adjusting nozzle temperature and infill density  
54 significantly increased PLA tensile strength. Further, Ahmad et al. [9] showed that build  
55 orientation and printing speed directly impacted mechanical performance and dimensional

56 accuracy. More recently, Zhang et al. [10] investigated the influence layer thickness and print  
57 speed on the fatigue behavior of PLA, finding that thinner layers and slower speeds improved  
58 durability. Li et al. [11] studied the effect of raster angle and the number of contours on the  
59 mechanical strength of PLA. They reported an increase in tensile and flexural strength for  
60 specific orientations. However, these studies mainly address standard PLA parts, leaving the  
61 combined effects of multiple FDM parameters on adhesion to natural cork underexplored.

62 Despite, the insights reported in the literature, there is a clear knowledge gap regarding the  
63 quantitative evaluation of adhesion strength and microstructural porosity for PLA–cork  
64 laminates under systematically varied FDM process parameters. Beyond the polymer’s intrinsic  
65 properties, the adhesion between the printed layers and the substrate is critical for mechanical  
66 integrity and durability. While adhesion on polymers and textiles is well studied, the  
67 applicability of natural porous materials such as cork remains less explored.

68 Filling this gap requires examining the influence of printing parameters on PLA–cork adhesion,  
69 providing both quantitative and reproducible data for future studies and design optimization.  
70 Recent research has shown that direct 3D printing using FDM can achieve satisfactory adhesion  
71 between PLA and porous or flexible substrates. For example, Demir and Seki [12], who  
72 investigated PLA adhesion on surface-treated cellulosic fabrics, showed surface roughness and  
73 chemical treatments significantly improve bonding. Similarly, Fernández et al. [13] examined  
74 the effect of surface roughness and plasma treatment on PLA adhesion to natural fiber  
75 composites, reporting improved interfacial strength. Ruiz et al. [14] studied the adhesion of  
76 PLA on wood-based substrates, revealing that substrate porosity and thermal expansion  
77 mismatch significantly affect bonding. However, these studies do not provide a comprehensive  
78 parameter-specific analysis for PLA–cork laminates.

79 Cork, with its unique cellular microstructure, porosity, and elasticity, presents distinct  
80 challenges and advantages when combined with PLA via FDM. Understanding this interaction

81 enables the design of lightweight, sustainable, and mechanically robust PLA–cork composites  
82 with tailored adhesion and functional properties. It also provides a foundation for developing  
83 innovative materials for applications requiring both functional performance and eco-  
84 friendliness [15–18].

85 When printing PLA on a cork substrate, the substrate’s thermal properties and elasticity are  
86 expected to influence the adhesion, mechanical behavior, and recovery characteristics,  
87 prompting a detailed study of the interplay between printing conditions and functional response  
88 [2,19–22]. This study addresses the gap by providing a systematic, quantitative, and  
89 reproducible analysis of PLA–cork interfacial adhesion, the highlighting novelty, relevance,  
90 and contributions of the research.

91 Compared with prior studies on FDM composites with natural or porous substrates, our work  
92 uniquely combines systematic parameter variation, quantitative adhesion measurements,  
93 microstructural porosity analysis, and regression modeling to identify the most influential  
94 factors governing the performance of the printed laminates and predict optimal printing  
95 conditions.

96