

Article

Injection Molding of Biodegradable Deciduous Teeth Dental Post

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Abstract

Dental caries can cause premature loss of deciduous teeth, affecting children's growth and development. Endodontic treatment using polymer posts is an effective solution. This study explores biodegradable root canal posts made from Polylactic Acid (PLA), Polycaprolactone (PCL), and amorphous calcium phosphate (ACP), aiming to enhance mechanical properties, minimize polymer degradation acidity, and prevent inflammation. A root canal post with a spherical head and serrated structure was designed and produced via micromolding and optimized using the Taguchi experimental method. The melt temperature, injection speed, and holding speed were analyzed for their influence on shrinkage, revealing an optimal rate of 2.575%, representing the sum of axial and radial shrinkage. The melt temperature had the highest impact (55.932%), followed by holding speed (33.575%), with there being minimal effect from injection speed. The composite exhibited a flexural strength of 21.936 MPa, a modulus of 2.083 GPa, and a hydrophilic contact angle of 73.73 degrees. Cell survival tests confirmed biocompatibility, with a survival rate exceeding 70% and no toxicity. These findings highlight the potential of PLA/PCL/ACP composites, combined with injection molding, for developing biodegradable root canal posts in primary teeth.

Keywords: biodegradable material; dental post; endodontic treatment; injection molding; deciduous dental teeth



Academic Editor: Iole Vozza

Received: 2 June 2025

Revised: 29 June 2025

Accepted: 29 June 2025

Published: 1 July 2025

Citation: Wang, M.-W.; Xu, M.-K.; Hasfi, S.E. Injection Molding of Biodegradable Deciduous Teeth Dental Post. *Appl. Sci.* **2025**, *15*, 7414. <https://doi.org/10.3390/app15137414>

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1. Introduction

Dental caries can affect deciduous teeth. According to the National Health and Nutrition Examination Survey (NHANES) from 2017 to 2018, 43.1% of U.S. children aged 2–5 years had experienced dental caries in their primary teeth, and 15.4% had untreated decay in their primary teeth [1]. Worldwide, dental caries mainly occurs in children around 2–5 years old. Extraction is the standard solution for treating children's teeth. However, it increases the chances of premature teeth loss and parafunctional habit development (e.g., speech problems, tongue thrusting), reduces masticatory efficiency, and results in a loss of vertical dimension. Additionally, it can be considered esthetically unpleasant, and psychological effects associated with early tooth loss are also an issue [2,3].

Endodontic treatment using dental posts is an excellent option for treating caries in deciduous teeth. In clinical settings, making evidence-based decisions regarding intracanal post selection is essential. However, pediatric dentists often encounter significant challenges due to the variability and inconsistency in the existing research on intracanal posts. Dental posts protect the remaining tooth structure and come in various shapes; for example, their shape can be tapered, serrated, or threaded, with parallel structures also being used.

Dental post materials must use biomedical materials, and the earliest known biomedical materials are precious metals [4]. Metal posts are known for their good retention and excellent fracture resistance [5]. Fiber posts, with modulus values close to dentin, can better distribute stress along the post [6,7]. Most studies on dental posts focus on dental caries in adults rather than deciduous teeth. Deciduous tooth posts are of critical interest because they must support the function of primary teeth while ensuring that they do not interfere with the eventual eruption and optimal positioning of permanent teeth. In deciduous teeth, root resorption is usually physiological and desirable, as it allows the underlying permanent successor to erupt [8]. This process absorbs the remaining hard tissue within the root canal and changes its shape. There is a risk of corrosion and enhanced inflammation for metallic dental posts if endodontic treatment leaks and bacteria enter the root canal. Another effect of using non-bioabsorbable materials in dental implants is metal hypersensitivity or metal allergy. The most common case of a patient with a metal allergy in dental implants is a lichenoid reaction characterized by oral lichenoid lesions [9]. Such cases occur in patients with metal dental implants exposed to metal allergens. Fiber posts are safer for dental post applications, but they experience problems related to debonding, which can cause fractures in the root structure and hinder the growth of new teeth. Therefore, choosing materials with low cytotoxicity that are safe for deciduous teeth is crucial for dental post applications.

Recent clinical studies have begun to explore the use of resorbable PLA-based intracanal posts in pediatric patients. Recent studies have explored the development of PLA-based posts for dental applications. For instance, Charasseangpaisarn et al. [10] reported a PLA/PMMA blend with improved mechanical properties and biocompatibility, highlighting its potential as a sustainable alternative to conventional post materials. In contrast, conventional fiber posts such as the D.T. Light-Post® [11] and stainless-steel posts [12] have been widely used but present limitations in pediatric applications, including risk of debonding, corrosion, or interference with physiological root resorption. Despite these advances, comparative clinical studies remain limited, and the long-term in vivo resorption behavior of PLA-based posts in the pediatric population is not yet fully understood. These gaps underscore the need for further investigation into biodegradable post systems tailored for deciduous teeth.

Among the available bioabsorbable materials, biodegradable plastics are a popular choice. Polylactic Acid (PLA) is known for its low levels of cytotoxicity and environmental friendliness; thus, it is widely used in the manufacturing of biodegradable implants, such as bone plates and screws [13]. Its degradation rate is similar to the physiological resorption of deciduous tooth roots, making it suitable for dental posts [14]. Moreover, through using PLA, there is unlikely to be a post-surgery mental burden because the dental post will degrade with the eruption of the child's teeth. The use of PLA also provides an opportunity to apply the advanced healthcare methods that contributed to the integration of open technology from multidisciplinary fields [15]. PLA's appearance also means it meets the demand for esthetic post systems and medical procedures due to its colorlessness. However, pure PLA has some drawbacks, such as its high brittleness and lack of elongation ability or flexibility, attributable to the long-chain hydrophilic segments in its structure [16–18]. Polycaprolactone (PCL) is a polymer that can be blended with PLA to improve rigidity, biocompatibility, and processability. It has been widely used in bone fixation, controlled drug release, and tissue engineering [19]. In oral medicine, hydroxyapatite (HA) is often mixed with PLA to neutralize the acidic by-products produced during PLA degradation, minimizing potential inflammatory symptoms [20]. As the precursor phase of HA, amorphous calcium phosphate (ACP) has a higher solubility than HA. It can prolong the entire degradation cycle compared to HA, making it a bioactive ceramic material with potential for bone regeneration in the future. ACP is compatible with PLA

for bone repair, supported by chemical properties similar to the mineral phase of bone [21]. ACP can also be prepared at lower temperatures compared to HA, reducing hydrophobicity and preventing inflammation inside the root canal when used as a filler in PLA/PCL combinations. In our previous study [22], ACP synthesized via a low-temperature aqueous route showed nanoscale particles with a predominantly amorphous structure, as confirmed by SEM and EDS analysis (average size $\sim 50\text{--}70$ nm, $\text{Ca/P} \approx 1.63$). These characteristics are conducive to enhanced reactivity and biocompatibility, supporting its suitability for dental post formulations. These results indicate that ACP has potential as a PLA/PCL additive for future dental posts in deciduous teeth.

Therefore, the objective of this study was to develop a biodegradable dental post composed of PLA/PCL/ACP that not only mimics the mechanical behavior of primary dentition but also enables fabrication via injection molding. To this end, we systematically evaluated the composite's thermal, mechanical, rheological, and biological properties, along with its molding performance. These integrated findings aim to inform the design of pediatric dental posts and support future translational efforts in pediatric endodontics.

2. Materials and Methods

2.1. Dental Post Design for Deciduous Teeth

A serrated dental post design was chosen to fit the root canal of deciduous teeth without damaging the tooth's structure. It retains the lower part of the root canal for treatment [23]. The inner diameter for the root canal of deciduous teeth typically ranges from 1.5 mm to 2 mm, so the threads have a diameter of 2 mm to 1.5 mm. The spherical head ensures good stress distribution on the dental post, preventing post breakage, treatment failure, and damage to the root canal structure caused by children's uncontrolled biting habits [24]. An adult's average total root canal length is 18 to 20 mm. In this study, the designed post length was 21.25 mm, as shown in Figure 1. This length was chosen to ensure sufficient post engagement within the canal during treatment. The post can be shortened by the pedodontist or endodontist as needed to accommodate different root lengths.

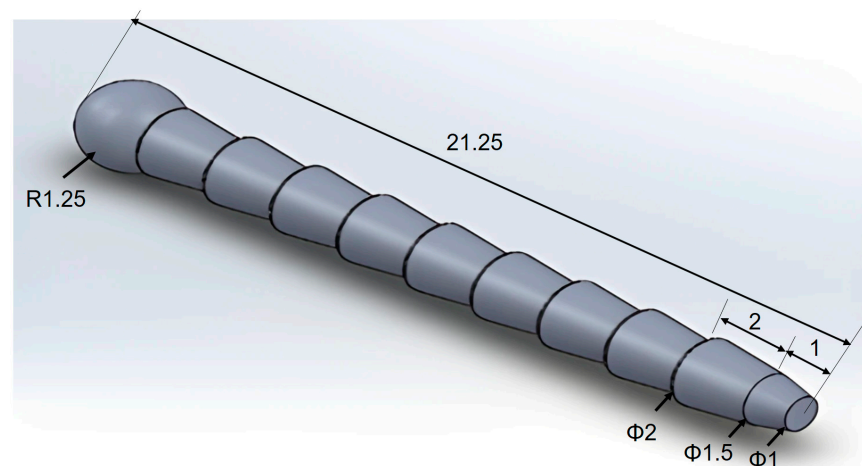


Figure 1. Schematic design of the serrated dental post for deciduous teeth. The post features a segmented taper with a total length of 21.25 mm and a maximum head radius of 1.25 mm. This geometry was used for mold fabrication and dimensional analysis.

2.2. Preparation of Study Material

This study prepared PLA/PCL/ACP composites for molding the post designed in Figure 1. Compared with pure PLA, the elongation and impact toughness of the PLA/PCL blends increased while the strength decreased. Among the possible PLA/PCL blend proportions, the 80/20% blend has previously been shown to yield the highest elongation

and impact strength [25]. Therefore, we referred to the above literature and configured a material with a weight ratio of PLA/PCL 80/20, also adding 10 wt% of laboratory-made ACP. The ACP powder was synthesized following the low-temperature wet precipitation method reported by S. Somrانيا et al. [26], in which calcium nitrate and ammonium phosphate solutions were reacted under alkaline conditions and immediately diluted to suppress crystallization. The precipitate was collected, freeze-dried, and characterized. Details of the synthesis protocol and the physicochemical properties of the resulting ACP—including SEM morphology, particle size, and Ca/P ratio—were previously reported in our earlier work [22]. PLA (Luminy@L175, Corbion Purac Group, Gorinchem, The Netherlands) and PCL (Capa 6800, Perstorp, Perstorp, Sweden) with 80/20 wt% and an extra 10 wt% of ACP were added and mixed for 10 min at 50 rpm and 190 °C using a Brabender (Plasti-Corder Lab-Station, Duisburg, Germany). The mixture was then cut into small pieces for injection molding.

2.3. Material Property Evaluation

After preparing the PLA/PCL/ACP composite, this study evaluated the bending strength, melting temperature, and biocompatibility properties of the material.

2.3.1. Bending Test

The 80 mm × 10 mm × 5 mm bending test sample was molded with a compression molding machine (Ling Fong, 30 Ton Hot Press, Tainan, Taiwan). The sample was molded with a mold temperature of 200 °C, while the compression pressure was 20 kg/cm², with holding for 5 min. The cooling water circuit was then used to cool the part to 50 °C, and the mold was opened to take out the molded sample, as shown in Figure 2. The bending strength measurement was carried out using a three-point bend testing machine (Hung Ta, HT-240, Taichung, Taiwan) at a loading speed of 2 mm/min and a support span of 95 mm, in accordance with ASTM D790 [27].

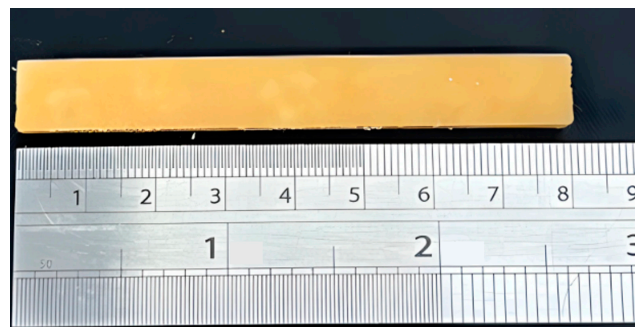


Figure 2. Rectangular test specimen (80 × 10 × 5 mm) prepared via compression molding using the PLA/PCL/ACP composite. The sample was used for three-point bending tests.

2.3.2. Thermal Property Test

The melting temperature of PLA/PCL/ACP is a key parameter of the molding process and was studied using Differential Scanning Calorimetry (TA Instruments DSC-Q10, New Castle, DE, USA) before the injection experiments to obtain the thermal properties of the composites.

2.3.3. Biocompatibility Test

A biocompatibility test for dental posts designed for deciduous teeth was conducted in accordance with ISO 10993-5 [28]. Cell viability was evaluated using a 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) assay (Tecan, ELISA reader M200 Pro, Männedorf, Switzerland). PLA/PCL/ACP samples were immersed in Dulbecco's Modified Eagle Medium (DMEM; Sigma, St. Louis, MO, USA) supplemented

with ascorbic acid (100 µg/mL), amino acids, antibiotics, and 10% fetal bovine serum (Gibco, Thermo Fisher Scientific, Waltham, MA, USA). After 72 h of extraction at 37 °C, the resulting extract was applied to NIH/3T3 mouse fibroblasts (BCRC 60091, Food Industry Research and Development Institute, Hsinchu, Taiwan) cultured in 96-well plates at a density of 1×10^4 cells per well. The assay included a negative control group (cells cultured in extract-free medium) and a test group (cells exposed to the extract of the soaked dental posts). After 24 h of incubation at 37 °C with 5% CO₂, MTT solution was added and incubated for an additional 2 h. Formazan crystals were dissolved using dimethyl sulfoxide (DMSO), producing a purple solution (Figure 3). Absorbance was measured at 570 nm. Higher absorbance indicates greater cell viability and biocompatibility.

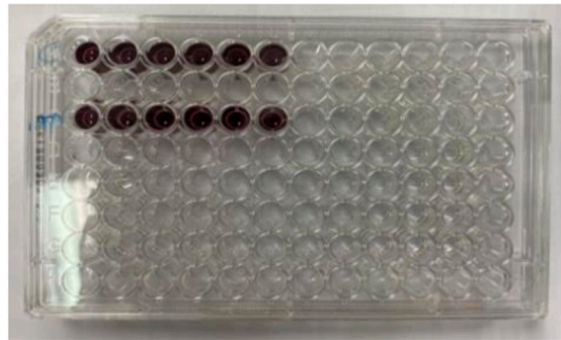


Figure 3. Formazan crystal formation in a 96-well plate after 24 h incubation with PLA/PCL/ACP composite extract, indicating cell viability based on colorimetric change.

2.4. Injection Molding Experiment

Injection molding is a rapid replication process that can produce complex and precise plastic parts with one mold. However, parameters such as injection speed, melt temperature, holding pressure, and cooling time all affect the quality of the injection-molded product. An experimental study by Chen et al. [29] demonstrated that process parameters—such as mold gate position, injection pressure, and injection rate—significantly impact the quality of injection-molded thermoplastic components. Optimizing these parameters is essential for achieving high-quality molded products. The Taguchi experiment is a process optimization tool commonly used in the industry to reduce the number of experiments and wasted time [30]. It helps determine the impact of parameters on process quality and identifies a better combination of process parameters. Therefore, this study used injection molding and Taguchi-based experimental methods to produce deciduous tooth posts. The experiment was conducted with a Battenfeld Microsystem 50 micromolding machine (Wittmann Battenfeld GmbH, Kottlingbrunn, Austria). Molding trials were carried out first to find the processing windows, and then Taguchi experimental methods were implemented to determine the best parameter combination for the post with shrinkage as the performance index.

3. Results and Discussion

3.1. Characterization of PLA/PCL/ACP Material

3.1.1. Thermal and Rheological Properties

The DSC scanning curve of PLA/PCL/ACP is shown in Figure 4. It reveals two melting temperatures: one at around 65 °C, which is the melting point of PCL, and the other at 172.58 °C, which is that of PLA. The processing temperature should be higher than 172.58 °C to process the composite successfully. Thus, 180 °C was selected as the starting temperature for shear viscosity measurements, with tests performed in 10 °C increments. When the temperature exceeds 200 °C, the material flow becomes discontinuous after passing through the rheometer nozzle. Therefore, experimental data at 180 °C, 190 °C,

and 200 °C were used to calibrate a temperature-dependent rheological model based on the Modified Cross formulation. This model, implemented in Moldex3D, is expressed in Equations (1)–(4):

$$\eta = \eta_0 / [1 + (\eta_0 \dot{\gamma} / \tau^*)^n] \quad (1)$$

$$\eta_0 = D_1 \times \exp [-A_1 (T - T_c) / (\bar{A}_2 + (T - T_c))] \quad (2)$$

$$T_c = D_2 + D_3 P \quad (3)$$

$$A_2 = \bar{A}_2 + D_3 P \quad (4)$$

where η is the viscosity, $\dot{\gamma}$ is the shear rate, T is the absolute melt temperature, and p is the absolute melt pressure. η_0 denotes the zero-shear viscosity, which varies with temperature according to a Williams–Landel–Ferry (WLF)-type relation. The model includes material parameters such as the relaxation stress τ^* , consistency coefficient D_1 , and temperature sensitivity constants A_1 , A_2 , and T_c , as defined in Table 1.

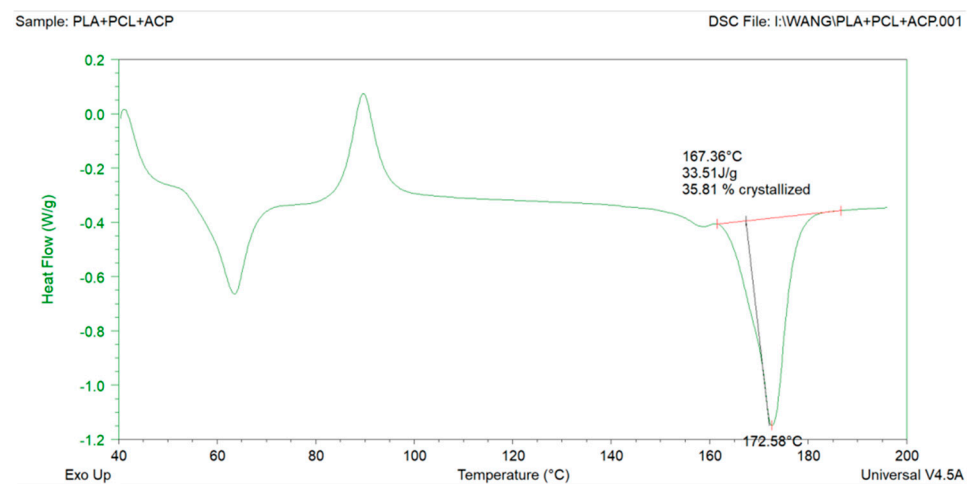


Figure 4. DSC curve of the PLA/PCL/ACP composite showing a melting peak at 172.6 °C. This thermal transition was used to guide melt temperature settings for micromolding and rheological testing.

Table 1. Rheological parameters used in the Modified Cross model for PLA/PCL/ACP composites. These values were applied to simulate shear viscosity behavior under various processing conditions.

Symbol	Value	Unit
n	0.3846	
τ^*	1.29×10^6	dyne/cm ²
D_1	2.048×10^8	(g/cm·s)
D_2	373.15	K
D_3	0	cm ² K/dyne
A_1	16.71	
$\bar{A}$	51.6	K

From the viscosity model, the melt viscosity at different shear rates can be calculated. Figure 5 shows the shear viscosity diagram between 180 °C and 200 °C. In the follow-up of this study, the rheological model and dental post mold design were input into the Moldex3D mold flow analysis software to determine the molding parameter levels before actual injection molding experiments.

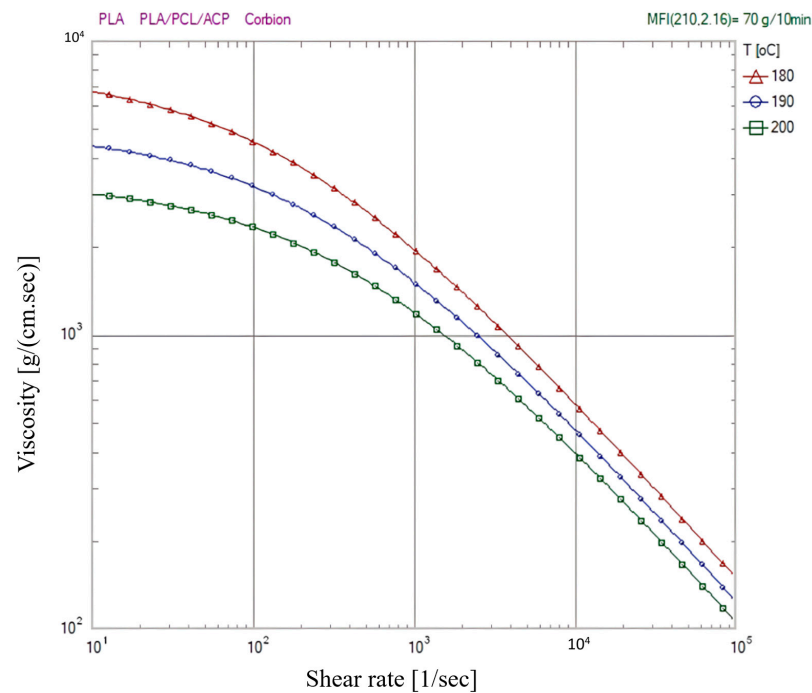


Figure 5. Shear viscosity of the PLA/PCL/ACP composite as a function of shear rate at 180 °C, 190 °C, and 200 °C. The temperature-dependent viscosity profiles were used to guide micromolding process settings.

3.1.2. Bending Test Results

A three-point bending test was conducted to evaluate the flexural strength and modulus of the PLA/PCL/ACP composite material. The results indicate a flexural strength of 21.9 ± 2.7 MPa and a flexural modulus of 2.08 ± 0.13 GPa, as summarized in Table 2.

Table 2. Flexural strength and modulus of PLA/PCL/ACP composites obtained from three-point bending tests.

Sample #	Flexural Strength (MPa)	Flexural Modulus (GPa)
1	19.13	1.95
2	25.69	2.28
3	24.87	2.16
4	19.42	2.08
5	20.57	1.95
Mean $\pm$ SD	21.934 ± 2.70	2.08 ± 0.13

Comparing these values with natural deciduous teeth, which exhibit a flexural modulus of 3.63 GPa [31], the PLA/PCL/ACP composite has a lower modulus. However, prior studies emphasize that dental post materials should not exceed the stiffness of natural teeth, as excessive rigidity increases the risk of tooth fractures [31,32]. Bhaktikamala et al. [32] demonstrated that using lower-modulus materials for dental posts minimizes stress transmission to the tooth structure, thereby reducing root fracture risks and enhancing the longevity of the restoration. These findings align with the present study, suggesting that PLA/PCL/ACP's inherent flexibility may contribute to better shock absorption and improved clinical outcomes.

Furthermore, when compared to fiber-reinforced dental posts, which typically have a modulus exceeding 5 GPa [21,23], PLA/PCL/ACP offers significantly greater flexibility. While fiber posts provide structural reinforcement, their stiffness can potentially concentrate stress on the surrounding dentin, increasing the likelihood of microfractures [21]. The

results of this study indicate that PLA/PCL/ACP may provide a safer alternative for primary teeth applications, as its lower modulus reduces excessive strain on the weakened dentin of deciduous teeth.

Additionally, research on biodegradable implants suggests that PLA-based materials exhibit promising biocompatibility and controlled degradation behavior [20,25]. Zhou et al. [20] highlighted the potential of PLA in biomedical applications, reinforcing the notion that a biodegradable dental post could facilitate natural healing while avoiding complications associated with permanent implants. Similarly, Umamaheswara et al. [25] demonstrated that blending PLA with PCL can improve mechanical properties while maintaining flexibility, further supporting the viability of PLA/PCL/ACP as an optimized dental post material.

In summary, the mechanical properties of PLA/PCL/ACP suggest that it is a suitable candidate for deciduous teeth applications, as its lower modulus reduces the risk of tooth fractures while maintaining sufficient structural integrity. The findings of this study align with prior studies in the literature supporting flexible post materials, reinforcing their potential in pediatric dentistry. To further contextualize its clinical relevance, a broader comparison with commercially available fiber posts, biodegradable PLA-based systems, and conventional metallic posts is presented in the following section.

3.1.3. Contact Angle Test

The contact angle test was performed with a distilled water droplet (approximately 12 μ L in volume), and a manual goniometer (FTA-1000B, First Ten Angstroms, Portsmouth, VA, USA) was used to obtain the measurements. The results, shown in Figure 6, indicate a mean contact angle of $73.73^\circ \pm 1.6^\circ$ for the PLA/PCL/ACP composite material across three trials, classifying it as a hydrophilic material. This value is lower than the typical contact angle of pure PLA, which is approximately 80° , as reported by Hendrick et al. [33], confirming that PCL and ACP influence the composite's surface wettability.

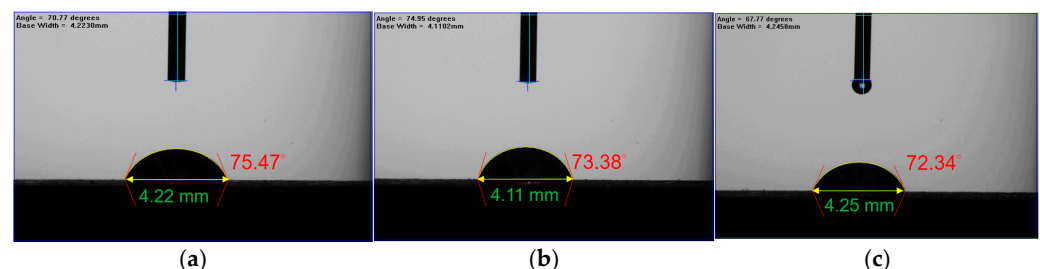


Figure 6. Contact angle measurements of the PLA/PCL/ACP composite: (a) 75.47° , (b) 73.38° , and (c) 72.34° , indicating moderate wettability.

Studies show that incorporating PCL enhances PLA's wettability due to the polar functional groups within PCL, which interact with moisture and reduce the contact angle. Li et al. [34] reported that adding up to 50% PCL significantly lowers the contact angle, further supporting this observation. However, while higher PCL content ($>20\%$) can improve hydrophilicity, it has been noted that mechanical properties are optimal when the PCL content remains at approximately 20%, as excessive PCL may compromise structural integrity.

Although the dental post does not directly contact the deciduous teeth, its hydrophilic nature can enhance adhesion to root canal fillers such as Malay glue, thereby improving fixation strength. According to Bourgi et al. [35], improved wettability—typically indicated by a contact angle below 75° —allows for deeper resin infiltration and the formation of a robust hybrid layer, ultimately leading to stronger adhesion between the dental post and the filling material.

Furthermore, Zhou et al. [20] investigated biodegradable scaffolds, demonstrating that materials with optimized wettability contribute to better biocompatibility. While the PLA/PCL/ACP post does not promote bone cell attachment or proliferation, its surface properties may enhance the compatibility of the root canal restoration process.

In summary, the PLA/PCL/ACP composite exhibits a favorable contact angle for dental applications, balancing hydrophilicity for improved adhesion to fillers while maintaining sufficient stability for primary tooth restorations. These results corroborate previous studies indicating that moderate wettability enhances fixation and material compatibility in biomedical applications [20,33–35].

3.1.4. Biocompatibility Assessment Results

The cell survival test results, shown in Figure 7, indicate that the cell viability of the group treated with extracts from the soaked deciduous tooth root canal posts (test group) exceeded 70%, confirming that the material does not induce cytotoxic reactions. This finding aligns with previous studies on amorphous calcium phosphate (ACP) particles and ACP-based composites, which have demonstrated excellent biocompatibility in cell viability assays and are widely used in medical applications [36].

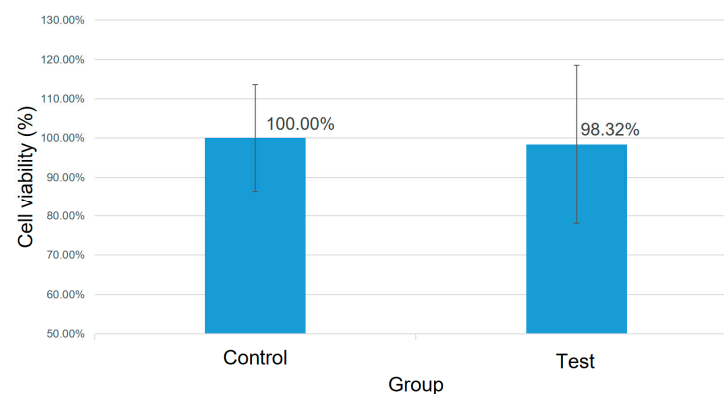


Figure 7. Cell viability of NIH/3T3 fibroblasts after 24 h exposure to the extract of PLA/PCL/ACP dental posts, prepared by 72 h extraction in DMEM at 37 °C. The MTT assay showed 98.32% viability compared to the negative control.

Research has shown that ACP exhibits superior bioactivity and osteoblast adhesion compared to hydroxyapatite (HAp), making it a promising material for biomedical use [20]. Zhou et al. [20] investigated ACP-modified PLA scaffolds and demonstrated that ACP enhances mineralization and bone defect repair, further supporting its suitability for dental applications.

Furthermore, Beigoli et al. [37] explored the green synthesis of ACP nanoparticles, assessing their cytotoxicity and antimicrobial properties. Their findings revealed that ACP nanoparticles exhibited no cytotoxicity in human epidermoid larynx carcinoma cells (HEp-2) and demonstrated antimicrobial activity against *Streptococcus mutans* (*S. mutans*) and *Enterococcus faecalis* (*E. faecalis*), indicating strong biocompatibility and potential for dental applications. These results align with the present study, confirming that PLA/PCL/ACP composites are safe for use in deciduous tooth root canal posts, while Beigoli et al. [37] confirmed the cytocompatibility and antimicrobial activity of ACP nanoparticles. Furthermore, the absence of cytotoxic effects observed in our composite supports its safe application in pediatric dental post systems. Although a positive control was not included in this assay, the cell viability results align with ISO-defined criteria, supporting the composite's non-cytotoxic classification.

3.2. Injection Molding Parameter Study and Taguchi Results

Molding shrinkage was selected as the performance index for the Taguchi experiment in this study. The key factors affecting molding shrinkage include melt temperature, injection speed, and holding speed (Microsystem 50 uses holding speed during the packing process). These three parameters were chosen as control factors for the experiment.

3.2.1. Parameter Setting

A series of molding trials were conducted to determine the optimal processing window for manufacturing the dental post. The selection of melt temperature, injection speed, and holding speed was based on the processing windows presented in Figures 8 and 9, which provide critical data for optimizing molding conditions.

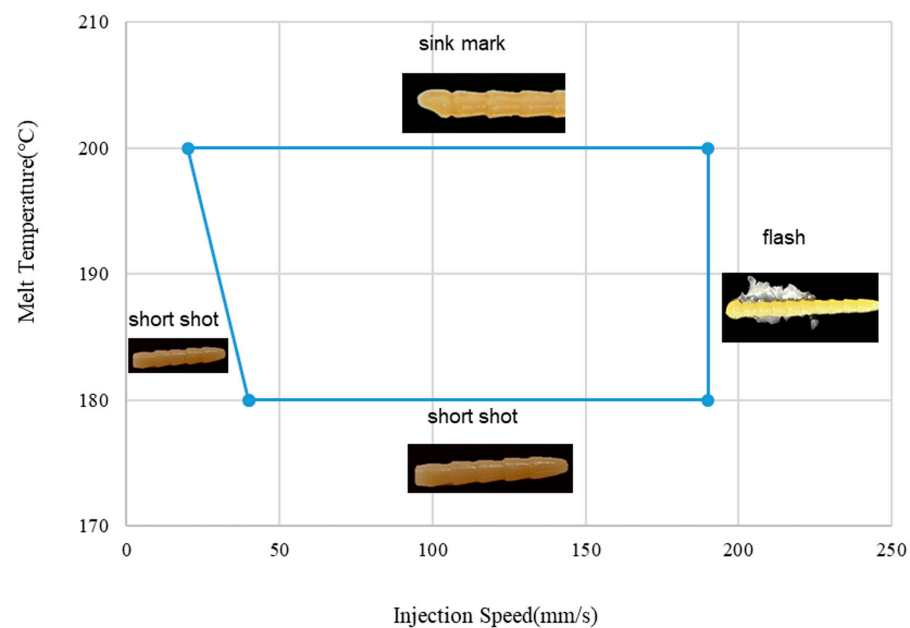


Figure 8. Molding window of PLA/PCL/ACP dental posts, illustrating the influence of melt temperature and injection speed on product quality. Representative molding defects—including short shot, sink mark, and flash—are shown at specific parameter combinations. The blue region indicates the optimal range for defect-free production.

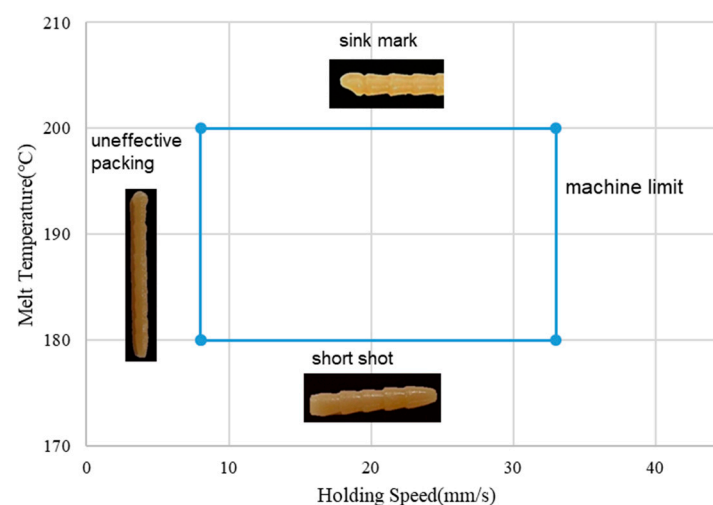


Figure 9. Molding window of PLA/PCL/ACP dental posts, showing the effect of melt temperature and holding speed on molding quality. Representative defects—including short shot, sink mark, and ineffective packing—are shown at specific conditions, along with the machine limit. The blue region indicates the optimal range for stable molding.

Melt Temperature:

- If the melt temperature is below 180 °C, poor melt fluidity leads to short shots, as shown in Figure 8.
- If the melt temperature exceeds 200 °C, sink marks form due to the high specific volume and shrinkage of the material, as illustrated in Figure 9.

Thus, the optimal melt temperature range was determined to be 180–200 °C.

Injection Speed:

- The processing window for injection speed ranges from 40 to 190 mm/s.
- Speeds below 40 mm/s resulted in short shots due to an insufficient injection rate.
- Speeds above 190 mm/s caused flash formation around the post.

Prior to molding trials, Moldex3D simulation was performed to analyze injection speed effects. As shown in Figure 10, injection pressure is lowest at 30 mm/s due to shear thinning effects. When the injection speed exceeds 30 mm/s, the required injection pressure increases with injection speed. To select a range with lower injection pressure while maintaining adequate filling efficiency, this study determined that 40–60 mm/s was optimal for the Taguchi experiment.

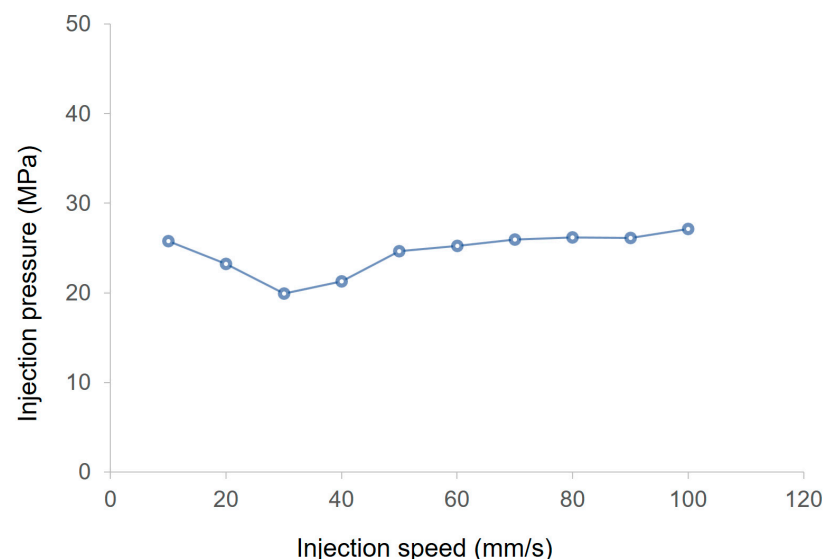


Figure 10. Moldex3D simulation showing the effect of injection speed on injection pressure for PLA/PCL/ACP dental posts. Pressure is lowest at 30 mm/s due to shear thinning but increases at higher speeds. A range of 40–60 mm/s was selected to balance filling efficiency and pressure for subsequent molding trials.

Holding Speed:

- When the holding speed exceeds 8 mm/s and continues up to the machine's maximum holding speed (33 mm/s), sufficient pressure retention is achieved.
- Based on Figure 9, the optimal holding speed range was selected to be 10–30 mm/s.

Figures 8 and 9 serve as the basis for defining these three processing windows, ensuring precise control factor selection.

For the Taguchi experiment, an orthogonal array was established based on control factor combinations. This study adopted an L9 orthogonal array, selecting three control factors with three levels. The levels were determined using the processing windows shown in Figures 8 and 9, as outlined in Table 3, rather than relying on trial and error. The L9 Taguchi experiment plan is presented in Table 4.

Table 3. Control factors and levels used in the Taguchi experimental design for PLA/PCL/ACP dental post molding.

Level/Factor	Melting Temperature (°C)	Injection Speed (mm/s)	Holding Speed (mm/s)
1	180	40	10
2	190	50	20
3	200	60	30

Table 4. L9 orthogonal array used in the Taguchi design, showing combinations of melt temperature, injection speed, and holding speed for PLA/PCL/ACP dental post molding. The optimal parameter set is highlighted in the last row.

Group	Melt Temperature (°C)	Injection Speed (mm/s)	Holding Speed (mm/s)
1	180	40	10
2	180	50	20
3	180	60	30
4	190	40	20
5	190	50	30
6	190	60	10
7	200	40	30
8	200	50	10
9	200	60	20
Optimal	180	50	30

Other fixed parameters during the experiments are listed in Table 5. The injection material prepared in this study consists of a PLA/PCL/ACP blend, with PLA as the primary component (80%). Due to PLA's significantly higher melting point compared to PCL, the blend must be heated beyond PLA's melting temperature to achieve complete melting.

Table 5. Fixed processing parameters used throughout the injection molding experiments for PLA/PCL/ACP dental posts. These values were held constant during the Taguchi trials.

Parameters	Numerical Value
Mold Temp	30 °C
Cooling Time	6 s
Holding Time	3 s
Back Pressure	15 bar
Screw Speed	80 rpm
Metering Volume	380 mm ³

During cooling, if the molten material remains inside the mold for over 6 s, the temperature difference within the cavity stabilizes within 10 °C, as depicted in Figure 11. If the temperature difference exceeds 10 °C, warpage and deformation may occur due to uneven cooling after demolding. Thus, the cooling time was set to 6 s.

Finally, Moldex3D analysis revealed that when the holding process exceeds 2.558 s, the gate completely solidifies, regardless of whether the injection melt temperature is 180 °C or 200 °C (Figure 12). Beyond this point, additional holding pressure has no effect. Consequently, the holding time was set to 3 s.

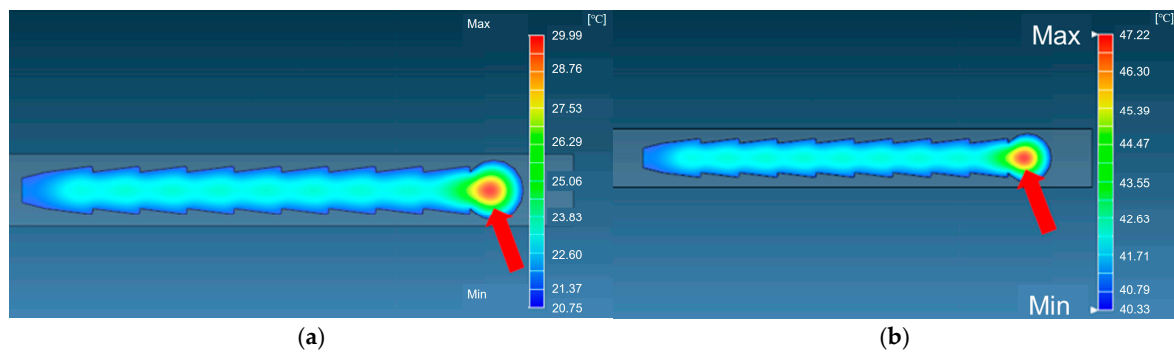
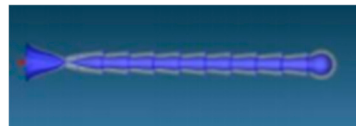


Figure 11. Melt temperature distribution after 6 s of cooling at (a) 180 °C and (b) 200 °C. In both cases, the temperature difference within the cavity stabilizes within 10 °C, reducing the risk of warpage due to uneven cooling. This analysis supports the selection of a 6 s cooling time.

Gate Solidification Situation at 180 (°C)

Holding time 1.173 s



Holding time: 2.438 s



Gate Solidification Situation at 200 (°C)

Holding time 2.085 s



Holding time: 2.558 s

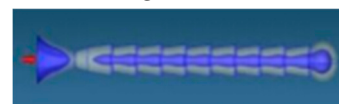


Figure 12. Moldex3D analysis of gate solidification at 180 °C and 200 °C under various holding times. The gate fully solidifies after 2.558 s at both temperatures, beyond which additional holding pressure has no effect. A holding time of 3 s was selected accordingly.

3.2.2. The Results of the Taguchi Experiment

Before each set of experiments in the Taguchi experiment, the parameters were set, and the machine was preheated for 30 min to ensure stable operating conditions. For each parameter combination, five finished products were molded, and their dimensions were measured after resting for one day to account for material stabilization. Data pertaining to the axial (length) and radial (head diameter) shrinkage, as well as the combined total shrinkage, are listed in Table 6, along with the S/N ratios of the total shrinkage.

The factor response graph (Figure 13) identified A1B2C3 as the optimal parameter combination. A verification experiment using this parameter set (melt temperature: 180 °C, injection speed: 60 mm/s, holding speed: 30 mm/s) resulted in a minimum average radial shrinkage of 2.09% and an average axial shrinkage of 0.485%. According to Table 6, the total shrinkage rate of 2.575% yielded an S/N ratio of 31.786, outperforming the 3.907% shrinkage rate and 28.163 S/N ratio observed in Taguchi's best L3 level, thus confirming the robustness of the selected parameters. Figure 14 displays the deciduous tooth root canal posts molded under the optimized settings.

The use of Taguchi's experimental design (L9 orthogonal array) to optimize injection molding parameters aligns with findings from prior studies. Kamarudin et al. [30] demonstrated that molding shrinkage serves as a key performance index in plastic injection molding, with orthogonal arrays improving process stability. Similarly, Chen et al. [29] examined the impact of melt temperature, injection speed, and holding speed on shrinkage, highlighting melt temperature as the most dominant factor—consistent with the present study's ANOVA results.

Table 6. Results of the Taguchi experiment showing dimensional shrinkage and signal-to-noise (S/N) ratios for each parameter set. The optimal combination minimized total shrinkage and maximized the S/N ratio.

Shrinkage (%) = (Mold Size – Post Size)/Mold Size × 100%				
Group	Axial	Radial	Sum	S/N
L1	0.427	7.202	7.628	22.351
L2	0.260	5.777	6.038	24.383
L3	0.140	3.767	3.907	28.163
L4	0.469	8.919	9.388	20.549
L5	0.248	4.992	5.240	25.614
L6	0.560	7.095	7.655	22.321
L7	0.463	8.613	9.076	20.843
L8	0.597	9.372	9.969	20.027
L9	0.704	9.957	10.662	19.444
Optimal	0.485	2.090	2.575	31.786

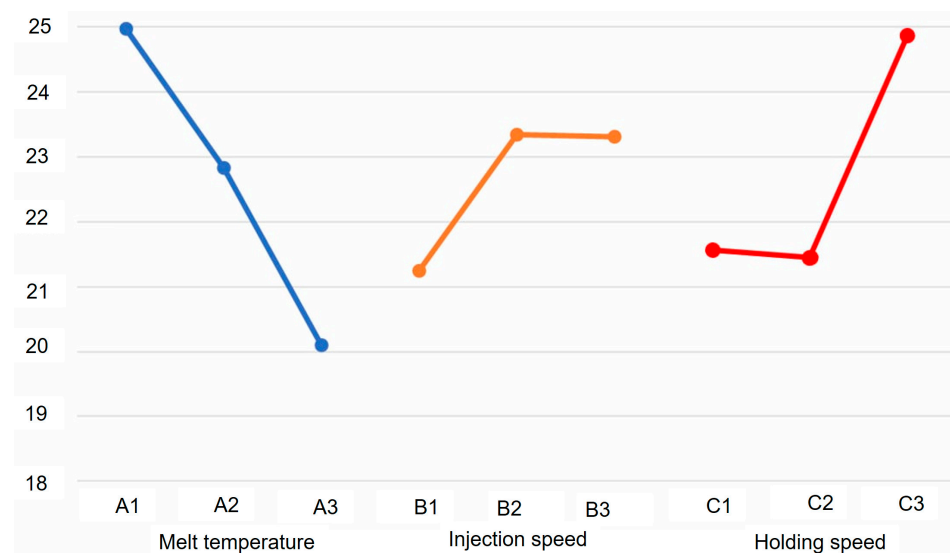


Figure 13. Main effects plot showing the influence of melt temperature (A), injection speed (B), and holding speed (C) on the selected response. The optimal parameter combination was A1B2C3.



Figure 14. Injection-molded PLA/PCL/ACP dental posts for deciduous teeth, produced using the optimal processing parameters (A1B2C3). A ruler is included for scale.

To determine the significance of each process parameter in injection molding, ANOVA was conducted. As shown in Table 7, melt temperature was the most influential factor, contributing 52.932% to molding shrinkage, followed by holding speed at 33.575%, whereas injection speed had a relatively smaller impact.

Table 7. ANOVA results for the Taguchi experiment, indicating the relative influence of each control factor on dimensional shrinkage.

Control Factor	Variance (S)	DoF (f)	Mutations (V)	Pure Change (S)	Contribution (ρ)%
A (Melt Temperature)	35.621	2	17.811	35.582	52.932
B (Injection Speed)	8.635	2	4.317	8.595	12.786
C (Holding Speed)	22.609	2	11.305	22.570	33.575
e (Error)	0.357	18	0.020	0.476	0.708
Total	67.222	24		67.222	100.000

Upon examining the radial and axial shrinkage, it was observed that radial shrinkage was significantly greater than axial shrinkage. The gate position plays a crucial role in injection molding, as it directly affects melt filling direction and solidification behavior [38]. Chavan et al. [38] emphasized that gate placement significantly influences cooling uniformity and shrinkage distribution, recommending that gates be positioned at thicker sections to optimize filling efficiency. In this study, the gate was positioned at the bottom of the post, in the section with the smallest diameter, to minimize defects on the spherical head, which is critical for gate removal. However, this placement resulted in reduced pressure-holding efficiency near the gate, leading to the highest shrinkage rate occurring at the head of the dental post. This phenomenon is consistent with molding principles observed in prior research.

3.3. Integrated Summary of Material Properties and Molding Performance

To provide a consolidated overview of the material behavior and processing outcomes, Table 8 summarizes the key mechanical, thermal, rheological, and biological properties of the PLA/PCL/ACP composite, alongside listing metrics related to its injection molding performance. The composite exhibited a flexural strength of 21.9 ± 2.7 MPa and a modulus of 2.08 ± 0.13 GPa, indicating sufficient mechanical integrity for pediatric dental post applications. Thermal analysis revealed a glass transition temperature (T_g) of around 65°C and a melting temperature (T_m) of 172.6°C , suggesting a stable thermal profile during molding. Rheological evaluation demonstrated moderate viscosity under shear, supporting processability via micromolding, as characterized by the Modified Cross model parameters (Table 1) and shear-dependent viscosity profiles (Figure 5). The contact angle of $73.73^\circ \pm 1.59^\circ$ indicated moderate hydrophilicity, while cell viability exceeding 70% confirmed acceptable biocompatibility. Molding performance, assessed through linear shrinkage and dimensional precision, showed consistent quality under optimized conditions derived from Taguchi analysis. This integrated presentation highlights the interplay between material formulation, biological response, and processing precision, providing a foundation for evaluating the clinical feasibility of the proposed system.

Table 8. Summary of key material properties and molding performance of the PLA/PCL/ACP composite. The table includes flexural properties, thermal transitions, wettability, shrinkage, and dimensional accuracy of the molded posts.

Category	Property	Value
Material Properties	Flexural Strength (MPa)	21.90 ± 2.70
	Flexural Modulus (GPa)	2.08 ± 0.13
	Glass Transition Temperature ($^{\circ}\text{C}$)	65.0
	Melting Temperature ($^{\circ}\text{C}$)	172.6
	Contact Angle ($^{\circ}$)	73.7 ± 1.6
Molding Performance	Average Linear Shrinkage (%)	1.29
	Length (mm)	21.153 ± 0.025
	Head Diameter (mm)	2.452 ± 0.011

3.4. Comparison with Existing Dental Post Materials

To better contextualize the flexural performance of the PLA/PCL/ACP composite, Table 9 summarizes its strength and modulus alongside representative values reported for conventional dental post materials, including biodegradable PLA-based systems [10], fiber-reinforced composite posts [11], and metallic posts [12].

Table 9. Comparative flexural properties of dental post systems. The PLA/PCL/ACP composite developed in this study is compared with PLA-based, fiber, and metal posts, as well as natural primary dentin, in terms of flexural strength and modulus.

Dental Post System	Flexural Strength (MPa)	Flexural Modulus (GPa)
PLA/PCL/ACP (This study)	21.94 ± 2.70	2.08 ± 0.13
PLA-Based Post [10]	64.2 ± 7.9	2.75 ± 0.3
Fiber Post (D.T. Light-Post [®]) [11]	1800–2000	15
Metal Post (Stainless Steel) [12]	230 ± 15	200 ± 10
Natural Primary Dentin [31]		~ 3.63

The PLA/PCL/ACP composite exhibited a flexural strength of approximately 22 MPa and a modulus of 2.08 GPa, which are considerably lower than those of commercial fiber posts (1800–2000 MPa; 15 GPa [11]) and stainless-steel posts (230 ± 15 MPa; 200 ± 10 GPa [12]). However, it is important to note that most of these reference data correspond to posts designed for permanent teeth, which experience greater functional loading demands due to higher occlusal forces. In contrast, deciduous teeth exhibit thinner dentin walls, shorter roots, and physiological resorption, necessitating more flexible and resorbable post systems to avoid excessive stress concentration and interference with natural exfoliation.

Compared to natural primary dentin, which has a flexural modulus of ~ 3.63 GPa [31], the PLA/PCL/ACP system's lower modulus may help reduce interfacial stress at the dentin–post junction, promoting better stress distribution and preservation of root integrity. This rationale aligns with modulus-matching strategies advocated for in pediatric endodontics [31,32].

While biodegradable PLA-based posts have demonstrated moderately higher mechanical values (e.g., 64.2 ± 7.9 MPa strength; 2.75 ± 0.3 GPa modulus [10]), the current composite remains compliant with structural requirements for primary teeth and demonstrates promising potential for pediatric endodontics. Notably, the inclusion of ACP provides biochemical benefits beyond mechanical reinforcement. As demonstrated in our

previous study [22], ACP neutralizes the acidic degradation by-products from PLA/PCL matrices, stabilizing the local pH and reducing the risk of inflammatory responses—an essential feature in pediatric applications.

Although variations in testing parameters and filler dispersion may affect absolute values across studies, flexural performance remains a valid metric for benchmarking candidate materials. Taken together, the PLA/PCL/ACP composite demonstrates a well-balanced profile of structural suitability, degradability, and biocompatibility, reinforcing its potential as a resorbable post system specifically tailored for primary tooth rehabilitation.

4. Conclusions

This study successfully developed and evaluated biodegradable dental posts using PLA/PCL/ACP composites customized for deciduous teeth. Through innovative design and injection molding parameter optimization, the following results were achieved:

Material properties: The PLA/PCL/ACP composite exhibits good flexural strength (21.936 MPa) and modulus (2.083 GPa) values, making it suitable for dental post applications. The material also exhibits hydrophilic properties with a contact angle of 73.73°, enhancing compatibility with dental fillings.

Biocompatibility: MTT experiments have confirmed that this composite material is non-toxic, has a cell survival rate of more than 70%, and has high biocompatibility for medical applications.

Injection molding: Using Taguchi's experimental method, the optimal injection molding parameters were determined, and the minimum shrinkage rate obtained was 2.575%. Melt temperature has the most significant impact on shrinkage, followed by holding speed and injection speed.

Overall, this study highlights the potential of PLA/PCL/ACP composites for the production of biodegradable posts for deciduous teeth based on comprehensive in vitro evaluations, including mechanical, thermal, rheological, and biological assessments. In contrast to conventional metal posts, quartz fiber-reinforced systems (e.g., D.T. Light-Post), and other PLA-based designs reported in previous studies, our approach features a distinct material formulation and injection molding process specifically tailored for pediatric applications. While the results are promising, this study is limited to in vitro analysis. Therefore, further preclinical and in vivo investigations are necessary to validate the clinical applicability of the developed PLA/PCL/ACP composite. In particular, future studies should incorporate functional simulations, such as cyclic loading, bonding performance with dental cements, and evaluations on extracted teeth to better reflect clinical conditions.

Author Contributions: Methodology, M.-W.W.; Software, M.-K.X.; Validation, M.-W.W. and M.-K.X.; Formal analysis, M.-K.X.; Investigation, M.-W.W. and M.-K.X.; Resources, M.-W.W.; Data curation, M.-W.W. and M.-K.X.; Writing—original draft, M.-W.W., M.-K.X., and S.E.H.; Writing—review and editing, M.-W.W.; Supervision, M.-W.W.; Project administration, M.-W.W.; Funding acquisition, M.-W.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Science and Technology Council, Taiwan, under grant number NSC 111-2221-E992-065.

Institutional Review Board Statement: This study involved only commercially available cell lines and reagents. The cell line used was NIH/3T3 (BCRC 60091, Food Industry Research and Development Institute, Hsinchu, Taiwan). Culture media and supplements, including DMEM (Sigma, St. Louis, MO, USA) and fetal bovine serum (Gibco, Thermo Fisher Scientific, USA), were all commercially obtained. No primary cells or animal/human-derived tissues were used. Therefore, ethical approval was not required in accordance with institutional and journal guidelines.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors acknowledge the use of AI tools, specifically Microsoft Copilot, during the preparation of the initial manuscript draft and the revision process. Copilot was employed to refine the language, enhance textual clarity, and ensure technical accuracy in descriptions. All experimental designs, data collection, analysis, and interpretations were performed solely by the authors without AI involvement.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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