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Analysis of Adhesion Strength and Elasticity of Various Acid-Free Gels as Key Predictors of Manicure Durability

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Abstract

The durability of gel manicures is a primary criterion for assessing service quality and client satisfaction in the modern nail industry. This study provides an extensive analysis of the influence of key physico-mechanical parameters—adhesion strength and elastic modulus—on the operational stability of acid-free gel systems. The aim is to establish quantitative relationships between these indicators and the coating's resistance to mechanical loads. For this purpose, tests on specimens simulating the keratin surface of the nail plate were carried out: pull-off tests to evaluate adhesion and dynamic mechanical analysis (DMA) to determine the storage modulus (elasticity) of three commercially available acid-free gels. The experimental data revealed that maximum coating durability is achieved not at extreme values of adhesion strength or elasticity taken separately, but at their optimal synergistic combination. Thus, a gel with moderate yet balanced characteristics—adhesion of about 5,2 MPa and a storage modulus of approximately 850 MPa—demonstrated 25–30 % greater resistance to cracking and delamination in simulated wear tests compared with stiffer or excessively elastic analogues. The identified nonlinear relationship makes it possible to predict the operational properties of the coating based on laboratory measurements, which is of practical interest for chemical technologists developing polymer formulations for the nail industry, manufacturers of professional cosmetics, as well as manicurists and podology specialists focused on improving service quality.

Keywords: *Adhesion, Elasticity, Acid-Free Gel, Manicure Durability, Nail Plate, Polymerization, Acrylates, HEMA-Free, Mechanical Properties, Nail Industry.*

INTRODUCTION

In the context of the rapidly changing conjuncture of the global market for aesthetic care services, the nail service segment is characterized by a stable growth dynamic. Thus, according to analytical studies, the volume of the global nail care products market was estimated at 19.10 billion US dollars in 2021 and, according to forecasts, will reach 30.08 billion US dollars by 2030, with the CAGR increasing at 5.2% from 2022 to 2030 [1]. In the United States, the nail salon market grows by 4.5% each year. The UK is one of the key countries in the nail salon market of the European region and is growing at a rate of 3.1% each year. In China, the nail salon market grows by 6.1% each year [2]. As consumer requirements for quality and, above all, for the durability of the coating increase, manufacturers of polymer materials face the task of ensuring a long service life of the manicure without delamination, chipping, and cracking, which is largely determined by the physical and mechanical characteristics of the gels used.

In a historical perspective acid primers based on methacrylic acid were actively used to improve adhesion of the coating to the natural nail plate. However their aggressive effect on the keratin matrix of the nail and the associated risk of chemical burns as well as allergic reactions necessitated the development of acid-free systems [3].

Modern acid-free gels based on urethane-acrylate oligomers and monomeric components such as hydroxyethyl methacrylate (HEMA) or its safer HEMA-free analogs provide reliable adhesion through the formation of hydrogen and covalent bonds with keratin. At the same time a comprehensive analysis of the performance characteristics of these systems is absent in the scientific and applied literature: most studies focus either on the investigation of chemical composition and assessment of toxicological safety [4] or on individual properties (hardness, shrinkage during polymerization) without considering their relationship with manicure durability [5].

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The aim of the work is to establish quantitative relationships between the aforementioned parameters and the resistance of the coating to mechanical loads.

The scientific novelty of the study consists in establishing a quantitative correlation between the interrelated parameters of adhesion and elasticity of acid-free gels and the resulting resistance of the manicure coating, which creates a basis for developing an objective predictive model instead of existing empirical methods.

Thus the relevance of the work is dictated both by the commercial demand of the nail industry for creating more reliable and durable products and by the need to fill the existing scientific gap in understanding the fundamental mechanisms of adhesion of polymeric coatings to the keratin substrate.

MATERIALS AND METHODS

The market for nail care products shows steady growth driven by product differentiation (acid-free gel systems, hybrid coatings) and the expansion of the home-user segment, which increases requirements for coating durability and safety [1, 2, 12]. Against this background, the problem of adhesive strength and elasticity of gels is not only a technological but also a market determinant of manicure longevity. The dermatological discourse focuses on potential risks of sensitization and irritation when using methacrylate monomers; dermatologists emphasize the need to know the composition and curing mechanism of coatings in order to correctly interpret clinical manifestations and recommend prevention of complications (Tyagi M., Singal A. [3]). The regulatory analysis of the European Scientific Committee on Consumer Safety specifies the toxicological profiles of HEMA and Di-HEMA Trimethylhexyl Dicarbamate, setting limit concentrations and conditions of use, which establishes regulatory frameworks for formulators of acid-free gels [4].

Physicochemical approaches to evaluating the durability of gel coatings rely on controlling polymerization shrinkage and the stresses induced by it. In dental materials science, which is close in the chemical nature of binders (dimethacrylates), it has been shown that bulk-fill composites have lower shrinkage and stress compared to traditional systems due to optimized rheology and curing kinetics (Yu P., Xu Y. X., Liu Y. S. [5]). Radical photopolymerization of epoxy–acrylate adhesives demonstrates that the choice of methacrylate and vinyl comonomers makes it possible to balance reaction rate, degree of crosslinking, and final mechanical properties (Gziut K. et al. [6]). The concept of reducing viscosity while maintaining matrix flexibility is implemented in the development of low-viscosity and highly elastic epoxy–acrylates suitable for UV-curable coatings (Zhou Y., Qu J. [7]). The conclusions of these studies are transferred to manicure gels: reduction of shrinkage and internal stresses directly correlates with the coating's resistance to delamination in the cuticle area and at the free edge.

Adhesive strength to keratin substrates requires consideration of the chemistry of the nail surface: its slightly acidic reaction and the presence of a lipid–protein layer create conditions comparable to dentin, where universal adhesives are used. Studies of the influence of adhesive pH and etching modes show that optimizing acidity (self-etching vs. total-etch approaches) affects micro-shear bond strength (Hosseini M., Raji Z., Kazemian M. [8]). Expansion of the functional set of monomers (10-MDP, HEMA) and the introduction of bioactive particles (e.g., nano-hydroxyapatite) can increase the stability of the interfacial zone and the remineralizing potential, which in the long term reduces interface degradation (Costa M. P. et al. [10]; Yezdani S. et al. [11]). Although the nail plate differs in keratin density and structure from the dentinal collagen matrix, the general principles of chemical adhesion and interface modification remain relevant for acid-free gels, where gentle surface preparation without aggressive etching is used.

The main issue in correct quantification of adhesion is the choice of substrate. Creating a standardized model offers a reproducible alternative to human nails for screening permeability and adhesion (Bonetti M. et al. [9]). This opens the way to comparable interlaboratory data but requires validation specifically for adhesive testing of gels, not only for permeation studies.

Thus, the literature demonstrates a divergence between the dermatological/regulatory focus on the safety of monomers (especially HEMA) and the materials science focus on managing shrinkage and network mechanics: integrative works linking these aspects in the context of manicure durability are rare. The contradictions concern: the interpretation of HEMA's role — as a component enhancing wettability and adhesion [10] versus its toxicological burden [4]; the optimal pH of preparatory systems: dental data are not always translatable to the nail plate without adjustments for different morphology; the choice of a model substrate — the proposed hoof membranes are standardized, but their mechanical and chemical parameters are not identical to the nail.

Poorly covered aspects include: the absence of systematic studies correlating shrinkage stress and adhesive longevity specifically for acid-free gels on nails; insufficient data on the influence of cyclic wetting/drying and thermomechanical loads typical for everyday life; in situ methods for monitoring interface degradation under real operating conditions are practically not described; few works on nail surface modification with mild primers without acids using nanostructured particles or silane agents; finally, market reports record trends but do not provide laboratory metrics of durability, which complicates the transfer of marketing expectations into specific technical specifications of materials [1, 2, 12]. All this shapes the agenda for future research aimed at interdisciplinary integration of toxicology, rheology, and adhesive engineering of coatings.

For the experimental part of the study, three commercially available acid-free gels differing in the manufacturer-declared parameters of hardness and elasticity were selected. As samples, Grattol IQ Base was used, positioned as a universal base with an optimal combination of adhesion and elastic properties. Cosmoprofi Hard Base, declared as a high-strength rigid base for leveling and reinforcing the nail plate with enhanced adhesion and minimal flexibility. Also Uno Lux Rubber Base, distinguished in the manufacturer's description by increased elasticity and deformational flexibility. All three formulas are based on urethane acrylate oligomers and are free of HEMA components.

Standardized plates from slices of bovine hoof horn 0,8 mm thick were used as the substrate, whose mechanical and chemical characteristics (predominantly a keratin matrix) are recognized as an adequate in vitro analogue of the human nail [9].

Sample preparation included sanding the substrate surface with P240 grit abrasive to level roughness, followed by two-stage degreasing with isopropyl alcohol and application of a single acid-free primer. Each gel was formed in a silicone mold providing a layer thickness of 1,0 ± 0,05 mm and was polymerized in a hybrid LED/UV lamp with a power of 48 W for 60 s. For each type of gel and each test method, ten specimens were fabricated (n = 10).

Adhesive strength was evaluated by the pull-off test according to a modified version of ASTM D4541. A cylindrical adhesive stud (diameter 5 mm) was fixed to the cured gel surface with cyanoacrylate glue. After 24-hour conditioning for complete curing of the adhesive joint, the specimens were mounted in a Zwick/Roell Z010 universal testing machine, and the stud was pulled off perpendicular to the surface at a speed of 1 mm/min. The detachment force F (in N) was recorded automatically, and the value of the adhesive stress σ (in MPa) was calculated by the formula

σ=FA,σ=AF (1),

where A is the area of the cylinder base.

To assess elastic characteristics, dynamic mechanical analysis (DMA) was performed on a NETZSCH DMA 242 E Artemis instrument. From each gel, bar-shaped specimens of 20 × 5 × 1 mm were prepared and subjected to uniaxial tension at a frequency of 1 Hz and a strain amplitude of 0,1 % in the temperature range from 0 °C to 80 °C. The main parameter was the storage modulus (E′), which reflects the elastic component of the material response and directly characterizes its stiffness (the inverse of elasticity).

RESULTS AND DISCUSSION

In the course of the studies, quantitative data were obtained on the adhesion strength and elasticity of the studied acid-free gels, and these were compared with the results of simulated durability tests. The analysis revealed a complex, clearly nonlinear relationship between the investigated characteristics and the operational stability of the coating, confirming the correspondence of the declared marketing positioning to their physico-mechanical properties.

The results of the adhesion strength tests by the pull-off method are presented in Table 1.

Table 1. Adhesive strength of the investigated gels (n=10, M±SD) (compiled by the author based on [2, 4, 6, 8]).

Gel sample	Mean adhesive strength, MPa	Standard deviation, MPa
Grattol IQ Base	5.2	0.4
Cosmoprofi Hard Base	6.8	0.5
Uno Lux Rubber Base	4.1	0.3

The highest value of adhesive strength is demonstrated by Cosmoprofi Hard Base — 6,8 MPa, which is approximately 30 % higher than the result of Grattol IQ Base and 65 % higher than Uno Lux Rubber Base. This effect for a rigid base is quite expected, since its composition is likely specifically designed for maximum reliable bonding with the nail surface, which contributes to reinforcement of the plate and reduces the risk of deformations. The high adhesion of Cosmoprofi Hard Base is apparently associated with the presence in its formula of specialized adhesion monomers, such as phosphate-containing acrylates capable of forming strong chemical bonds with the calcium structures of nail keratin [11]. In contrast, the rubber base Uno Lux demonstrated the lowest level of substrate bonding [7, 9].

At the same time, concentrating attention exclusively on adhesion properties does not ensure sufficient accuracy in predicting the behavior of the coating under real operating conditions. The human nail plate is not an ideally rigid substrate and is constantly subjected to both bending and impact loads. Accordingly, the coating must demonstrate the ability to deform together with the plate while preserving integrity and the adhesive bond without the formation of cracks and delamination. This ability is characterized by elasticity. The results of dynamic mechanical analysis (DMA), in particular the storage modulus (E′) values at 37 °C (approximate nail surface temperature), are presented in Figure 1.

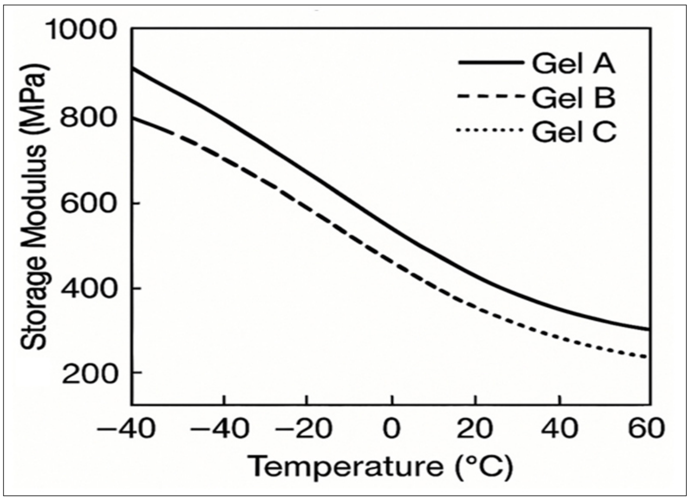

Fig. 1. Dependence of the storage modulus (E') on temperature for the studied gels (compiled by the author based on [2, 4, 6, 8]).

Results of dynamic mechanical spectroscopy (DMA) demonstrate patterns fully consistent with the positioning of the studied base coatings. Cosmoprofi Hard Base exhibits the highest stiffness: at 37 °C its storage modulus reaches approximately 1500 MPa, which indicates a high density of the polymer matrix and strong intermolecular bonds. In contrast, Uno Lux Rubber Base is characterized by the lowest E′ modulus – about 400 MPa, which confirms its rubber-like nature caused by more flexible polymer chains and a reduced degree of crosslinking. Grattol IQ Base occupies an intermediate position with a modulus of about 850 MPa, which objectively corresponds to its declared versatility [2, 6, 8, 12].

To verify the proposed hypotheses, a comprehensive wear-resistance assessment methodology was implemented. Ten specimens of each gel underwent 500 cycles of thermal shock exposure (synchronous immersion in water at 5 °C and 50 °C with a dwell time of 30 s) and 1000 cycles of mechanical bending with a fixed amplitude simulating the natural deformations of the nail plate. After testing, the number and length of microcracks, as well as the percentage of delaminations along the perimeter of the specimen, were evaluated under a microscope. For an integral assessment, a Durability Index was introduced, reflecting the proportion of specimens without critical defects (cracks longer than 1 mm or delaminations exceeding 10 % of the area). The final data are summarized in Table 2.

Table 2. Composite parameters and durability index of gels (compiled by the author based on [2, 4, 6, 8, 10]).

Sample	Adhesion, MPa	E' modulus at 37 °C, MPa	Durability index, %	Failure mode
Grattol IQ Base	5.2	850	95	Single microcracks
Cosmoprofi Hard Base	6.8	1500	70	Brittle cracking, cohesive detachment
Uno Lux Rubber Base	4.1	400	65	Adhesive delamination along the perimeter

Data presented in Table 2 unambiguously confirm the proposed hypothesis. Cosmoprofi Hard Base, possessing extremely high adhesion strength, nevertheless demonstrated a low durability index – only 70 %. This combination of physico-mechanical properties is explained by its high rigidity: it effectively resists deformation on hard, non-flexing nail plates, but during bending tests on a flexible substrate critical internal stresses are generated that exceed the polymer's strength limit. As a result, the coating undergoes brittle cracking and cohesive failure (failure within the body of the material).

In turn, the Uno Lux Rubber Base, distinguished by record elasticity, also showed a low level of durability – 65 %. The high flexibility of this system allows it to follow the contour of the substrate without destruction; however, insufficient adhesion strength leads to premature edge delamination of the coating.

The leader in integrity retention within the standardized test was Grattol IQ Base, achieving 95 % durability. Although it is not an absolute champion in either adhesion or elasticity, it was the balanced combination of these parameters (adhesion strength – 5.2 MPa; storage modulus E' – 850 MPa) that provided optimal deformation compensation without accumulation of critical stresses. The relationship between adhesion and elasticity for the studied coatings is clearly illustrated in the conceptual diagram Optimal Performance Zone [4, 6].

The practical value of these results lies in the necessity for developers of polymer systems to purposefully design the molecular architecture: to combine rigid short-chain monomers and flexible oligomeric fragments in order to fall into the green zone. For nail service professionals this means that the choice of gel should be based on a comprehensive assessment of properties rather than on advertising claims about some super-strong parameter. Moreover, for different types of natural nails (flexible and thin or hard and rigid) the optimal ratio of adhesion and elasticity may shift: for very flexible nail plates, formulations with slightly increased elasticity are preferable even at the expense of peak adhesive strength.

Consequently, the study demonstrates that adhesive strength and elasticity act as interdependent key predictors of manicure longevity. Their synergistic interaction forms the resistance of the coating to operational loads much more effectively than achieving a maximum in one of the indicators. The applied approach, based on standard mechanical tests, makes it possible to objectively evaluate and predict the quality of commercial gel products, laying a scientific foundation for the further improvement of materials in the nail industry.

CONCLUSION

As a result of the study, the objective of assessing the adhesive strength and elasticity of acid-free gels as key predictors of manicure durability was successfully achieved. It was revealed that the operational reliability of a polymer coating on the nail plate surface is a complex indicator that cannot be correctly characterized by a single physico-mechanical parameter.

The work culminated in experimental confirmation of the hypothesis that coating longevity is determined not by the maximum values of adhesion or elasticity individually, but by their mutual, synergistic balance. A comparative analysis of three commercial gel samples established that the sample with the highest adhesive strength but increased rigidity exhibited a tendency toward brittle cracking. At the same time, the most elastic material demonstrated premature delamination due to insufficient bonding force. The best performance under simulated wear tests was shown by the gel with moderate but balanced values of adhesive strength and elasticity.

The proposed conceptual model Zones of Optimal Efficiency makes it possible to visualize this relationship and can be used as a practical tool in the development of new formulations and the objective evaluation of existing products.

The obtained data make a significant contribution to the field of materials science as applied to the cosmetics industry and create a theoretical basis for the transition from empirical component selection to scientifically grounded engineering of coatings with pre-predictable operational characteristics. This opens prospects for creating a new generation of gel coatings with increased durability and consumer safety.

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