Jurnal Farmasi Ma Chung: Sains Teknologi dan Klinis Komunitas

p–ISSN : **2986-8270**
e-ISSN : **2986-5972**
DOI: 10.33479/jfmc.v4i2.218
Research Article

Formulation Optimization of a Water-Based Adhesive for Medical Plasters Using Simplex Lattice Design

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Article History:
Accepted: 28 August 2026
Revised: 27 October 2026
Published: 23 November 2026

Keywords:
adhesive performance;
medical plasters;
mixture optimization;
polybutene;
water-based adhesives

Pressure-sensitive adhesives for medical plasters must balance interfacial adhesion with cohesive resistance. This study optimized a water-based adhesive by varying polybutene and sodium phosphate using a two-component Simplex Lattice Design (SLD). Eight experimental runs comprising six unique mixture compositions were evaluated for appearance, pH, homogeneity, viscosity, adhesion, 180° peel strength, and shear displacement rate. Multiresponse optimization selected a composition containing 5.450% w/w polybutene and 2.550% w/w sodium phosphate (desirability = 1.000). Model predictions were 3.797 N/cm for adhesion, 2.528 N/cm for peel strength, and 0.414 mm/min for shear displacement; confirmation testing yielded 3.66 ± 0.14 N/cm, 2.47 ± 0.06 N/cm, and 0.42 ± 0.03 mm/min, respectively. During eight weeks of accelerated storage at 40 °C/75% RH, adhesion decreased by 10.2% (3.52 to 3.16 N/cm), peel strength decreased by 22.5% (2.49 to 1.93 N/cm), and shear displacement increased by 90.0% (0.50 to 0.95 mm/min). One-way ANOVA indicated time-related differences in all three responses ($p \leq 0.001$); however, replicate independence and packaging configuration were not documented. These results identify a composition that met the specified model-based optimization goals within the studied design space, but do not establish shelf life or clinical suitability. Further testing over longer periods, with documented packaging, independent batches, and skin biocompatibility assessment, is required.

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Medical plasters must adhere reliably to the skin while minimizing mechanical trauma during removal. Their performance depends on the balance among initial tack, peel resistance, and cohesive strength, which is governed by the viscoelastic properties of the pressure-sensitive adhesive (PSA) and the skin–adhesive interface [1–3]. Perspiration and repeated application can further alter adhesion and affect medical-device fixation and user comfort [4–6].

Water-based PSAs can reduce reliance on organic solvents during coating, but achieving stable film formation and dispersion while balancing adhesion and shear resistance remains challenging. Previous studies have demonstrated the feasibility of water-based drug-in-adhesive patches and have shown that adhesive performance varies with polymer matrix and composition [7,8]. Other work has linked polymer architecture, tackifiers, softening agents, and formulation design to tack, peel strength, and cohesion [9,11–13].

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Recent studies illustrate this formulation dependence. Arunprasert et al. [7] developed water-based drug-in-adhesive patches using poly(N-vinylpyrrolidone-co-acrylic acid)/poly(methyl vinyl ether-alt-maleic anhydride) (PVPAA/PMVEMA) and showed that polymer ratio influenced tack and patch performance. Badía et al. [11] reported biobased waterborne PSAs with tunable removability, while Márquez et al. [12] and Shi et al. [13] examined the effects of acrylic polymer composition and modification on adhesive performance. These systems differ from the latex-containing medical-plaster adhesive examined here. In the present formulation, polybutene was examined as a plasticizing component and sodium phosphate as a component intended to support aqueous-phase stability. The cited studies do not directly evaluate the combined effects of these components in this system over a fixed total concentration of 8.0% w/w. This leaves uncertainty about how their proportions jointly affect adhesion, peel strength, and resistance to sliding.

Because the mixture components are constrained to sum to a fixed total, the formulation is a mixture-design problem rather than a set of independent factor experiments. Simplex Lattice Design (SLD) can model responses as a function of component proportions and support systematic optimization within the studied mixture region; the method has also been applied to pharmaceutical matrix-patch formulation [10,18,19]. Multiresponse optimization is relevant because maximizing adhesion and peel strength alone may not ensure adequate cohesive resistance; in this study, shear performance is expressed as displacement rate, for which lower values indicate better resistance to sliding. A desirability-based approach was therefore used to balance the three mechanical responses.

The primary objective was to optimize the proportions of polybutene (4.5–5.5% w/w) and sodium phosphate (2.5–3.5% w/w), maintained at a combined concentration of 8.0% w/w, in a latex-containing water-based adhesive for medical plasters. The primary responses were adhesion and 180° peel strength, both targeted for maximization, and shear displacement rate, targeted for minimization. Appearance, pH, homogeneity, and viscosity were assessed as secondary physicochemical attributes. The selected composition was prepared for confirmation testing, and its mechanical performance was monitored during an eight-week observation period.

Results and Discussion

Experimental design and formulation properties

Eight experimental runs were evaluated with polybutene ranging from 4.5 to 5.5% w/w and sodium phosphate from 2.5 to 3.5% w/w; their combined concentration was maintained at 8.0% w/w. The remaining components were latex smoked sheet (4.2%), Harz-100 resin (1.3%), lanolin (10.2%), zinc oxide (8.8%), and distilled water to 100%. The design comprised six unique mixture compositions because F1, F3, and F5 were repeated design points with the same polybutene/sodium phosphate composition (5.2%/2.8% w/w). Table 1 presents all eight experimental runs, their mixture compositions, and the mean mechanical responses. The preparations were semi-solid, off-white to slightly yellowish, and exhibited a characteristic rubber odor, without visible sedimentation.

The eight preparations showed near-neutral pH values (approximately 6.58–6.79, calculated from triplicate measurements) and were visually homogeneous. Viscosity values ranged from 50,297 to 55,228 cP. One-way ANOVA indicated no significant between-formulation difference in pH ($F = 0.64$; $p = 0.719$), whereas differences in viscosity were statistically significant ($F = 5.27$; $p = 0.003$). These results suggest that changes in component ratio exerted a stronger influence on rheological properties than on pH within the evaluated mixture region.

Adhesion, peel strength, and shear displacement

The highest mean adhesion was measured for F4 (5.5% polybutene and 2.5% sodium phosphate: 3.72 N/cm), whereas F7 exhibited the lowest mean adhesion (2.10 N/cm). A linear mixture model described the adhesion response ($F = 15.68$; $p = 0.0074$;

lack-of-fit p = 0.1049; adjusted R^2 = 0.6772; predicted R^2 = 0.5176). Adhesion generally increased toward the polybutene-rich region, consistent with the influence of polymer mobility and interfacial contact on PSA performance [9,12]. This pattern is consistent with studies showing that polymer composition and matrix architecture influence waterborne PSA performance [9,11–13]. Because the two components were varied as a constrained mixture, their contributions should be interpreted jointly. Peel strength ranged from 1.37 to 2.55 N/cm, with the highest mean recorded for F4. The peel-strength response was described by a cubic mixture model (F = 129.78; p = 0.0002; lack-of-fit p = 0.8035), indicating a nonlinear dependence on mixture composition. This finding is consistent with the broader evidence that polymer composition and matrix constituents influence the adhesive performance of water-based patches. For example, Arunprasert et al. [7] reported that the PVPAA/PMVEMA ratio affected tack and peeling characteristics in water-based drug-in-adhesive patches. However, absolute peel values should not be compared directly because the polymer matrix, substrate, and test protocol differ. Peel strength is also a distinct performance attribute and does not independently establish skin compatibility [3,5,14].

Table 1. SLD experimental runs and mean mechanical responses. Eight runs represent six unique mixture compositions; F1, F3, and F5 are repeated design points.

Run	Poly. (%)	Na phos. (%)	Adhes. (N/cm)	Peel (N/cm)	Shear* (mm/min)
F1	5.2	2.8	3.24	2.03	0.50
F2	4.9	3.1	3.17	1.41	1.00
F3	5.2	2.8	3.50	2.12	0.50
F4	5.5	2.5	3.72	2.55	0.80
F5	5.2	2.8	3.44	2.10	0.40
F6	4.8	3.2	3.41	1.37	1.10
F7	4.5	3.5	2.10	1.77	1.30
F8	4.7	3.3	2.26	1.40	1.40

Abbreviations: Poly., polybutene; Na phos., sodium phosphate; Adhes., adhesion; Peel, 180° peel strength; Shear*, shear displacement rate. Values are means of three reported determinations per run. The source records do not specify whether these determinations represent independent specimens or batches. A higher shear displacement rate indicates greater sliding and poorer resistance.

Mean shear displacement rates ranged from 0.40 to 1.40 mm/min. F5 had the lowest displacement rate (0.40 mm/min), whereas F8 had the highest (1.40 mm/min). These results demonstrate that the formulation giving the highest adhesion and peel strength did not also provide the lowest shear displacement rate, underscoring the need for multiresponse optimization. This interpretation is consistent with studies linking PSA viscoelasticity, network structure, and interfacial chemistry to the balance between adhesion and cohesive resistance [9,11,12,15,16]. The present study extends this formulation–performance perspective to a latex-containing adhesive in which polybutene and sodium phosphate were varied as constrained mixture components. Because shear was measured as displacement rate rather than holding time or force to failure, direct numerical comparisons with those endpoints are not appropriate. Lower displacement rates indicate better resistance to sliding under the present test conditions.

Numerical optimization and verification

Multiresponse optimization using Design-Expert identified an optimal mixture containing 5.450% w/w polybutene and 2.550% w/w sodium phosphate, with a desirability value of 1.000. At this composition, the model predicted adhesion of 3.797 N/cm, peel strength of 2.528 N/cm, and shear displacement of 0.414 mm/min (Table 2). The three reported confirmation determinations yielded means of 3.66,

2.47, and 0.42 in the respective units, corresponding to descriptive differences from the predictions of approximately −3.6%, −2.3%, and +1.4%. The confirmation and week-0 storage series reported slightly different means (3.66 versus 3.52 N/cm for adhesion; 2.47 versus 2.49 N/cm for peel strength; and 0.42 versus 0.50 mm/min for shear displacement). The available records do not establish whether the two series originated from the same manufacturing batch; therefore, these values should not be interpreted as a direct within-batch change.

No commercial reference plaster or product-specific acceptance criterion was included in this study. Accordingly, the verification result of 3.66 N/cm demonstrates the measured response of the selected formulation and its descriptive agreement with the model prediction; it does not establish equivalence to a marketed product or clinical adequacy for medical use.

Table 2. Optimal formulation: modeled predictions versus experimental verification.

Response	Prediction[1]	Verification[2]
Adhesion (N/cm)	3.797	3.66 ± 0.14
Peel strength (N/cm)	2.528	2.47 ± 0.06
Shear displacement (mm/min)	0.414	0.42 ± 0.03

[1]Model-predicted values for selected Solution 1 in Design-Expert; [2]confirmation values are mean ± SD (n = 3), based on three replications.

Eight-week physical stability

During the eight-week accelerated-storage period at 40 °C/75% RH, mean adhesion decreased from 3.52 ± 0.03 to 3.16 ± 0.06 N/cm (approximately 10.2%), and peel strength declined from 2.49 ± 0.02 to 1.93 ± 0.07 N/cm (approximately 22.5%). Conversely, shear displacement increased from 0.50 ± 0.04 to 0.95 ± 0.15 mm/min (approximately 90.0%), indicating reduced resistance to sliding under the test conditions. Figure 1 illustrates the time-dependent changes in the three mechanical responses. Thus, the selected composition did not maintain constant mechanical performance over the observation period. Only mechanical properties were monitored during storage; pH, viscosity, appearance, and moisture content were not reassessed at the weekly time points.

The reported one-way ANOVA indicated an effect of observation time on adhesion ($F = 15.70$; $p < 0.001$), peel strength ($F = 31.98$; $p < 0.001$), and shear displacement ($F = 5.83$; $p = 0.001$). These inferential results should be interpreted cautiously because the available records do not specify whether the three determinations at each time point were independent specimens, independent batches, or repeated measurements on the same specimens. The time-dependent changes differ from the six-month evaluation reported for the distinct PVPAA/PMVEMA water-based patches developed by Arunprasert et al. [7]. A direct comparison is not appropriate because the polymer matrices, formulation components, substrates, and storage protocols are not equivalent. Rather, the findings emphasize that storage performance is formulation-specific and must be established for each adhesive system. Similar changes in adhesive properties may arise from storage exposure and changes in cohesive behavior [4,14,17]. The present observations describe mechanical changes under the selected eight-week accelerated-storage condition; because packaging configuration and replicate independence were not documented, they cannot support a shelf-life estimate.

Interpretation and study limitations

A desirability value of 1.000 indicates that the specified optimization goals were simultaneously achieved within the examined design space; it does not establish clinical suitability or environmental superiority. This work was limited to laboratory-scale formulation and mechanical testing on stainless-steel substrates. No commercial reference product or pre-established product-specific acceptance criteria were

used. The optimized adhesive was stored for eight weeks at 40 °C/75% RH; however, the packaging configuration was not documented. The conditioning conditions of 23 ± 2 °C and 50 ± 6% relative humidity described for mechanical testing are distinct from the accelerated-storage condition. In addition, the records do not establish whether the confirmation and week-0 storage samples came from the same batch, or whether replicate determinations were independent specimens or batches. Only mechanical properties were monitored during storage; pH, viscosity, appearance, and moisture content were not reassessed. Cytotoxicity, irritation, sensitization, removal-related skin trauma, solvent-emission reduction, and life-cycle impacts were not experimentally assessed. These are distinct considerations in the development of skin-contact adhesives [2,3,5,20]. Future studies should evaluate longer-term storage, document packaging, use independent batches, apply predefined product-specific acceptance criteria, include a suitable reference product, and conduct comprehensive physicochemical and skin-biocompatibility testing before clinical suitability or shelf life is considered.

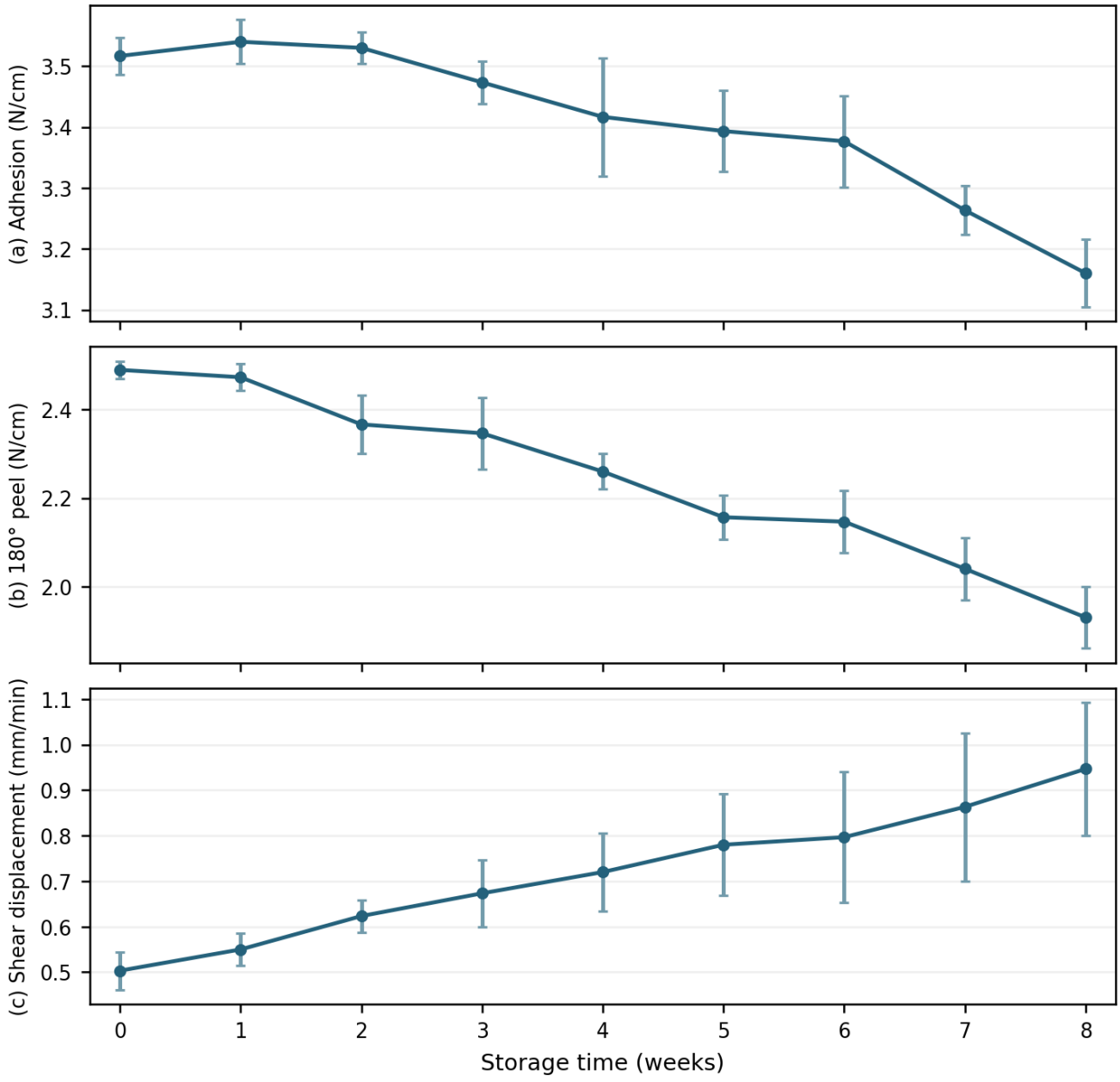


Figure 1. Weekly adhesion, 180° peel strength, and shear displacement of the optimized adhesive during eight-week storage at 40 °C/75% RH.

Conclusion

The two-component SLD procedure identified a laboratory-scale water-based medical-plaster adhesive composition containing 5.450% w/w polybutene and 2.550% w/w sodium phosphate that balanced adhesion, 180° peel strength, and shear displacement under the selected model-based optimization criteria. The confirmation measurements were descriptively close to the model predictions. However, the available records do not establish whether the confirmation and week-0 storage samples came from the same batch or whether replicate determinations were independent specimens or batches. During eight weeks of accelerated storage at 40 °C/75% RH, adhesion and peel strength decreased, while shear displacement increased. Because only mechanical properties were monitored at one accelerated-storage condition and packaging configuration was not documented, the study does not establish comprehensive physical stability, shelf life, or clinical suitability. Longer-term stability studies and skin biocompatibility assessment are required before clinical application can be considered.

Materials and Methods

Materials, experimental setting, and mixture design

The experiment was performed between April and June 2026 at the research and development facility of PT Beiersdorf Indonesia, Malang Regency, East Java, Indonesia. Materials comprised latex smoked sheet (RSS), polybutene, Harz-100 resin, lanolin, zinc oxide, sodium phosphate, and distilled water. The fixed components were latex RSS (4.2%), Harz-100 resin (1.3%), lanolin (10.2%), and zinc oxide (8.8%) by weight. Polybutene and sodium phosphate concentrations followed the mixture design presented in Table 1, with distilled water added to achieve 100% w/w. Eight experimental runs were conducted, representing six unique mixture compositions because F1, F3, and F5 were repeated design points at 5.2% w/w polybutene and 2.8% w/w sodium phosphate.

Preparation and physical evaluation

The adhesive ingredients were dispersed and mixed in an aqueous phase using a homogenizing mixer. Mixing was conducted at 70–80 °C, followed by a holding stage. The mixture was coated onto a backing substrate at a target thickness of 0.5–1.0 mm and dried at 80–100 °C for approximately 5 min. Viscosity was measured with a rotational viscometer using approximately 30 g of sample, spindle 70, and a rotational speed of 30 rpm.

Adhesion and peel testing

Mechanical specimens were conditioned at 23 ± 2 °C and 50 ± 6% relative humidity before testing. These conditions describe specimen conditioning for mechanical measurements and are distinct from the accelerated-storage condition (40 °C/75% RH) used during the eight-week observation period. For adhesion measurements, specimens were applied to stainless-steel panels, pressed using a roller, and measured with a universal testing machine. For peel testing, specimens were attached to stainless steel, kept in contact for at least 30 min, and detached at 180° at 500 mm/min. Forces were reported in N/cm. Three measurements per formulation were tabulated; the source records do not specify whether these measurements represented independent specimens or independently prepared batches. Adhesive bandage performance is sensitive to the test substrate and procedural choices [3].

Shear test, numerical optimization, and statistics

For the shear test, a specimen covering approximately 1 × 1 in^2 was attached to a vertically mounted stainless-steel panel and subjected to a 1,000-g load. Shear performance was expressed as displacement rate (mm/min); this study-specific endpoint is not interchangeable with shear holding time or force-to-failure endpoints. Formulation data were analyzed in Design-Expert version 13 using an SLD mixture model, ANOVA, lack-of-fit assessment, and multiresponse desirability optimization [10,18,19]. Adhesion and 180° peel strength were assigned goals for maximization, whereas shear displacement rate was assigned a goal for

minimization. The selected optimal composition was prepared for confirmation testing and assessed using three reported determinations. Between-formulation pH and viscosity responses and storage-time effects were evaluated by one-way ANOVA, with $p < 0.05$ considered statistically significant. Because replicate independence was not specified in the source records, inferential results are interpreted as exploratory.

Stability observations

The optimized adhesive was stored at 40 °C/75% RH and evaluated at weeks 0–8. Three determinations of adhesion, peel strength, and shear displacement were reported at each of the nine observation times. Results are expressed as mean ± sample standard deviation. The effect of observation time on each response was evaluated using one-way ANOVA. The source records do not specify whether the three determinations at each time point were independent specimens, independent batches, or repeated measurements on the same specimens. The packaging configuration was not documented. Because only mechanical properties were monitored, these data characterize changes in mechanical performance under the selected accelerated-storage condition and are not used to estimate shelf life.

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