

Shear Strength Optimization of Brake Pad Adhesive Layer Using Statistical Design Approach

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Abstract

The shear strength of brake pad adhesive layers is a critical factor that affects the brake performance and safety. This study examined the effects of retention time (0–24 h), adhesive thickness (1–3 layers), and solvent ratio (10–20%) on shear strength using response surface methodology (RSM) with a central composite design (CCD). Analysis of variance revealed that among the main variables, only retention time had a statistically significant effect on shear strength. Nevertheless, the combination of solvent ratio with retention time, as well as solvent ratio with adhesive thickness, played an important role in the shear performance. A second-order quadratic model was developed to represent these effects and provide accurate predictions of shear strength. The proposed model shows strong predictive ability, with a determination coefficient (R^2) of 0.82, indicating that the selected factors and their interactions account for 82% of the variation in shear strength. The process parameters optimization showed that the highest cold shear strength of 3.55 MPa can be achieved with a solvent content of approximately 15%, a single adhesive layer (about 60 μm), and zero retention time. These findings emphasize the importance of both individual effects and interactions, and show that careful control of process parameters can significantly enhance the shear strength of the adhesive line in brake pad production.

Keywords: Brake pad adhesive; Design of experiments; Shear strength; Process optimization; Retention time

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1. Introduction

Shear strength is a key indicator of brake pad quality and has a direct effect on the performance and safety of the final product [1, 2]. Several factors influence the strength and durability of adhesive-bonded joints [3]. However, removing the contaminants such as oils and greases can provide a high initial bond strength, proper surface preparation remains one of the most critical parameters. In addition to surface condition, the adhesive itself and its thickness play an important role. Previous studies show that the joint strength tends to increase as the adhesive layer becomes thinner, which shows the mutual importance of material properties and application parameters [4–6].

The shear-bond strength between the friction material and the backing plate is a critical factor in brake pad performance, as it directly affects the structural integrity, safety, and wear characteristics during braking operations. Insufficient bond strength can lead to delaminate, reduce efficiency, and cause early failure

of the pad under high loads or thermal stresses. Therefore, maintaining optimal shear-bond strength is essential for both performance and long-term reliability of NAO (Non-Asbestos Organic) brake pads. Factors that affect this strength include material composition, surface treatment, and curing processes, which can significantly affect the overall effectiveness of the braking system [7, 8]. Pupan and coworkers (2017) examined the effect of post-curing temperature and surface treatment on the shear-bond strength of NAO brake pads. They found that higher molding temperatures improved bond strength, while excessive post-curing reduced adhesion. They also reported that aluminum back plates showed better bonding than steel, and smoother surfaces enhanced adhesion compared to more rough ones [7]. Pereira and coworkers (2010) investigated the shear strength of single-lap aluminum adhesive joints and the effect of surface preparation. Their results showed that proper surface treatment, including sulfuric acid–sodium dichromate (CSA) and abrasive polishing (AP), significantly improved shear-bond strength, and reduced surface roughness further enhanced joint performance [9].

da Silva et al. (2009) studied the effects of material type, joint geometry, surface preparation, and environmental conditions on the shear strength of single-lap adhesive joints. They found that accurate choice of materials, joint design optimization, and effective surface treatment improve bond performance and durability and give valuable insights for automotive applications [6].

In addition, the conditions during molding and pressing play an important role in the final properties of brake pads [10, 11], so optimization of both formulation and process can significantly enhance shear strength [12]. The type of adhesive and the method of its application are also important. Phenolic resole adhesive, a thermosetting resin with high thermal resistance produced from phenol and formaldehyde under basic conditions, and cardanol resins are widely used in brake pad production [13]. Besides, design parameters affect the mechanical behavior of adhesively bonded joints [14]. Factors such as adhesive viscosity, retention time before pressing, adhesive thickness, pressing temperature, pressure, and curing time all determine how well the composite bonds to the back plate [6, 7, 15]. Among these, pressing and curing conditions were previously selected to achieve optimal tribological properties, including normal and hot friction coefficients and wear resistance [16-20]. As a result, retention time, adhesive thickness or number of layers, and solvent content in the adhesive were chosen for present investigation. In this study, these parameters were systematically examined to determine their effect on the shear strength of the adhesive line in brake pad production.

2. Materials and Methods

2.1. Materials

The formulation of friction materials includes binders, reinforcing fibers, fillers, friction modifiers, and abrasives [21, 22]. In this study, a non-asbestos semi-metallic composition was obtained from the production line (Remapuya Company, Iran) to ensure industrial relevance. The investigated semi-metallic brake pad formulation generally consists of reinforcements including metallic fibers, iron powder, and aramid fibers at approximately 40–50 wt.%, a phenolic resin binder at about 6–9 wt.%, fillers such as barite, vermiculite, and friction dust at roughly 35–40 wt.%, and graphite as a solid lubricant in the range of 7–10 wt.%. In this work, a local phenolic resin-based adhesive was applied to bond the brake lining to the back plate. The adhesive is a brown liquid with a viscosity of 80–100 cP and a density of 1.55 g/cm³ that can resist temperatures up to 600 °C and remains effective in range of 180 to 220 °C. It is insoluble in water and was diluted with solvent. In this survey, methanol at concentrations of 10, 15, and 20% was used for adhesive dilution. It was distributed uniformly on the cleaned back plate surface after removing any dust, grease, or contaminants. The adhesive coated back plates were used for lining pressing after retention times of 0 h (immediately after coating), 12 h, and 24 h at room temperature.

2.2. Procedure for Adhesive Bonding of Back-Plates

To investigate the effects of adhesive application on back-plate

performance, a systematic experimental procedure was designed. The factors and their related responses are summarized in Table 1. In this survey, three factors were studied at three coded levels (-1, 0, +1) and retention time varied from 0 to 24 h, thickness from 1 to 3 layers, and solvent ratio from 10% to 20%.

Table 1. Experimental design factors with coded levels and actual ranges.

Factor name	Level -1	Level 0	Level +1
Retention Time (h)	0	12	24
Thickness Layers	1	2	3
Solvent Ratio (%)	10	15	20

2.3. Experimental design approach

Given the large number of experiments that would be required using a full factor approach (27 tests), the experimental design was developed with Design-Expert software. This design allowed systematic evaluation of main factors as well as their effects on shear strength. In this study, RSM was used to explore how the response depends on key process variables. Based on statistical analysis of the experimental data, a polynomial model including linear, interaction, and quadratic effects was proposed, as shown in Eq. (1):

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Using RSM, both linear and second-order models were built to show how process variables and their interactions influence the response [23].

2.4. Brake pads sample preparation

The mixtures were hot pressed at 170 °C under 100-ton force for 5 minutes to achieve proper characteristic. The specimens were then post-cured in a controlled oven, with the temperature gradually raised from 140 °C to 180 °C over 8 h. This step ensured complete binder curing and improved the structural integrity of the composites [24]. To carry out the experiments, the base adhesive was diluted with methanol to concentrations of 10, 15, and 20%. Depending on the number of layers specified by the experimental design (Table 2), the adhesive was applied multiple times using a coating roller as shown in Figure 1. Retention time was set immediately after adhesive application at 0, 12, and 24 h. Finally, the cold shear strength of the samples was measured after sample curing and the results were compared.

2.5. Shear strength test

To assess how well the brake pad composites were bonded, shear tests were performed at room temperature according to ISO-6312 [1, 25, 26]. Each sample was placed in a shear fixture, and a side force was applied at a loading rate of 4500 N/s until the friction layer completely detached from the steel backing plate. The shear strength was calculated by dividing the maximum force recorded at failure by the bonding area, which was determined from the measured dimensions of the sample.

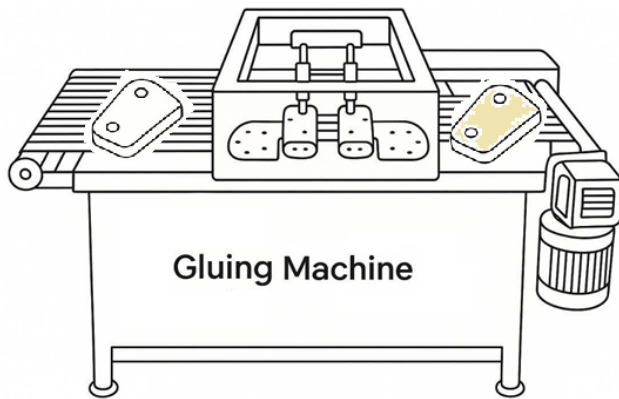


Figure 1. Schematic of the automatic brake lining back plate gluing machine

3. Results and Discussion

3.1. Visual Observations and Surface Adhesion Assessment

Figure 2 shows various samples of back plates coated with adhesive at different concentrations, with a retention time of 12 h and varying numbers of layers after application and following the shear strength test. The results of the back plate surface coverage show that in all cases complete adhesion of the material to the back plate was maintained after the shear strength tests, which indicates the strong bonding capability of the adhesive.

Table 2. Experimental design and shear strength results of samples

Std	Retention Time (h)	Thickness Layer	Solvent Ratio (%)	Shear Strength (MPa)
1	0	1	10	3.4
2	24	1	10	3.37
3	0	3	10	3.22
4	24	3	10	2.98
5	0	1	20	3.43
6	24	1	20	3.05
7	0	3	20	3.55
8	24	3	20	3.09
9	0	2	15	3.27
10	24	2	15	3.18
11	12	1	15	3.33
12	12	3	15	3.36
13	12	2	10	2.98
14	12	2	20	2.95
15	12	2	15	3.02
16	12	2	15	3.13
17	12	2	15	3.3

3.2. Evaluation of Shear Strength with ANOVA

In this study, the effect of three variable including retention time (RT), adhesive thickness (Thick.), and solvent ratio (SR) on the adhesive line shear strength was studied. As shown in Table 2. the highest shear strength (3.55 MPa) was achieved with 0 h retention time, 3 adhesive layers, and 20% solvent ratio, while a similarly high value (3.4 MPa) was obtained with 0 h retention time, a single layer, and 10% solvent ratio, which demonstrates that strong bonding can be obtained either with a thicker layer and higher solvent or with a thinner layer and lower solvent content. The lowest shear strength (2.95 MPa) was recorded at 12 h retention time, 2 layers, and 20% solvent ratio. These findings emphasize the interactive effect of the factors, and show that adhesive performance depends not only on individual variables but also on their combinations. This results highlights the importance of simultaneous evaluation of variables and their interactive effect.

As shown in Table 3. analysis of variance indicated that the overall model for the prediction of the shear strength of the adhesive bond was significant ($F=5.896$, $p=0.0085$) and lack of fit in not significant ($F=0.397$, $p=0.8501$). Among the variables investigated, retention time had a significant effect on shear strength ($F=13.63$, $p=0.005$), while adhesive thickness and solvent ratio showed no significant linear effects ($p>0.05$). However, quadratic effects of retention time and solvent ratio, as well as the interaction between thickness and solvent ratio, were significant ($p<0.05$). The interaction between retention time and thickness (AB) and the quadratic term of retention time (A^2) were not significant and therefore removed from the final model. A multiple regression model was developed to predict the shear strength of brake pad adhesive layer based on three key factors. The resulting model, derived from ANOVA analysis, is expressed as Eq. (2):

$$\text{Shear strength (MPa)} = 3.28 + 7.81 \times 10^{-3} \text{RT} - 1.25 \text{Thick.} + 0.15 \text{SR} - 1.18 \times 10^{-3} (\text{RT} \times \text{SR}) + 0.018 (\text{Thick.} \times \text{SR}) + 0.234 \text{Thick.}^2 - 5.83 \times 10^{-3} \text{SR}^2 \quad (2)$$

Table 3. ANOVA for shear strength of produced brake pads

Source	Sum of Squares	df	Mean Square	F Value	P value
Model	0.436	7	0.0623	5.896	0.0085
A-Retention Time	0.144	1	0.144	13.63	0.0050
B-Thickness	0.0144	1	0.0144	1.367	0.2724
C-Solvent Ratio	0.0014	1	0.0014	0.136	0.7205
AC	0.0406	1	0.0406	3.844	0.0816
BC	0.0666	1	0.0666	6.305	0.0333
B ²	0.1663	1	0.1663	15.742	0.0033
C ²	0.0643	1	0.0643	6.082	0.0358
Residual	0.0951	9	0.0106		
Lack of Fit	0.0553	7	0.0079	0.397	0.8501
Pure Error	0.0398	2	0.0199		
Cor Total	0.5311	16			

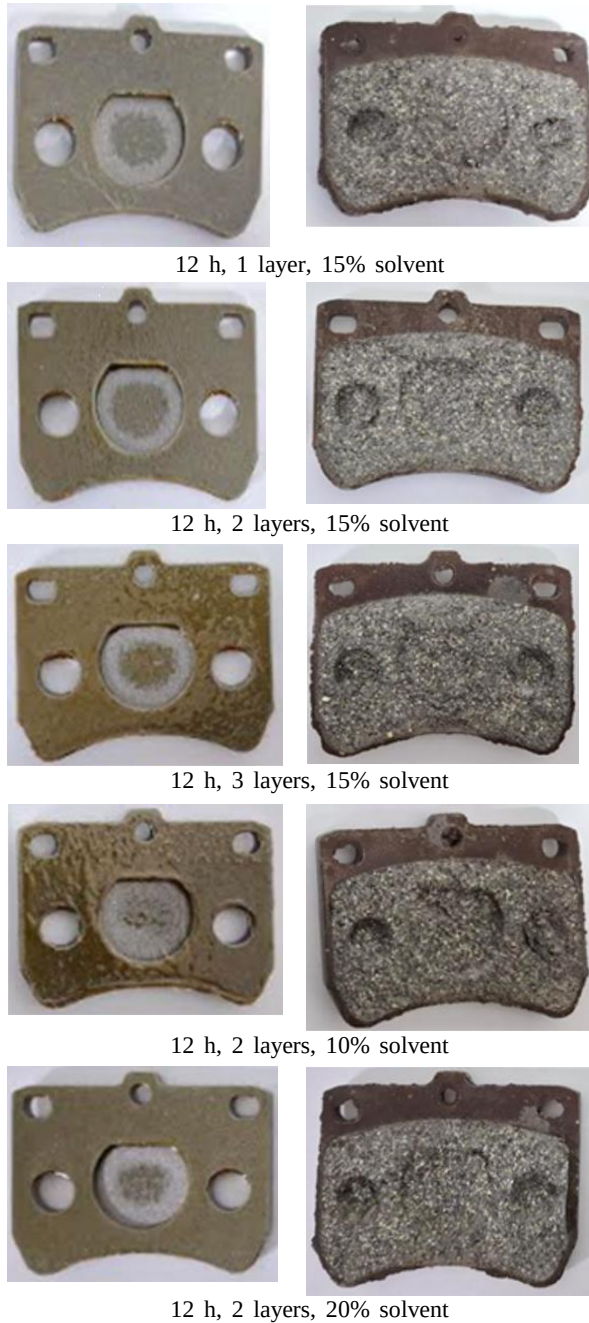


Figure 2. Back plate samples with adhesive and composite residue after the shear strength test at various retention time, adhesive thickness and solvent ratio

The proposed model exhibits strong predictive capability, with a coefficient of determination (R^2) of 0.82, indicating that 82% of the variability in shear strength can be explained by the selected factors and their interactions. Both linear and quadratic effects, as well as two-factor interactions, were found to significantly influence the adhesive performance. This model provides a quantitative basis for optimization of process parameters to maximize the shear strength of brake pad adhesive layers.

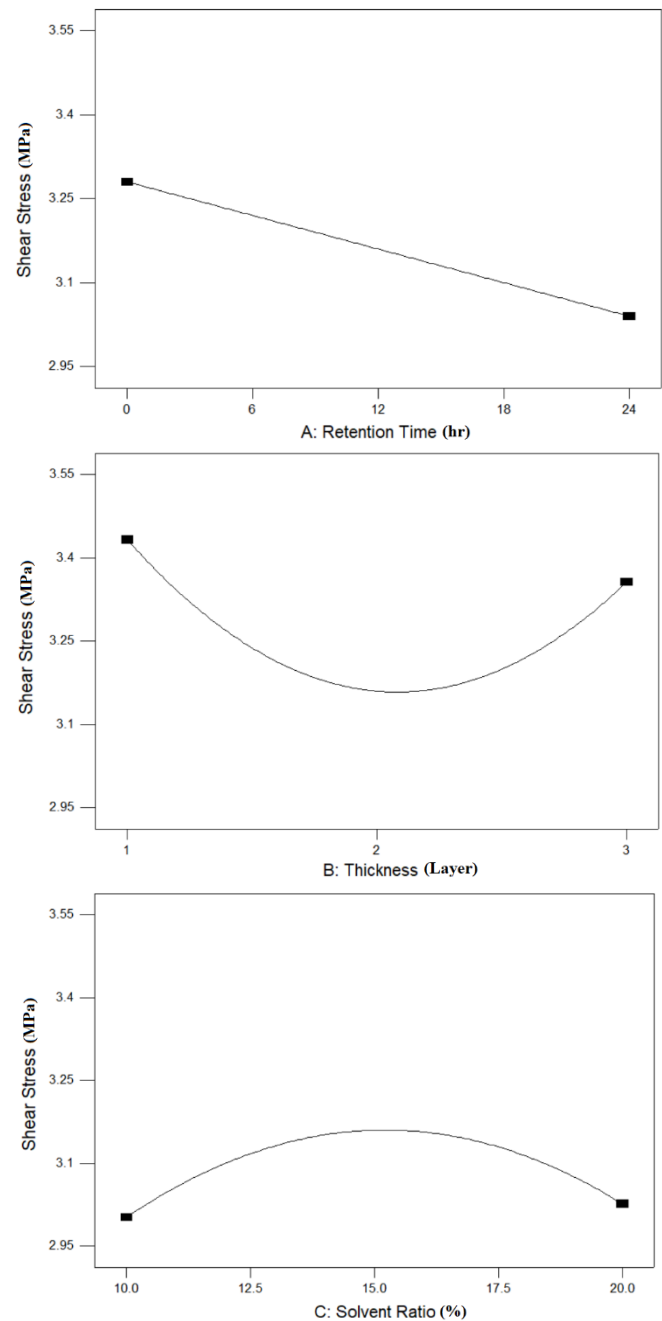


Figure 3. Variables effect of retention time (a) thickness (b) solvent ratio (c) on glue line shear strength

3.3. Individual Parameters Effect on Adhesion Performance

According to Figure 3, shear strength of the selected adhesive was tested under different conditions. In Figure 3a, shear strength decreased from 3.28 MPa at 0 h to 3.0 MPa after 24 h, which shows a decrease in bonding with longer retention. Figure 3b illustrates the effect of number layers of adhesive on the back plate affects performance. According to the results, a single layer led to shear strength of 3.4 MPa, then decreased slightly,

and reached 3.36 MPa with three layers. This suggests that one layer has a best bonding performance. Overall, Figure 3 highlights the dependence of shear strength on processing conditions. Longer retention times tend to weaken the adhesive interface, likely due to structural changes such as solvent evaporation or molecular relaxation within the adhesive layer. In addition, increasing the number of adhesive layers does not result in improved bonding performance; instead, excessive adhesive thickness may limit effective stress transfer and promote internal imperfections. These results emphasize the importance of optimizing processing parameters rather than increasing material usage to achieve reliable and durable adhesive joints. Similarly, Adams and Peppiatt suggested that thicker adhesive layers tend to reduce the strength of the connection because they are more prone to flaws such as voids and micro-cracks [5]. Also, previous studies reported that thicker adhesive layers show higher interface stresses [6, 27]. In another research, Grant et al. reported that as the adhesive layer becomes thicker, the bending stress also rises due to the larger bending force, which leads to a reduction in the overall strength of the connection [28]. Figure 3c presents the effect of methanol concentration as a solvent, where shear strength increased from 10% to 15% methanol, then decreased at higher amounts, which emphasizes the key role of solvent content in achieving the best adhesion.

3.4. Interactive Effects of Variables on Shear Strength

According to Figure 4., the interaction plots show that solvent ratio affects retention time and adhesive thickness differently in relation to the shear strength of the brake pad adhesive joint. The highest shear strength occurred at a retention time of 0 h, meaning immediately after adhesive application, for both 10% and 20% solvent ratios. As the retention time increased, shear strength dropped clearly, with the reduction being most evident at the higher solvent ratio of 20% (red line). At 10% solvent (black line), shear strength is slightly decreased as retention time is increased, whereas at 20% solvent, the initial strength is higher but it is decreased more sharply when retention time is extended. In the case of adhesive thickness, both solvent levels show higher shear strength at thinner layers (1 layer), a decrease at moderate thickness (2 layers), and an increase again at thicker layers (3 layers). Overall, the interaction between adhesive thickness and solvent ratio shows that the two factors work against each other, and the best performance was achieved with a single adhesive layer at the lower solvent ratio of 10%. However, statistical analysis confirms that only retention time has a significant effect on shear strength, while solvent ratio and adhesive thickness do not have meaningful impacts. In the other word, the surface plots clearly show that retention time has the strongest impact on shear strength, with longer times consistently reducing performance. While solvent ratio and adhesive thickness do affect the trends, their influence is relatively minor. This highlights that careful control of retention time is key to achieving strong and reliable adhesive bonding.

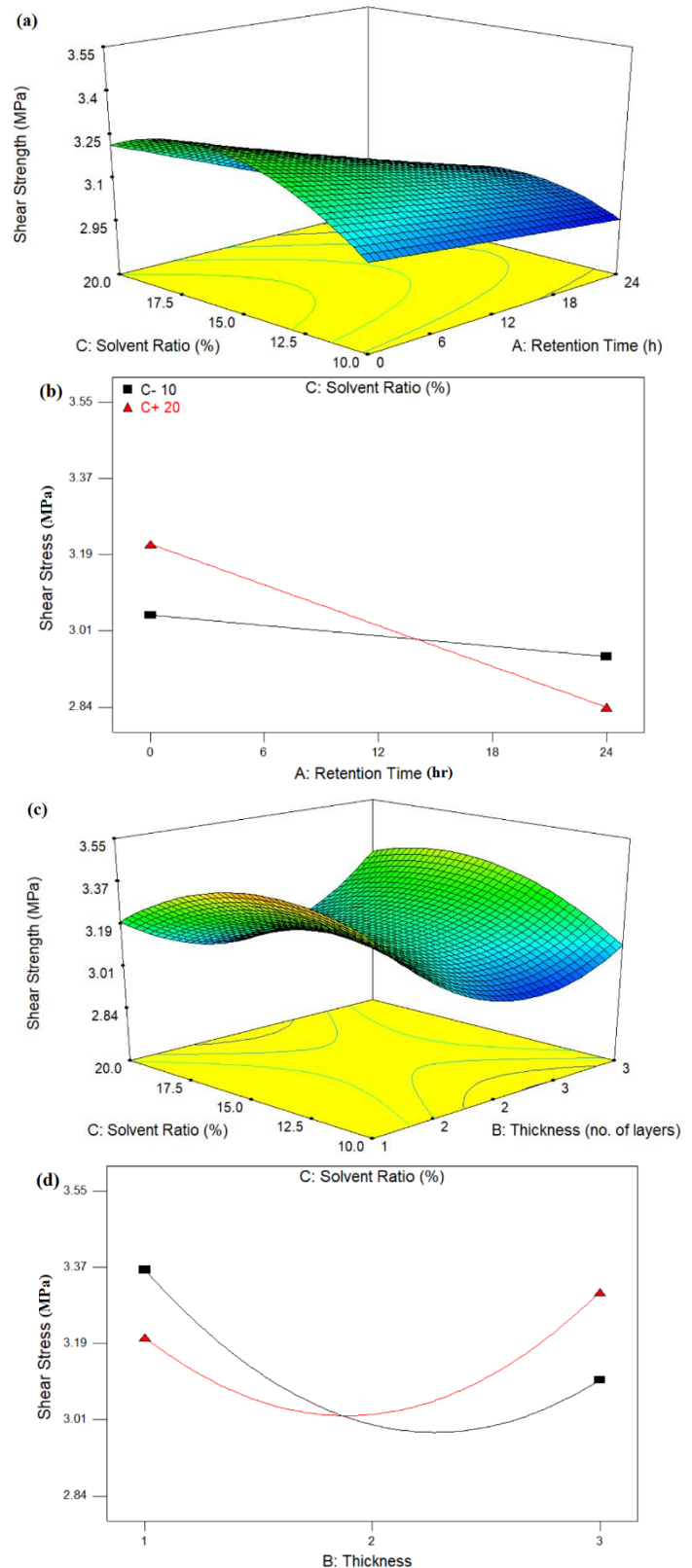


Figure 4. 3-D plots and interaction of parameters on shear strength (a,b) retention time $\times$ solvent ratio (c,d) thickness $\times$ solvent ratio

3.5. Parameter Optimization for Maximum Shear Strength

As shown in Figure 5, the highest cold shear strength of 3.55 MPa is achieved at a solvent content of approximately 15%, with a single adhesive layer (about 60 μm) and no retention time. These findings suggest that for the selected adhesive in this study, achieving maximum performance requires not only the correct solvent level but also precise control over adhesive layer application and immediate use after application to prevent early strength loss. It should be noted that the optimal conditions may vary with adhesives of different compositions or properties.

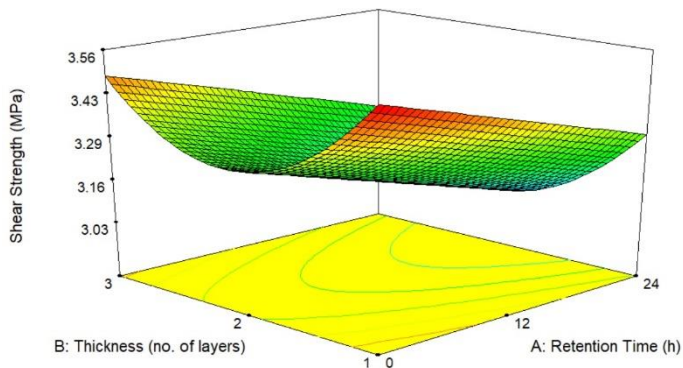


Figure 5. 3D surface plot for shear strength optimization

3. Conclusions

This study highlights the critical influence of process parameters on the shear strength of brake pad adhesive layers. Statistical analysis indicated that retention time is the most significant factor can affect the adhesion process, while interactions between solvent ratio and retention time, as well as solvent ratio and adhesive thickness, also play a key role in the performance. A second-order quadratic model effectively represented these relationships and provided reliable predictions. Overall, the findings show that control of process parameters with consideration of both individual and interactions effects, can significantly improve the adhesive performance of brake pad materials. It is important to note that the results of this study are strongly related to the specific adhesive formulation tested. In real manufacturing conditions, some adhesives require at least 24 hours of retention after application to achieve full bonding strength. Therefore, these findings should not be considered broadly relevant to all adhesive systems. The main purpose of this work is to highlight the role of process parameter interactions and to provide a basis for future studies that take into account the wide range of adhesives used in brake pad production. The results of this research offer a practical approach to improve brake pad manufacturing processes and achieve consistent, reliable performance in real-world applications.

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Nomenclature

Y	: measured response
X_i	: main variable i
X_j	: main variable j
β_0	: intercept
β_i	: linear effects
β_{ii}	: quadratic effects
β_{ij}	: interaction effects
ε	: random error

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRedit Author Statement

Ali Partovinia: Investigation, Methodology, Conceptualization, Supervision, Software, Formal Analysis, Writing, Review and Editing the paper.

Zahra Shamsollahi: Investigation, Methodology, Formal Analysis, Validation.

Declaration of Generative AI in the Writing Process

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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