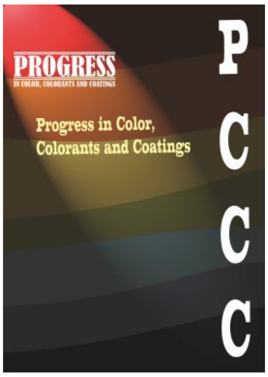

# Title: Enhancing Automotive Bumper Performance through Advanced Materials, Surface Treatments, and Design Optimization

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# Enhancing Automotive Bumper Performance through Advanced Materials, Surface Treatments, and Design Optimization

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## Abstract

Automotive bumpers play a critical role in vehicle safety by absorbing impact energy. Polypropylene (PP) composites reinforced with ethylene propylene diene monomer (EPDM) rubber are widely used for their flexibility and impact resistance. However, low surface energy limits coating adhesion. In this study, flame treatment was systematically optimized using Box-Behnken design and Response Surface Methodology (RSM) to enhance surface and adhesion performance of PP/EPDM bumpers. Effects of air pressure inside the cabin, flame gas pressure, flame/surface gap, and treatment time were evaluated for surface tension, adhesion strength, moisture and immersion resistance, and high-pressure wash durability. Results indicated that flame/surface gap, treatment time, and flame gas pressure were the most influential factors. The optimal conditions—10 cm gap, 120 s treatment, and 200–220 mbar flame pressure—simultaneously improved physical and chemical responses. These findings provide a practical guideline for industrial applications, improving coating durability and bumper performance through controlled surface modification and design optimization.

**Keywords:** Automotive bumper, PP/EPDM composites, Flame treatment, Impact resistance, Design of Experiments.

## 1. **Introduction**

The production of automobiles is increasing globally. Among the various components of a vehicle, the bumper stands out as a vital element of the car body, performing an essential protective role. Understanding the structure, function, and types of bumpers is crucial to appreciating their significance in enhancing vehicle safety[1]. Bumpers are typically constructed from lightweight and durable materials, such as engineered plastics or composites. These materials are specifically chosen for their ability to absorb energy during collisions, thereby mitigating the transmission of impact forces to sensitive parts of the vehicle. This energy absorption capability is critical in protecting both the vehicle structure and its occupants [2].

In recent years, with the rise in public awareness of vehicle safety, along with increased legal regulations and mandatory standards imposed on car manufacturers, enhancing vehicle performance and safety in accidents has become a key focus within engineering research. This shift reflects a broader commitment to improving road safety through innovative design and technology [3]. The geometry of the bumper, along with the materials utilized in its construction, significantly affects its ability to absorb and dissipate energy during a collision. Therefore, thorough research into and application of suitable materials and design compounds are essential for enhancing the durability and effectiveness of bumper components [4].

Polypropylene and EPDM (Ethylene Propylene Diene Monomer) compounds are extensively employed in the manufacturing of flexible, impact-resistant components. The flexibility of polymer alloys exhibits an inverse relationship with their hardness: as hardness decreases, flexibility and impact resistance tend to increase. The degree of flexibility in the final product is strongly influenced by the proportion of additives incorporated during production [5].

Low surface coverage of PP/EPDM shield parts can result in inadequate adhesion of the colored layers, which may compromise the aesthetic quality and durability of the final product. To address this issue, it is essential to evaluate and improve the surface coverability during the film application process. Several process factors influence coverability, including surface roughness, application temperature, film thickness, pressure applied during coating, and pre-treatment methods. Adjusting these parameters can significantly impact the degree of coverage and adhesion quality [6].

Other surface modification techniques, such as plasma treatment, corona discharge, and chemical treatments, have been reported to improve the adhesion of PP/EPDM composites. However, flame treatment is particularly attractive for automotive applications due to its cost-effectiveness, simplicity, and scalability. Comparative studies with these methods are suggested for future research. Flame treatment is a widely employed surface modification technique to improve the adhesion performance of polymeric materials such as polypropylene (PP) and EPDM rubber. This process utilizes high-temperature flames to chemically alter the surface, thereby promoting better bonding with paints, adhesives, or coatings [7].

Extensive studies and research on propylene/rubber alloys have demonstrated that these materials exhibit significant flexibility. The addition of rubber particles has been shown to increase the impact strength of polypropylene, enhancing its toughness. The softening temperature, or brittle-to-flexible transition temperature, depends on multiple factors, including the substrate’s nature, the microstructure of the alloy, and test conditions. The deformation mechanisms in rubber-toughened polypropylene are primarily attributed to yielding and microcracking, which contribute to the material’s improved toughness and impact resistance [8].

Nikzad et al. [9] reported the development of polypropylene (PP)-based composite materials for the fused filament fabrication (FFF) process with the aim of enabling the application of fully automated robotic repair of plastic components in the automotive industry. The results for components manufactured from polypropylene-based materials showed that the addition of ethylene propylene diene monomer (EPDM) successfully modified the matrix and produced an ideal composite material for surface repair, which is important in the automotive manufacturing industry.

Haji Babazadeh et al. [10] performed a detailed fracture analysis of ternary polypropylene/ethylene-propylene-propylene-diene monomer rubber/nano-silica (PP/EPDM/$SiO_2$) nanocomposites using both Izod impact and quasi-static fracture tests. In this work, the phase morphology and fracture surfaces were evaluated using scanning electron microscopy. Morphological observations showed that SiO2 nanoparticles were mainly located around EPDM particles or at the PP/EPDM interface. The results suggest that there is a synergistic effect between soft EPDM rubber particles and rigid SiO2 filler on the activation of different toughening micromechanisms, such that the impact strength of ternary systems is significantly higher than that of the corresponding binary blends.

Mitchell [11] investigated the deformation mechanisms of rubber-toughened polypropylene at -40 °C and reported that the dominant failure mechanism was microcracking. Lopez et al. [12] showed that in polypropylene/rubber alloys, two mechanisms of cracking and yielding occur simultaneously. It has been shown that the deformation mechanism in polypropylene/ethylene propylene diene monomer alloys is dependent on the size of the rubber particles. Thus, particles of about half a micron in size lead to the initiation of crack growth, while particles larger than this size lead to the occurrence of the yield mechanism. Deformation in these alloys is accompanied by the phenomenon of stress whitening, which occurs due to the cavitation phenomenon in this system.

A study by Vanderwaal et al. [13] has been conducted on the effect of test speed on the deformation mechanism of polypropylene toughened with ethylene propylene diene monomer. In the study, the presence of a single layer of cavitation (1) in brittle failure and three layers of (1) cavitation, (2) yielding, and (3) relaxation below the fracture surface of the specimen in the ductile failure mode was observed.

Holden et al. showed in a study that the special feature of these alloys, also called polyolefin thermoplastics (TOP), is that they exhibit rubber-like behavior (elasticity, etc.) while undergoing the same processing as thermoplastics. However, to achieve a product with appropriate hardness, the use of fillers seems necessary; however, since reinforcement with conventional fillers requires the use of high filler percentages, which, in addition to increasing weight, also reduces other alloy performances [14], the use of nanoparticles or alloying with another suitable polymer seems to be a more reasonable solution.

Wu et al. stated in a study that to obtain the desired toughness in polypropylene, it is necessary for the ethylene propylene diene monomer particles to be dispersed in the polypropylene matrix in sizes of 0.3–0.5 microns. In immiscible alloys, such a dispersion can be achieved when the viscosity of the substrate and the dispersed component are close to each other [15]. Therefore, to achieve the appropriate microstructure in the polypropylene/ethylene propylene diene monomer alloy, since the melt viscosity of the rubber component is much higher than that of polypropylene, it is necessary to use polypropylene with a high molecular weight.

To systematically optimize these factors, the use of experimental design software—such as Design of Experiments (DoE) tools—allows for the efficient exploration of the multiple variables involved. By applying a structured experimental approach, it is possible to identify the combination of process parameters that maximizes surface coverability.

In this study, the coating ability of PP/EPDM shield parts prepared by the flame method is investigated using experimental design. Although previous studies have used a PP/EPDM combination, in this study, experimental design software will be used to optimize each of the parameters, which can make the method more accurate and provide strong confirmation of the results reported in this study. Given that most polyolefins and polymer composites that are used in industry have low surface free energy and lack polar functional groups on their surface, which has led to poor adhesion properties, there has been a strong research motivation to understand polymer adhesion and the growing needs of the automotive industry for better adhesion of components and surface coatings. Therefore, recent research has focused on polymer adhesion with special focus on adhesion mechanisms. It is worth noting that many studies have been done to increase the coverability of the aforementioned bumper parts, but in this study, the desired parameters will be carried out with the help of special software, which, to our knowledge, has not been done so far. In this method, by changing the variables of air pressure inside the cabin, flame gas pressure, flame/surface gap from the flame to the part, and treatment time, and using experimental design software to increase the coverability on the PP/EPDM bumper part.

Unlike previous studies that mainly focus on individual parameters or single-response optimization, this study presents a systematic multi-response optimization of flame treatment for PP/EPDM automotive bumpers using DoE and RSM. In addition, the experiments are performed on real industrial components rather than laboratory-prepared samples, which enhances the practical relevance of the findings. The simultaneous evaluation of mechanical and environmental performance provides a more comprehensive understanding of coating durability, offering a practical process window for industrial applications

## 2. Experimental

### 2.1. Materials

All PP/EPDM sheets were cut from recently manufactured bumper parts and stored under controlled laboratory conditions prior to testing to minimize environmental aging effects. The influence of material history or storage time on surface properties and adhesion was considered negligible.

### 2.2. Methods

### 2.2.1. Flame treatment

Flame treatment was carried out on 10×15 $cm^2$ PP/EPDM sheets that were cut from the original bumper part. In the flame treatment process, four variables, including air pressure inside the cabin, flame gas pressure, flame/surface gap (i.e., the distance between the tips of the flame cones and the PP/EPDM surface), and treatment time at three levels, as shown in Table 1, have been investigated.

Flame treatment modifies the surface by introducing polar functional groups and oxidizing the outermost polymer layer, which enhances surface energy and adhesion without significantly affecting bulk properties. Previous studies have shown that flame treatment can generate carbonyl and hydroxyl groups on polypropylene surfaces, significantly improving coating adhesion.

The flame was generated using a controlled gas system under stable operating conditions. All experiments were performed under identical environmental conditions to ensure reproducibility

**Table 1**: Factors and levels used in the BBD based on RSM

| Factors | Symbol | Unit | Levels | | |
|---|---|---|---|---|---|
| | | | -1 | 0 | 1 |
| **Air pressure inside the cabin** | A | m/s | 0.3 | 0.4 | 0.5 |
| **Flame gas pressure** | B | mbar | 180 | 200 | 220 |
| **Flame/surface gap** | C | cm | 10 | 20 | 30 |
| **Treatment time** | D | s | 60 | 120 | 180 |

## 2.3. Characterization

The resistance of the treated sheets to high-pressure wash was determined based on the PSA D255376 test method. The object of this test is to characterize the resistance of the coating to the action of a high-pressure wash. The moisture strength of the sheets was examined according to the PSA D271571 test method. This test was carried out to determine the resistance of a paint film to the phenomenon of blistering from humidity. The resistance of the treated sheets to water immersion was characterized based on the PSA D231327 test method, and the objective of this test is to determine the resistance of a film to immersion in deionized water. Surface tension and adhesion of the samples were also measured according to the ISO 2409 test method, respectively. Based on Box-Behnken design (BBD), multivariate process optimization has been applied for four parametric variables, namely air pressure inside the cabin, flame gas pressure, flame/surface gap, and treatment time, each at three levels (Table 1).

According to Table 1, the 27th sets of experiments were designed to explore the effects of the chosen parameters on the response variables, surface tension, adhesion, high-pressure wash strength, moisture strength, immersion strength, adhesion after immersion, and humidification. Treatment recipes designed for composite as well as handsheet measured characteristics are given in Table 2.

The optimum point was defined as the case where three physical responses, including surface tension, adhesion strength, and resistance to high-pressure washing (water jet), and two chemical responses, including moisture resistance and immersion resistance of the composite, are simultaneously minimized.

**Table 2**: Experimental design plan based on RSM

| Run | Air pressure inside the cabin m/s | Flame gas pressure mbar | Flame/surface gap cm | Treatment time S | Surface tension mN | Immersion strength | Adhesion | Moisture strength | High-pressure wash strength | Adhesion after humidification | Adhesion after immersion |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.5 | 200 | 10 | 120 | 58 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2** | 0.4 | 180 | 20 | 60 | 48 | 3 | 2 | 3 | 4 | 5 | 5 |
| **3** | 0.4 | 200 | 10 | 180 | 54 | 2 | 0 | 1 | 0 | 2 | 2 |
| **4** | 0.3 | 200 | 30 | 120 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **5** | 0.3 | 180 | 20 | 120 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **6** | 0.4 | 220 | 30 | 120 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **7** | 0.4 | 200 | 30 | 180 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **8** | 0.4 | 200 | 30 | 60 | 48 | 3 | 2 | 3 | 4 | 5 | 5 |
| **9** | 0.4 | 180 | 30 | 120 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **10** | 0.4 | 200 | 20 | 120 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **11** | 0.5 | 200 | 30 | 120 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **12** | 0.5 | 180 | 20 | 120 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **13** | 0.3 | 200 | 20 | 60 | 48 | 3 | 2 | 3 | 4 | 5 | 5 |
| **14** | 0.4 | 220 | 10 | 120 | 58 | 0 | 0 | 0 | 0 | 0 | 0 |
| **15** | 0.4 | 200 | 10 | 60 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **16** | 0.5 | 200 | 20 | 60 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **17** | 0.4 | 180 | 10 | 120 | 56 | 1 | 0 | 0 | 0 | 0 | 0 |
| **18** | 0.4 | 200 | 20 | 120 | 54 | 2 | 0 | 1 | 0 | 2 | 2 |
| **19** | 0.4 | 180 | 20 | 180 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **20** | 0.4 | 220 | 20 | 60 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |
| **21** | 0.5 | 220 | 20 | 120 | 54 | 2 | 0 | 1 | 0 | 2 | 2 |
| **22** | 0.3 | 200 | 10 | 120 | 56 | 1 | 0 | 0 | 0 | 0 | 0 |
| **23** | 0.3 | 220 | 20 | 120 | 54 | 2 | 0 | 1 | 0 | 2 | 2 |
| **24** | 0.4 | 200 | 20 | 120 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **25** | 0.5 | 200 | 20 | 180 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **26** | 0.4 | 220 | 20 | 180 | 52 | 3 | 0 | 2 | 0 | 3 | 3 |
| **27** | 0.3 | 200 | 20 | 180 | 50 | 3 | 1 | 2 | 2 | 3 | 3 |

## 3. Results and Discussion

Flame treatment modifies the surface of PP/EPDM composites by introducing polar functional groups and oxidizing the outermost polymer layer, thereby increasing surface energy and improving adhesion. The microstructure is affected primarily at the interface, where flame-induced oxidation can enhance coating wetting and bonding, while the bulk properties of the composite remain largely unchanged.

Box-Behnken design with four factors (air pressure inside the cabin, flame gas pressure, flame/surface gap, and treatment time) at three levels was employed to determine the effect of factors on three physical responses: surface tension, adhesion strength, and resistance to high-pressure washing (water jet), and two chemical responses, including moisture resistance and immersion resistance of the composite. To the best of our knowledge, flame treatment aspects have been rarely focused on to be optimized systematically through systematic experimental design policies. It is worth mentioning that the type of experimental design plan selected for designing experiments strongly affects the degree of our understanding of the individual and/or mutual effects of a process or material parameters on the selected responses. The analysis was performed on the data given in Table 2 using Expert-Design software based on RMS and four-factor three-level BBD. In the case of single-objective optimization, we applied a second-order regression function to obtain predictive functions. Correspondingly, the best model was selected based on the quantity of $R^2$ (Figure 1), P-value, and Lack of fit. The ANOVA was used to find $R^2$ and Adjusted-$R^{2,}$ by which the adequacy of the developed model was checked. To assess the reliability of each model in tracking the behavioral changes over the studied range of explanatory variables, the sequential squared errors are obtained and discussed. A given mathematical model is acceptable when its ANOVA reaches high statistical significance, with F-values at a confidence level of 95% and P-values less than 0.05 [16]. The ANOVA revealed the best second-order model in each case. The fitted equations for each response are as follows:

$$\begin{aligned}\mathit{Surface\ tension} &= +52.67 + 0.5000 * A + 1.17 * B - 2.50 * C + 1.17 * D + 0.5000 * AB + 0.0000 \\ &* AC + 0.0000 * AD + 0.000 * BC + 0.0000 * \mathrm{BD} + 0.5000 * \mathrm{CD} - 0.0833 * A^2 \\ &- 0.0833 * B^2 + 1.42 * C^2 - 2.58 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{Immersion\ strength} &= +0.0000 - 0.1667 * A - 0.3333 * B + 0.3333 * C - 0.5000 * D - 0.2500 * AB \\ &- 0.2500 * AC + 0.0000 * AD - 0.2500 * BC + 0.0000 * \mathrm{BD} - 0.5000 * \mathrm{CD} + 0.2083 \\ &* A^2 + 0.2083 * B^2 - 0.0417 * C^2 + 0.7083 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{Adhesion\ strength} &= +0.0000 - 0.1667 * A - 0.3333 * B + 0.3333 * C - 0.5000 * D - 0.2500 * AB \\ &- 0.2500 * AC + 0.0000 * AD - 0.2500 * BC + 0.0000 * \mathrm{BD} - 0.5000 * \mathrm{CD} + 0.2083 \\ &* A^2 + 0.2083 * B^2 - 0.0417 * C^2 + 0.7083 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{Moisture\ strength} &= +1.67 - 0.2500 * A - 0.4167 * B + 1.00 * C - 0.8333 * D - 0.0000 * AB \\ &- 0.0000 * AC + 0.7500 * AD + 0.0000 * BC + 0.7500 * \mathrm{BD} - 0.5000 * \mathrm{CD} - 0.1250 \\ &* A^2 - 0.1250 * B^2 - 0.5000 * C^2 + 1.25 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{High\ pressure\ wash\ strength} &= +0.0000 - 0.3333 * A - 0.6667 * B + 0.6667 * C - 1.00 * D - 0.5000 * AB \\ &- 0.5000 * AC + 0.0000 * AD - 0.5000 * BC + 0.0000 * \mathrm{BD} - 1.0000 * \mathrm{CD} + 0.4167 \\ &* A^2 + 0.4167 * B^2 - 0.0833 * C^2 + 1.42 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{Adhesion\ after\ humidification} &= +2.67 - 0.2500 * A - 0.4167 * B + 1.33 * C - 0.8333 * D + 0.0000 * AB \\ &+ 0.0000 * AC + 0.7500 * AD + 0.0000 * BC + 0.7500 * BD - 0.5000 * CD \\ &- 0.2083 * A^2 - 0.2083 * B^2 - 0.8333 * C^2 + 1.42 * D^2\end{aligned}$$

$$\begin{aligned}\mathit{Adhesion\ after\ immersion} &= +2.67 - 0.1667 * A - 0.3333 * B + 1.25 * C - 0.5833 * D + 0.0000 * AB \\ &+ 0.0000 * AC + 0.5000 * AD + 0.0000 * BC + 0.5000 * \mathrm{BD} - 0.2500 * \mathrm{CD} - 0.2083 \\ &* A^2 - 0.2083 * B^2 - 0.8333 * C^2 + 1.17 * D^2\end{aligned}$$

These second-order interpolating functions can be employed for the prediction of PP/EPDM samples' characteristics at levels of material variables for which no experimental data are collected.

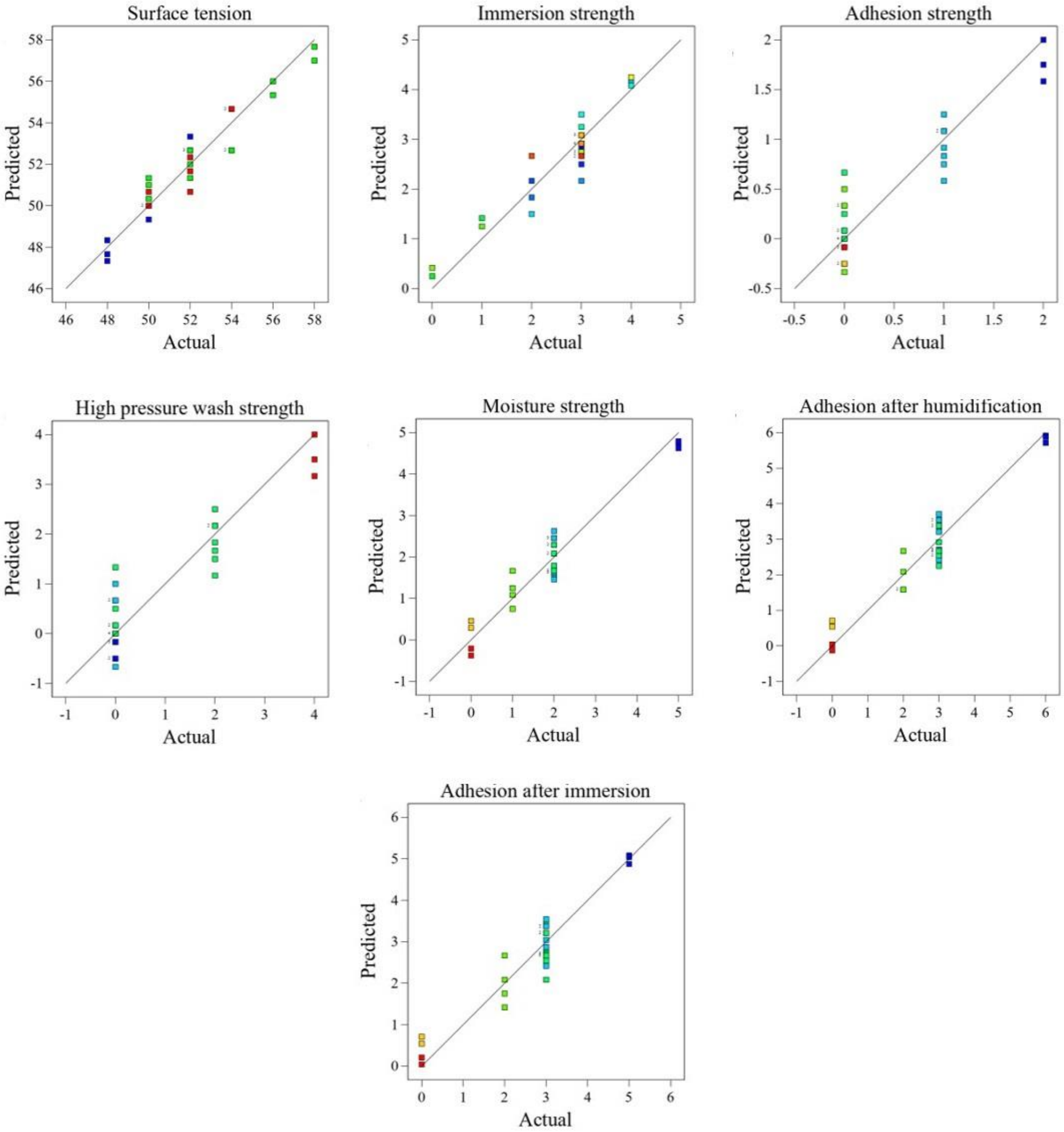
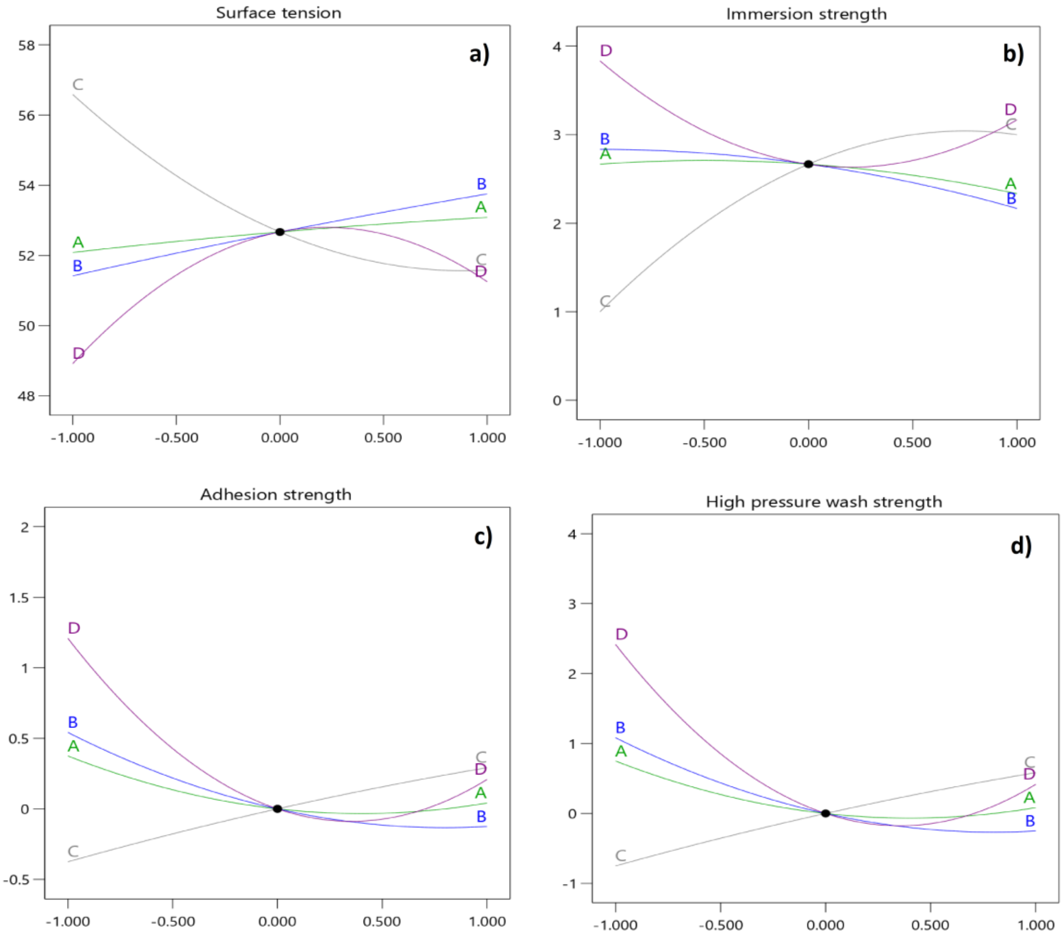


**Figure 1:** Experimental data versus predicted values for three physical responses, including surface tension, adhesion strength, and resistance to high-pressure washing (water jet), and two chemical responses, including moisture resistance and immersion resistance of the composite

### 3.1. Optimization of surface tension

As shown in Figure 2, surface tension increases with higher air pressure and flame gas pressure, while a shorter flame/surface gap enhances this effect. Treatment time significantly influenced surface tension, with the optimal value at 120 s. Deviations from this duration led to reduced surface tension. Across all interactions, the combination of a 10 cm flame/surface gap, 120 s treatment time, and gas flame pressure of 200–220 mbar resulted in maximum surface tension, demonstrating the synergistic effect of time and flame proximity. This indicates a balance between sufficient surface activation and avoidance of thermal degradation at longer exposure times. This behavior is attributed to flame-induced oxidation, which introduces polar functional groups on the polymer surface and increases surface energy[15] .


Surface tension
a)
58
56
54
52
50
48
-1.000
-0.500
0.000
0.500
1.000
A
B
C
D
Immersion strength
b)
4
3
2
1
0
-1.000
-0.500
0.000
0.500
1.000
A
B
C
D
Adhesion strength
c)
2
1.5
1
0.5
0
-0.5
-1.000
-0.500
0.000
0.500
1.000
A
B
C
D
High pressure wash strength
d)
4
3
2
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-1
-1.000
-0.500
0.000
0.500
1.000
A
B
C
D

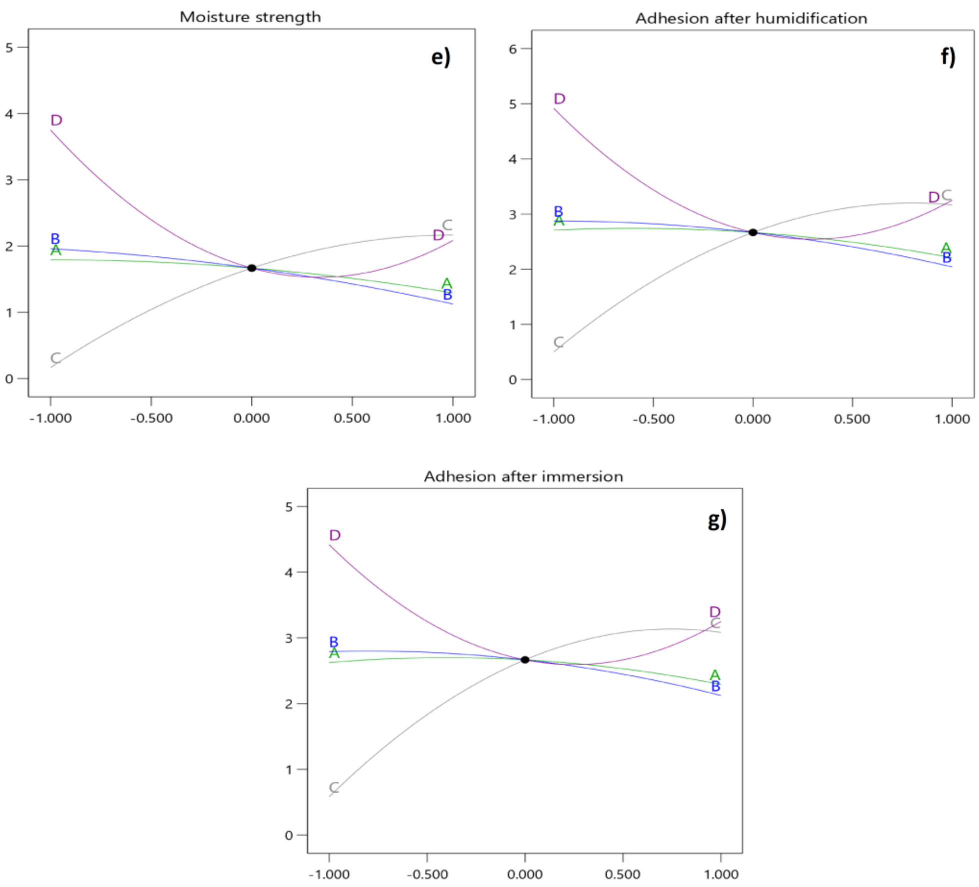

**Figure 2:** Experimental data versus predicted values for physical responses, including surface tension, Immersion strength, adhesion, and High-pressure wash strength (water jet), and chemical responses, including moisture strength Adhesion after immersion, and Adhesion after humidification of the composite

### 3.2. Optimization of immersion

Immersion and moisture resistance were strongly affected by flame/surface gap, treatment time, and air pressure. As indicated by Figures 2 and 3, decreasing the flame/surface gap to 10 cm and maintaining a treatment time of 120 s provided the best chemical resistance, while moderate increases in air and gas flame pressure further enhanced performance. These results confirm that sufficient thermal activation of the polymer surface is critical for improving coating durability and preventing blistering or adhesion loss under humid or immersion conditions.

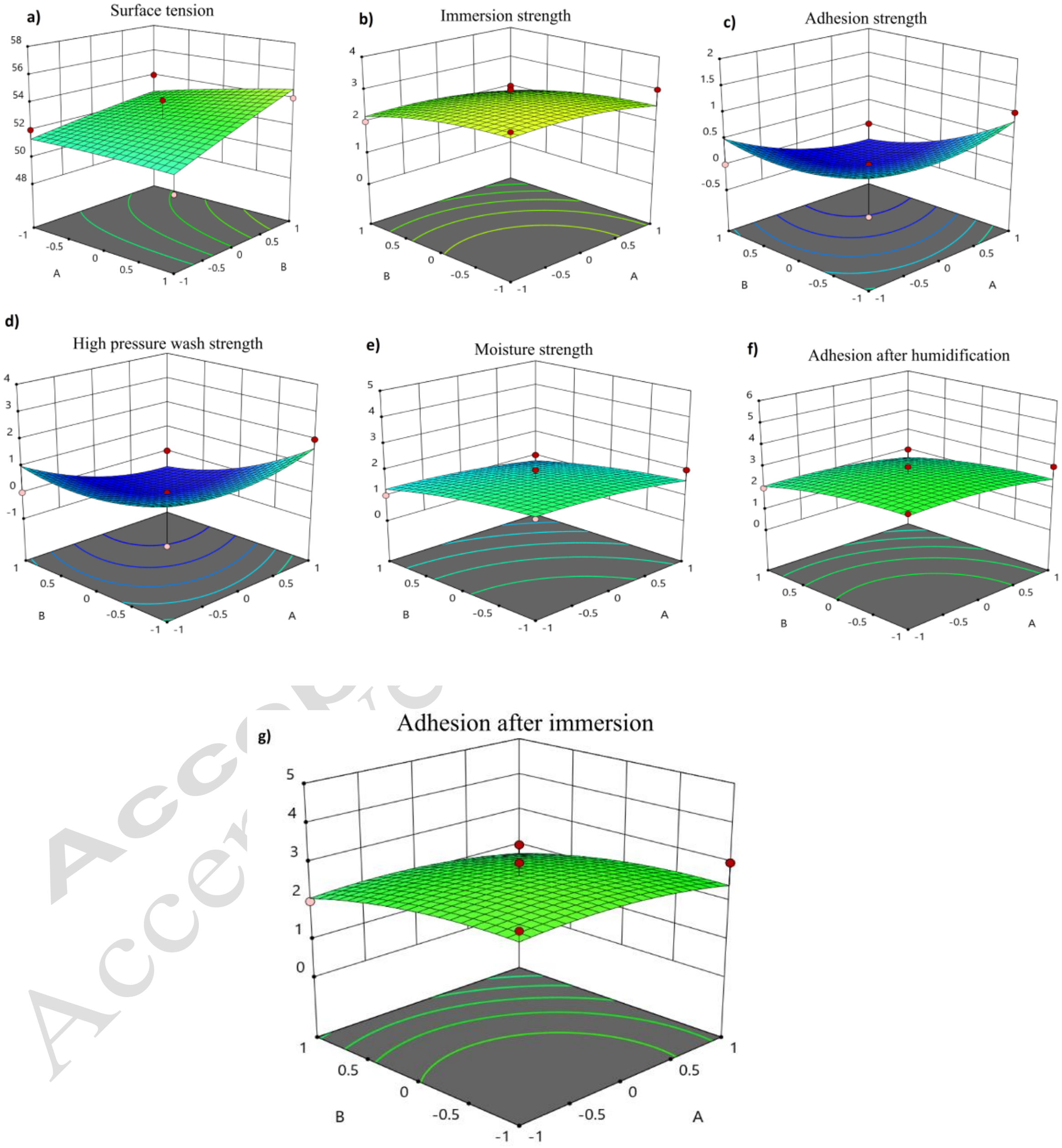

Figure 3: Experimental data versus predicted values for physical responses, including surface tension, Immersion strength, adhesion, and High-pressure wash strength (water jet), and chemical responses, including moisture strength Adhesion after immersion, and Adhesion after humidification of the composite

### 3.3. Optimization of adhesion strength

Adhesion strength, including post-humidification and post-immersion adhesion, followed trends similar to surface tension and chemical resistance. Optimal adhesion was observed at a 10 cm flame/surface gap, 120 s treatment time, and moderate pressures (air pressure 0.4 m/s, flame gas pressure 180–200 mbar), as reflected in Figure 3. Shorter or longer treatment times or larger flame gaps led to decreased adhesion, highlighting the necessity of controlled flame exposure for effective surface activation .The observed enhancement in surface tension, adhesion, and resistance to moisture and immersion can be attributed to the formation of polar groups and surface oxidation induced by flame treatment, which increase surface energy and coating wetting. Similar trends have been reported in previous studies on flame-treated polyolefins, where surface oxidation plays a key role in improving adhesion [16-18].

### 3.4. Optimization of moisture resistance

Moisture resistance was highly affected by flame/surface gap and treatment time with the optimal condition of 10 cm gap and 120 s exposure time respectively. Any deviation from this condition destroyed the moisture resistance. However, other two factors i.e. air pressure and fuel pressure had neglectable effects (Figure 2).

### 3.5. Optimization of high-pressure washing resistance

Resistance to high-pressure washing was primarily influenced by flame/surface gap and treatment time. Optimal resistance occurred at a 10 cm gap and 120 s exposure, whereas air pressure played a secondary role (Figure 2). These trends were consistent across multiple responses, demonstrating the importance of balanced flame exposure for overall surface performance.

### 3.6. Optimization of adhesion strength after humidification and immersion

The 3D chart clearly shows that flame/surface gap, treatment time and fuel pressure had the most effect on adhesion resistance after humidification respectively. However, adhesion strength after immersion were affected only by flame/surface gap and treatment time and fuel pressure had neglectable impact on this response. The best adhesion resistance after humidification and immersion grades, which are equal to zero, could be achieved through the treatment time of 120 seconds, flame/surface gap of 10 cm, minimum air pressure inside the cabin equal to 0.4m/s and the minimum flame gas pressure of 180mbar.

### 3.7. Global optimization

Global optimization was conducted to determine the factor levels at which the desired responses fall within an optimal range. In this study, we assumed that the physical properties, including surface tension, adhesion strength, moisture resistance, immersion resistance, high-pressure washing resistance, post-moisture adhesion strength, and post-immersion adhesion strength, should be simultaneously optimized. To achieve the goal above, experimental designs were implemented, and the corresponding responses were analyzed using specialized statistical software. The closest point to the ideal optimization solution was then identified. The results are summarized in Table 4, which presents the output of three distinct optimization scenarios based on combinations of the input variables: air pressure inside the cabin, flame gas pressure, flame/surface gap, and treatment time**.** The final desirability index was used to evaluate overall performance. These results are consistent with previous studies on surface modification of polypropylene [16].

According to Table 4, Solution 1 represents the most optimal point among the tested conditions. Further analysis revealed that treatment time and flame/surface gap were the most influential factors affecting the overall optimization. In Solutions 2 and 3, the treatment time was shorter than in Solution 1, which may explain the lower overall desirability values.

The results of the global optimization reveal a multi-objective trade-off between physical durability characteristics and process parameters. Notably, flame exposure time and distance between the sample and flame emerged as critical variables influencing coating performance across multiple metrics. In Solution 1, where the highest desirability was observed, these two factors were maintained at moderate, balanced levels (Distance ≈ -0.99; Time ≈ 0.54), suggesting a synergistic interaction that contributes to optimal surface and adhesion properties.

Shorter treatment times, as observed in Solutions 2 and 3, led to marginally reduced performance, especially in parameters such as adhesion after moisture and immersion. This may be attributed to insufficient activation of the polymer surface, leading to weaker bonding at microstructural levels. Furthermore, the cabin and air pressures appear to play a secondary role compared to the thermal exposure parameters. These findings are consistent with literature on flame treatment optimization, where thermal activation time and proximity to flame significantly affect surface energy and subsequent bonding characteristics in polymeric systems [17, 18].

Future research may incorporate desirability function modeling combined with response surface methodology (RSM) to further refine process windows, especially for industrial-scale applications where robustness and repeatability are essential.

**Table 4.** Solution of global optimization derived from BBD.

| Run | Air pressure inside the cabin | Flame gas pressure | Flame/ surface gap | Treatment time | Surface tension | Immersion resistance | Adhesion strength | Humidity resistance | High-pressure washing resistance | adhesion strength after humidification | Adhesion strength after immersion |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1.00 | 1.00 | -0.99 | 0.54 | 58.15 | 0.02 | 0.00 | 0.26 | 0.00 | 0.48 | 0.39 |
| **2** | -0.50 | 0.94 | -1.00 | 0.44 | 56.88 | 0.53 | 0.00 | 0.00 | 0.00 | 0.27 | 0.29 |
| **3** | 0.53 | 1.00 | -1.00 | 0.62 | 57.57 | 0.34 | 0.00 | 0.46 | 0.00 | 0.75 | 0.62 |
| **4** | -1.00 | 0.75 | -0.97 | -0.06 | 56.26 | 0.80 | 0.00 | 0.00 | 0.01 | 0.22 | 0.28 |

## 4. Conclusion

Flame treatment conditions for PP/EPDM automotive bumpers were successfully optimized using Design of Experiments and Response Surface Methodology. Four parameters—air pressure inside the cabin, gas flame pressure, flame/surface gap, and treatment time—were examined for their effects on physical responses (surface tension, adhesion strength, high-pressure washing resistance) and chemical responses (moisture and immersion resistance). The results show that flame/surface gap, treatment time, and gas flame pressure are the most critical factors influencing both physical and chemical properties. Optimal flame treatment conditions were identified as a 10 cm flame/surface gap, 120 s treatment time, and gas flame pressure of 200–220 mbar. Under these conditions, surface tension, adhesion strength, and resistance to moisture, immersion, and high-pressure washing were simultaneously maximized.

This study demonstrates the effectiveness of systematic experimental design in identifying optimal flame treatment conditions, providing practical guidance for industrial applications. The findings enable improved coating adhesion, durability, and overall performance of PP/EPDM bumper surfaces while ensuring efficient processing conditions.

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