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# Experimental and Data-Driven Prediction of Post-Cure Dimensional Stability and Compression Set in Extruded HCR Silicone Profiles

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## ABSTRACT

High-consistency rubber (HCR) silicone profiles serve as sealing gaskets, glazing beads and structural seals in automotive, construction and appliance applications, where dimensional stability and low compression set are essential to sealing performance. This study pairs a Box-Behnken response surface design with a data-driven Random Forest model to characterize and predict post-cure linear shrinkage and compression set in extruded, peroxide-cured HCR silicone profiles as a function of post-cure oven temperature (180–220 °C), post-cure duration (20–60 min) and extrusion line speed (2–8 m/min). The quadratic RSM model for compression set achieved $R^2 = 0.984$ (17-run design) and $R^2 = 0.947$ on held-out test batches; a Random Forest model trained on an expanded 84-batch dataset achieved lower prediction error (RMSE = 1.42 vs. 2.31 percentage points) on the same test batches. The optimized post-cure condition (213 °C, 46 min) produced a verified compression set of 21.6 ± 1.3% and shrinkage of 2.4 ± 0.2%, both within automotive sealing specification.

## OBJECTIVES

- Characterize effects of post-cure temperature, duration & line speed on shrinkage, compression set, hardness and tensile retention (17-run Box-Behnken design)
- Fit and validate quadratic response-surface models for each response
- Train a Random Forest model on an expanded 84-batch dataset and benchmark it against the RSM model
- Relate compression set to measured crosslink density via equilibrium swelling
- Identify and experimentally verify an optimized post-cure condition

## STUDY WORKFLOW

**1. DESIGN** — Box-Behnken, 17 runs; 3 factors, 5 center points → **2. PRODUCE & TEST** — Extrude → post-cure → measure shrinkage, comp. set, hardness, tensile → **3. MODEL** — RSM quadratic regression + Random Forest (84 batches) → **4. OPTIMIZE & VERIFY** — 213 °C, 46 min, 5.4 m/min; 3 verification batches

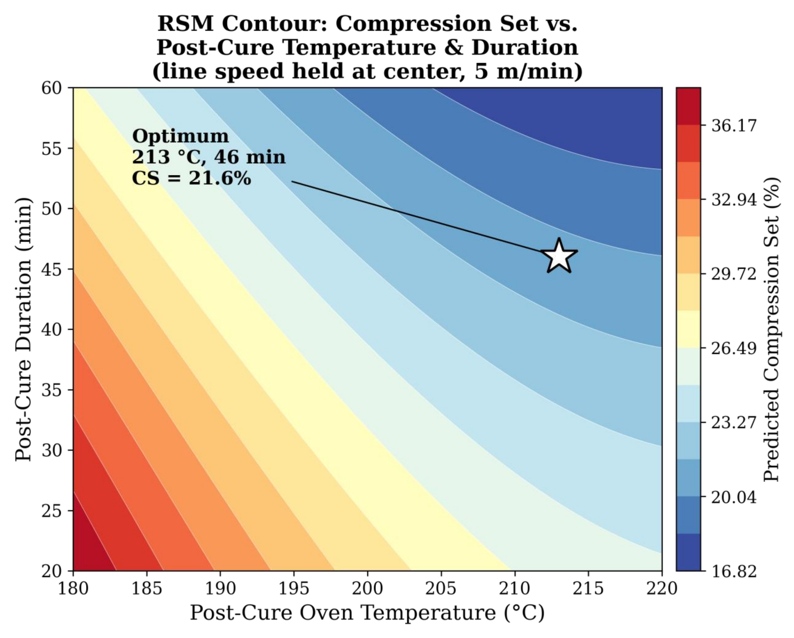
## METHODOLOGY

- Design of Experiments: 17-run Box-Behnken design — post-cure temperature (180–220 °C), post-cure duration (20–60 min), extrusion line speed (2–8 m/min) — with five center-point replicates.
- Response Measurement: linear shrinkage; compression set (ASTM D395 Method B, 22 h at 175 °C); Shore A hardness shift and tensile retention (ASTM D412); crosslink density via equilibrium solvent swelling and the Flory–Rehner relation (9-run subset).
- Modeling: quadratic RSM regression validated by ANOVA; Random Forest ensemble trained on an expanded 84-batch dataset, with desirability-function optimization of the post-cure window.

| Factor | Low (−1) | Center (0) | High (+1) |
|---|---|---|---|
| Post-cure Temperature (°C) | 180 | 200 | 220 |
| Post-cure Duration (min) | 20 | 40 | 60 |
| Extrusion Line Speed (m/min) | 2 | 5 | 8 |

## KEY RESULTS

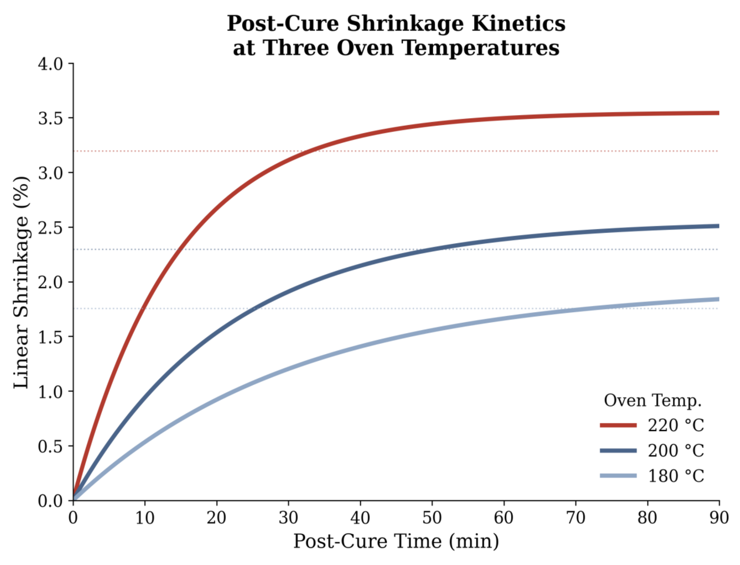
- Compression set ranged 18.2–38.6%; linear shrinkage ranged 1.6–3.8% across the design space.
- Post-cure temperature dominated compression set (52.3% of model sum of squares), then duration (27.6%); line speed had a minor effect (4.8%).
- Both RSM models fit strongly: $R^2 = 0.987$ (shrinkage), $R^2 = 0.984$ (compression set); non-significant lack-of-fit ($p > 0.10$); adequate precision > 26.
- Crosslink density correlated strongly and inversely with compression set ($r = -0.86$, $p = 0.003$) — ranked 3rd in Random Forest feature importance behind temperature and duration.





## POST-CURE SHRINKAGE KINETICS

Higher oven temperatures produce both a higher asymptotic shrinkage magnitude and a faster approach rate. The 220 °C condition reaches ~90% of its asymptotic shrinkage within ~33 minutes, compared with over 70 minutes projected at 180 °C — consistent with accelerated network-densification kinetics at elevated temperature.




### ✓ OPTIMIZED & VERIFIED POST-CURE CONDITION

213 °C • 46 minutes • 5.4 m/min line speed (desirability = 0.911)

Verified compression set: 21.6 ± 1.3% Verified linear shrinkage: 2.4 ± 0.2%

Both within automotive sealing spec — bias +1.2% / +0.8%, well inside the 5% validation threshold

## WALL-THICKNESS SENSITIVITY (Random Forest projection)

| Wall Thickness (mm) | Projected Compression Set at 46 min (%) | Post-Cure Duration for Equivalent Set (min) |
|---|---|---|
| 4 | 17.8 | 24 |
| 8 | 21.6 | 46 (reference) |
| 12 | 27.4 | 78 |

## CONCLUSIONS

- Post-cure oven temperature and duration — not extrusion line speed — govern shrinkage and compression set, so throughput can rise via line speed without hurting post-cure performance.
- Random Forest on an expanded dataset improved accuracy over RSM (RMSE 1.42 vs. 2.31), while RSM retains an explicit, analytically usable polynomial equation.
- Equilibrium swelling confirms crosslink density as the physical driver linking post-cure conditions to compression set.
- The optimized schedule (213 °C, 46 min) should be adjusted for wall thickness beyond the nominal 8 mm profile evaluated here.

## KEYWORDS

HCR Silicone Rubber · Extrusion · Post-Cure · Compression Set · Dimensional Stability · Response Surface Methodology · Random Forest · Crosslink Density

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