

# Improving Rubber Mixing Performance of Hot Water Bag Compound

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**ABSTRACT** A rubber factory in India encountered extensive amount of rework at the rubber mixing stage for one of its medicare products, the hot water bag. The scorch time and the optimum cure time of the rubber-mixing compound were the potential product parameters for which this rework took place. Regression analysis shows that the process parameters, the temperature of the dispersion kneader and the temperature of the open mill, with adjusted  $R^2$  values of 79.9 and 89.5%, respectively can predict both the scorch time and the optimum cure time. Subsequently analyzing the multiple linear regression equation for optimum cure time, which is the key process output variable, with the help of linear programming has arrived at the optimum levels of these temperatures. Besides this, analysis of variance for scorch time has shown that the mixing technique of the workers is not identical. Duncan's multiple range tests has revealed operator group 3 as the best performer for scorch time. Bartlett's test has revealed inequality of variances of four operator groups for optimum cure time. This substantiated the training need of the concerned operators. The study has resulted in reduction of the extent of rework from 80762 to 17865 PPM. Naturally this substantial reduction in rework will reduce the process cycle time and cost of production immensely.

**KEYWORDS** ANOVA, Bartlett's test, characteristic curve, defects per unit (DPU), Duncan's multiple range test, linear programming, optimum cure time (OCT), regression analysis, scorch time (ST), sensitivity analysis, sigma level

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## INTRODUCTION

This study pertains to a rubber factory in India. It produces waterproof products such as medicare, footwear, rainwear and defense items. The hot water bag is one of their crucially important medicare products. In the manufacture of hot water bag, one of the key processing stages is the rubber mixing process. This is also the very first processing stage. In the rubber mixing process, the natural rubber ( $P_{12}$ ) is mixed with some chemicals such as sulfur, stearic acid, elasto, zincoleate, etc. in appropriate proportions to produce the hot water bag compound which is technically coded in the factory as "501 red". After producing the compound (501 red), random samples are collected and taken to the technical laboratory for testing the characteristic

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**FIGURE 1** The hot water bag.

curve. There are four parameters like scorch time (ST), optimum cure time (OCT), minimum torque ( $T_{\min}$ ) and maximum torque ( $T_{\max}$ ) by which one can define the characteristic curve. If these parameters significantly cross their respective specification limits then the curve will be grossly deviated from the desirable standard curve and the corresponding batch will be released after rework subject to obtaining the desired curve. The objective of this study is to reduce the extent of rework for the characteristic curve. It is expected that consequently the bottom line impact will be achieved in terms of increased profitability and lower cycle time.

## THE PRODUCT

The appearance of a hot water bag is shown in Figure 1.

The hot water bag is one of the “medicare” items manufactured by the factory. The technical name of the compound used for manufacture of hot water bag is 501Red. The bag is used for keeping the water warm for a long time and the patients get relief primarily from orthopedic problems.

## THE PROCESS

The process starts with mixing of natural rubber with different chemicals by means of open mill and dispersion kneader. After mixing, the samples are taken to the technical laboratory for testing. If the results of sample testing are satisfactory, the release orders are given. If

they are unsatisfactory, they are sent to the mixing unit for rework. The released lots are taken to the calendaring unit for sheeting out operation. In this unit the compounds are given proper thickness by means of cracking mill, worming mill and calendaring mill. Then these sheets are taken to the press shop or molding unit. There the sheets are molded, trimmed, and knobs are fitted at the neck of the hot water bags (Figure 2).

But if one observes the details of the mixing process, one can understand the different steps in a much better manner. At first, natural rubber and other chemicals, according to the proper recipe card, are weighed in the balance. The composition is given in the Appendix 1. Then the ingredients are brought near the dispersion kneader. Rubber is put into the bucket elevator of the kneader and the elevator takes the rubber into the mixing chamber of the kneader, where the rotating arms and pressurized piston break down the rubber. After 4 min, the rest of the chemicals, except sulfur, are added and mixed for 4 min. Then the mixture is taken out of the kneader and transferred to the open mill, where it is mixed with sulfur and finally sheeted out and samples are taken and supplied to the laboratory (Figure 3).

Dispersion kneader is an automated device. Movements of the bucket elevators, closing and opening of the mixing chamber are automated. It has a temperature-measuring device by which the temperature inside the mixing chamber can be controlled. It also has a watch, which gives an alarm after every 4 min.

## THE OBJECTIVE OF THIS STUDY

The objective of this study is to reduce the extent of rework for the characteristic curve at the mixing stage. The variation between the characteristic curves of different samples of 501Red compound is supposed to have some relation with the pertinent process parameters. Therefore, establishing the relationship between the characteristic curve and the related process parameters and arriving at their optimum levels for which the rework percentage can be immensely reduced are the objectives of the study.

## THE DETAILS ABOUT TESTING AND MEASUREMENT

The following discussions lead to measuring the process to determine current performance. It helps to quantify the problem.

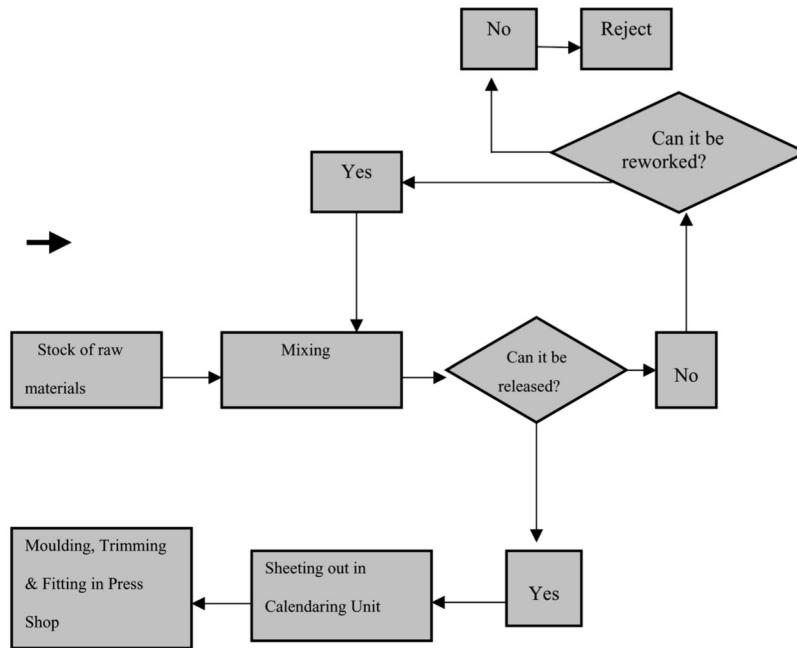


FIGURE 2 The overall manufacturing process flow chart of the hot water bag.

## The Potential Process Input Variables (PPIVs)

In the mixing process there are four PPIVs that can affect the curing characteristic of the 501Red compound. These are mixture composition, mill temperature, friction ratio, and mixing time. However, a constant friction ratio is maintained as per the guideline provided by the manufacturer of dispersion kneader and open mill. Also, a fixed mixing

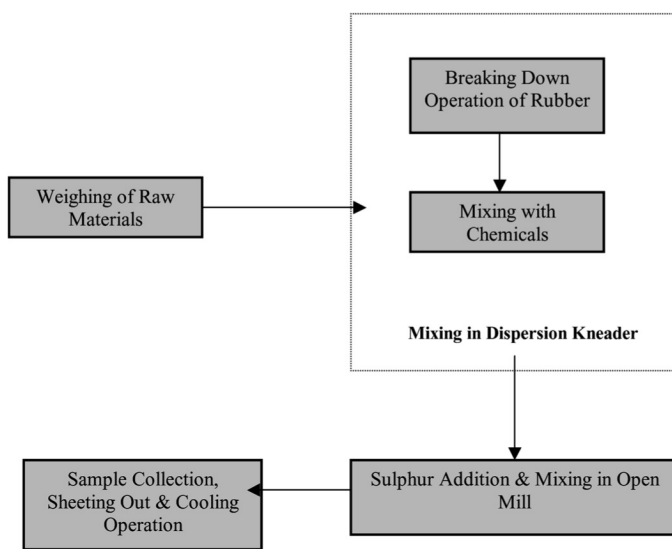


FIGURE 3 The process flow chart in the mixing unit.

recipe is used (see Appendix 1) based on technological consideration. So, the key process input variables (KPIVs) on which the analysis has been carried out are given in the following.

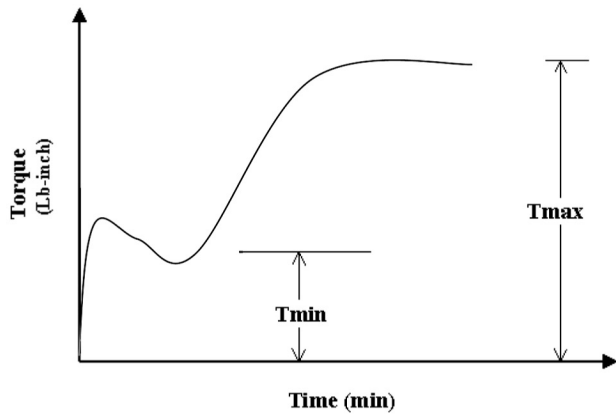
## The Key Process Input Variables (KPIVs)

Initial temperature of the dispersion kneader ( $Temp_i$ )  
 Final temperature of the dispersion kneader ( $Temp_f$ )  
 Open mill temperature ( $Temp_{om}$ )  
 Time in open mill ( $t$ )  
 Operator group

## The Potential Process Output Variables (PPOVs)

From the Rheometer graph (see Figure 4), one can get four PPOVs. These are:

Minimum torque ( $T_{min}$ )  
 Maximum torque ( $T_{max}$ )  
 Scorch time ( $ST$ ) corresponding to  $T_s$ , which is the torque for scorching  
 Optimum cure time (OCT) corresponding to  $T_o$ , which is the torque for curing



**FIGURE 4** The Rheometer graph.

Note that  $T_s$  involves  $T_{min}$  and  $T_o$  involves both  $T_{min}$  and  $T_{max}$  in their computations. It is relevant to mention here that technically the premature vulcanization of rubber compound is known as scorch ( $T_s$ ) and the corresponding time is  $ST$ . On the contrary,  $OCT$  is the time required by a rubber compound for complete curing or formation of cross-links over the entire compound (Naskar & Noordermeer, 2005). This understanding leads to identifying  $OCT$ , which is the key process output variable (KPOV).

### The Characteristic Curve for Measuring the KPOVs

The characteristic curve is measured by the oscillating Rheometer. It measures the dynamic viscosity through the application of a sinusoidal strain to an uncured rubber specimen molded in a sealed, pressurized cavity. Note that the viscosity is the resistance offered by a material to flow under stress. The samples of 8 g of 501 Red are placed into the pressurized cavity of the Rheometer. It provides the curing characteristics of rubber compound. There is a graphical attachment along with the Rheometer. From the Rheometer graph it is possible to interpret the curing

**TABLE 1** Significant Factors of Regression Analysis for Scorch Time (ST)

Predictors	Coefficient	SE coefficient	t-value	p-value	VIF
Constants	10.1000	0.664300	15.18	0.000	
Temp <sub>i</sub>	0.0335	0.008735	3.84	0.000	4.3
Temp <sub>f</sub>	-0.0676	0.013630	-4.96	0.000	4.2
Temp <sub>om</sub>	-0.0631	0.004982	-12.67	0.000	1.1

**TABLE 2** Analysis of Variance for Scorch Time (ST)

Source	DF	SS	MS	F-value	p-value
Regression	3	14.2715	4.7572	69.18	0.000
Error	49	3.3696	0.0688	-	-
Total	52	17.6411	-	-	-

nature of 501 Red and one can calculate scorch time ( $ST$ ), optimum cure time ( $OCT$ ) of the specimen. In addition, one can read the minimum and maximum torques ( $T_{min}$  and  $T_{max}$ ). The values of scorch and cure time correspond to that particular temperature, as the operating temperature of the Rheometer is kept at around  $160^{\circ}C$ . Rheometer graph is shown in Figure 4. In this graph torque versus time diagram is plotted. If one analyzes the graph he can get two important parameters, minimum torque ( $T_{min}$ ) and maximum torque ( $T_{max}$ ). These two parameters are the basis for calculating  $ST$  and  $OCT$ . The Figure 4 reveals that after a certain time the curve is stabilized, that is, it almost becomes a horizontal straight line. It indicates the specimen has reached the curing level. Note that it represents the curing of the specimen at  $160^{\circ}C$  temperature. Generally it takes two or three years for complete natural curing.

### Calculation for Scorch Time (ST) and Optimum Cure Time (OCT)

$$T_s = T_{min} + 2 \text{ units rise in torque}$$

The corresponding time is known as scorch time ( $ST$ ). The premature vulcanization of rubber compound is known as scorch, and the corresponding time is  $ST$ . Vulcanization is an irreversible process during which a rubber compound, through a change in its chemical structure (cross-linking), becomes less plastic and more resistant to swelling by organic liquids while elastic properties are conferred,

**TABLE 3** Significant Factors of Regression Analysis for Optimum Cure Time (OCT)

Predictors	Coefficient	SE coefficient	t-value	p-value	VIF
Constant	12.6000	0.664500	19.01	0.000	-
Temp <sub>i</sub>	0.0350	0.010120	3.46	0.001	3.5
Temp <sub>f</sub>	-0.0706	0.013490	-5.24	0.000	3.5
Temp <sub>om</sub>	-0.0844	0.004752	-17.75	0.000	1.0



**TABLE 4 Analysis of Variance for Optimum Cure Time (OCT)**

Source	DF	SS	MS	F-value	p-value
Regression	3	18.3142	6.1047	123.09	0.000
Error	40	1.9838	0.0496	–	–
Total	43	20.2980	–	–	–

improved or extended over a greater range of temperature. Note that the cross-links are the chemical bonds bridging one polymer chain to another.

$$T_o = T_{\max} - (T_{\max} - T_{\min}) \times 0.1$$

The corresponding time is the optimum cure time (OCT) (Chakravarty et al., 2000). Note that it is the time required by a rubber compound for complete curing or formation of cross-links over the entire compound.

## Measuring the KPIVs

For collecting data on the KPIVs, the instruments used were:

**Pyrometer:** This was used for measuring temperature of open mill rolls.

**Stopwatch:** This was used for time measurement of the open mill mixing process.

At the beginning of each process  $Temp_i$ , the initial temperature was measured from the temperature display of the dispersion kneader unit and similarly  $Temp_f$ , the final temperature was measured at the end of the dispersion kneader mixing operation. Then the mixed compound was put into the rotating rolls of the open mill and stopwatch was switched on. At the very end of the process,  $Temp_{om}$ , the open mill temperature was measured by pyrometer and as soon as the process terminated,  $t$ , the time in the open mill was measured by switching off the watch. For each process, the operator groups were noted. The pertinent data are given in Appendix 2.

**TABLE 5 Objective Coefficient Ranges for Optimum Cure Time (OCT)**

Variable	Current coefficient	Allowable increase	Allowable decrease
$Temp_i$	0.0350	Infinity	0.0000
$Temp_f$	-0.0706	0.0000	Infinity
$Temp_{om}$	-0.0844	0.0844	0.0000

**TABLE 6 Right-hand Side Ranges for Optimum Cure Time (OCT)**

Current RHS	Allowable increase	Allowable decrease
67.50	26.00	19.58
93.50	Infinity	26.00
74.50	19.50	Infinity
94.00	9.71	19.50
46.10	8.12	Infinity
72.10	Infinity	17.88
8.85	1.51	0.69

## The Process Baselines

In order to determine the current sigma level and defective PPM level of the rubber mixing process for this product, the following terms are important (Harry et al., 2000).

Unit: A mixing lot that has been produced.

Defect: A mixing lot whose characteristic curve has substantially deviated from the desired characteristic curve.

DPU: Defects per unit (see Appendix 5 for abbreviation glossary)

The number of units produced during one month before the study was 188. And the number of reworks that had taken place during the period due to defect generation was 16. Therefore, the  $DPU = 0.0851$  and the corresponding  $Z_{LT} = 1.37$ . Thus,  $Z_{ST} = 1.37 + 1.5 = 2.87$ . So, before implementation, the sigma level of the mixing process was 2.87. The corresponding yield was 0.92 and defective PPM was 80762.13. See Appendix 5 (abbreviation glossary) for the meanings of  $Z_{LT}$ ,  $Z_{ST}$ , yield, and PPM.

## ANALYSIS

Since minimum torque ( $T_{\min}$ ) and maximum torque ( $T_{\max}$ ) are used to calculate scorch time (ST) and optimum cure time (OCT), it has been decided to carry out the analysis based on the PPOVs ST and OCT. The concerned technicians of the factory also attach immense importance to these output variables of the mixing process. The multiple linear regression analysis has been done to arrive at the relationship between the above PPOVs and the corresponding KPIVs, namely, initial temperature of the dispersion kneader ( $Temp_i$ ), final temperature of the dispersion kneader ( $Temp_f$ ), open mill temperature ( $Temp_{om}$ ), and time in open mill ( $t$ ).

## The PPOV: Scorch Time (ST)

At first, considering ST as response the analysis has been carried out with  $Temp_i$ ,  $Temp_f$ ,  $Temp_{om}$  and  $t$  as predictors. From the data given in the Appendix 2 the following stepwise regression equation has been obtained by using the MINITAB Software. The model contains the “best” subset of independent variables (Hines & Montgomery, 1980) without including the independent variable  $t$  and the interaction between  $Temp_i$  and  $Temp_f$  due to statistical insignificance.

$$ST = 10.1 + 0.0335 Temp_i - 0.0676 Temp_f - 0.0631 Temp_{om}$$

The small  $p$ -values suggest that all the factors chosen are significant (Table 2). Since the variance inflation factor (VIF) values are less than 10, they suggest that there is not much multicollinearity among the predictors (Table 1).

The  $p$ -value indicates that the regression coefficients are significantly different from zero.

The proportion of the variation in the PPOV scorch time (ST) that can be explained by the above regression model is  $R^2 = 80.9\%$  and  $R^2_{Adj} = 79.9\%$ .

## The KPOV: Optimum Cure Time (OCT)

Considering OCT as response, the stepwise regression analysis has been carried out with  $Temp_i$ ,  $Temp_f$ ,  $Temp_{om}$ , and  $t$  as predictors from the data given in the Appendix 2. The following stepwise regression equation has been obtained by using the MINITAB Software. The model contains the “best” subset of independent variables (Hines & Montgomery, 1980) without including the independent variable  $t$  and the interaction between  $Temp_i$  and  $Temp_f$  due to statistical insignificance.

$$OCT = 12.6 + 0.0350 Temp_i - 0.0706 Temp_f - 0.0844 Temp_{om}$$

The small  $p$ -values suggest that all the factors chosen are significant (Table 4). Since the variance inflation factor (VIF) values are less than 10, they suggest that there is not much multicollinearity among the predictors (Table 3).

The  $p$ -value indicates that the regression coefficients are significantly different from zero.

The proportion of the variation in the KPOV optimum cure time (OCT) that can be explained by the regression model is  $R^2 = 90.2\%$  and  $R^2_{Adj} = 89.5\%$ .

## Model Adequacy Checking

The following graphs for adequacy checking are given in the Appendix 3.

Normal probability plot of the residuals

Histogram of the residuals

Residuals vs. order of the data

Residuals vs. fitted value (Montgomery et al., 2003)

For ST, the residuals versus order of the data indicate that the errors are not independent, thus violating a model assumption. It is worthwhile to mention here that the OCT response model is the primary model of interest.

## Arriving at the Optimum Levels of the KPIVs for OCT

The regression equation for the optimum cure time (OCT) has been further analyzed by applying linear programming (Kasana & Kumar, 2005). The concerned technicians have determined on the basis of pure technological consideration that the target value for OCT is 3.75 min. The objective function that is to be minimized is defined as the deviation between predicted OCT and its target value. The regions of exploration of predictors, obtained from the data given in Appendix 2, are considered as constraints. In addition, non-negativity restriction has been imposed on the deviation between the predicted response and the target value.

## Formulation for the KPOV: Optimum Cure Time

Minimize ( $\hat{Y}$  - Target)

$$\Rightarrow \text{Minimize } (12.6 + 0.0350 Temp_i - 0.0706 Temp_f - 0.0844 Temp_{om} - 3.75)$$

$$\Rightarrow \text{Minimize } (8.85 + 0.0350 Temp_i - 0.0706 Temp_f - 0.0844 Temp_{om})$$

Subject to:

$$67.5 \leq Temp_i \leq 93.5$$

$$74.5 \leq Temp_f \leq 94.0$$

$$46.1 \leq Temp_{om} \leq 72.1$$

$$12.6 + 0.0350 Temp_i - 0.0706 Temp_f - 0.0844 Temp_{om} \geq 3.75$$

## Solution for the KPOV: Optimum Cure Time

By using the LINDO package the following results have been obtained.

$$Temp_i = 67.5$$

$$Temp_f = 94.0$$

$$Temp_{om} = 54.2$$

The corresponding optimum cure time (OCT) and scorch time (ST) are obtained as 3.75 minutes and 2.59 min, respectively. At present, the respective averages of OCT and ST are 4.34 and 3.21 min, respectively.

## Sensitivity Analysis for the Linear Programming Model

By using the LINDO package the following ranges in which the basis remains unchanged have been obtained (Taha, 1982) (Table 5 and 6).

## Performance Analysis of the Workers

There existed a popular belief among the concerned technicians about difference in workers' performance during the mixing process. This difference can have a bearing on the product characteristics, OCT and ST. In this section it has been discussed whether the variation in performance of the workers has significant effect or not. In order to verify this speculation, analysis of variance has been carried out for the data on ST in Appendix 2 by using the MINITAB package. For doing ANOVA two assumptions are vital, the assumption of normality and the assumption on equality of variances (homoscedasticity). Appendix 4 reveals that the assumption of normality has not been grossly violated. The equality of variance

**TABLE 7** The ANOVA Table for Scorch Time (ST)

Source	DF	SS	MS	F-value	p-value
Worker group	3	14.323	4.774	32.65	0.000
Error	55	8.042	0.146	–	–
Total	58	22.365	–	–	–

**TABLE 8** The Mean and Standard Deviation of ST (Target = 2.25 Min)

Level	N	Mean	Standard deviation
Group-1	7	3.6586	0.4582
Group-2	8	3.3575	0.5623
Group-3	28	2.7150	0.3370
Group-4	16	3.8163	0.3165

among the four groups of operators has been checked by doing Bartlett's Test with the help of the MINITAB package. The Bartlett's test suggests that while the operators can be considered as homoscedastic for the response ST, they are to be considered as heteroscedastic for the response OCT (see Appendix 4).

Table 7 indicates that the means of the four groups of workers are significantly different for the PPOV scorch time (ST). Further analysis by applying Duncan's multiple range tests for ST with significance level 0.05 has revealed that the mean of operator group 3 is different from the other operator groups (see Table 8). For OCT, the variability of group 2 is significantly on the higher side compared to the other groups (see Table 9).

## CONCLUSIONS

Subsequent to carrying out the analysis, the following conclusions have been arrived at. Before this study the sigma level of the mixing process ( $Z_{ST}$ ) was 2.87. The corresponding yield was 0.92 and defective PPM was 80762.13.

Regression analysis shows that the temperatures of the dispersion kneader and the open mill are the KPIVs, which influence the variation in the characteristic curve.

The groups of workers performing the mixing operation are also responsible for the variation in the mixing process. The mean of the operator group 3 is found to be closer to meeting scorch time target than other groups.

**TABLE 9** The Mean and Standard Deviation for OCT (Target = 3.75 Min)

Level	N	Mean	Standard deviation
Group-1	7	4.8171	0.3969
Group-2	8	4.5575	0.8394
Group-3	28	3.7532	0.3582
Group-4	16	5.0319	0.3680

The variability of operator group 2 is found to be significantly higher than other groups for optimum cure time. This study is an illustration of predicting PPOVs (ST and OCT) through the relevant KPIVs with the help of regression analysis. However, to achieve improvement, the regression model for the KPOV (OCT) is subjected to linear programming technique for obtaining the optimum levels of the KPIVs. Thus, the study depicts as to how the regression model is to be used for control and improvement purposes apart from its usual purpose of prediction.

The sensitivity analysis establishes the adequacy of the linear programming model (see Tables 5 and 6).

The optimum KPIVs could be found by using the technique of design of experiments (DOE). Factorial experiments or response surface methodology (RSM) could be applied for the purpose of optimization. But conducting designed experiments on the shop floor is always tougher than dealing with happenstance data that does not hamper the production. There remains scope to apply DOE in general and RSM in particular for future research developments on the topic.

## RECOMMENDATIONS FOR FUTURE CONTROL

In order to reduce the extent of rework at the rubber mixing process, adequate control has to be exercised on scorch time (ST) and optimum cure time (OCT). The equations for prediction of ST and OCT are given in the following.

$$ST = 10.1 + 0.0335 Temp_i - 0.0676 Temp_f - 0.0631 Temp_{om}$$

$$OCT = 12.6 + 0.0350 Temp_i - 0.0706 Temp_f - 0.0844 Temp_{om}$$

where  $Temp_i$  is the initial temperature of the dispersion kneader,  $Temp_f$  is the final temperature of the dispersion kneader,  $Temp_{om}$  is the temperature of the open mill. The ranges of these predictor variables corresponding to which the above equations will be valid are given below.

$$67.5 \leq Temp_i \leq 93.5$$

$$74.5 \leq Temp_f \leq 94.0$$

$$46.1 \leq Temp_{om} \leq 72.1$$

To obtain the target value of 3.75 min for the KPOV OCT, the optimum levels of  $Temp_i$ ,  $Temp_f$ , and  $Temp_{om}$  are to be maintained like this.

$$Temp_i = 67.5$$

$$Temp_f = 94.0$$

$$Temp_{om} = 54.2$$

The corresponding ST is found to be 2.59 min. The 95% confidence limits for OCT and ST have been found to be  $\pm 0.44$  and  $\pm 0.51$  approximately. At present, the averages of OCT and ST are found to be 4.34 and 3.21 min, respectively.

Last but not the least, the process of rubber mixing is crucially dependent on the knowledge and skill of the mixing operators. The study reveals that the operators are not falling in the same homogeneous group. Therefore, proper training has to be offered to the different operator groups to achieve uniformity in their performance. The performance of the operator group 3 can be considered as an internal benchmark for improving the performance of the other groups.

## IMPLEMENTATION

After implementing the above recommendations the sigma level of the mixing process has been recomputed by considering the data given in the Appendix 2 (Breyfogle, 1999). The results are given in the following.

Number of units = 118

Number of defects noticed = 2

$$DPU = \frac{2}{118} = 0.0169$$

Hence,  $Z_{LT} = 2.12$  and  $Z_{ST} = 2.12 + 1.5 = 3.62$ .

Corresponding to  $Z_{ST} = 3.62$  the yield would be 0.98 and the defective PPM would be 17864.53. See Appendix 5 (abbreviation glossary) for the meanings of  $Z_{LT}$ ,  $Z_{ST}$ , yield, and PPM. The following (Table 10) demonstrates the impact of the study.

**TABLE 10** Impact of the Study

Six sigma metrics	Before implementation	After implementation
Sigma level	2.87	3.62
Yield	0.92	0.98
Defective ppm	80762.13	17864.53

## ACKNOWLEDGMENT

The author is grateful to Prof. Sadhan K. Ghosh of the Mechanical Engineering department of the Jadavpur University, the reviewer of this article and Dr. J. R. Simpson (Editor-in-Chief, Quality Engineering) for their valuable suggestions.

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## APPENDIX 1

### Mixing Recipe of Hot Water Bag Compound

Name	Technical name	Weight (in kg)
Natural rubber	P12	19.000
Red colour	MB 768	1.780

(Continued)

Continued

Name	Technical name	Weight (in kg)
Accinox	C120	0.400
Stearic acid	C117	0.120
Sulfur	C1	0.320
Vulkacit	C10	0.080
CBS	C7	0.080
TMT	C5	0.030
Activated calcium carbonate	C48	0.006
Whiting	C58	0.003
Precipitated silica	C68	1.100
Elasto (Oil)	C217	2.400
Dibond (H.S.)	MB 785	0.080
Zincoleate	C118	0.200
Benzoic acid	C24	0.005

## APPENDIX 2

### Data on Process and Product Parameters

Sl No.	Temp <sub>i</sub>	Temp <sub>f</sub>	Temp <sub>om</sub>	t	Worker group	Worker		ST	OCT
						T <sub>min</sub>	T <sub>max</sub>		
1	85.5	87.5	57.2	402	Group-1	12.0	42.5	3.26	4.65
2	87.5	89.0	53.8	336	Group-1	11.9	41.8	3.20	4.68
3	90.5	91.5	52.3	347	Group-1	10.8	39.2	3.65	4.65
4	87.5	83.5	53.1	351	Group-1	11.3	35.0	4.23	4.54
5	56.5	73.5	53.6	361	Group-1	11.2	43.2	3.52	4.80
6	75.5	85.5	54.8	393	Group-1	11.3	44.0	3.40	4.70
7	86.0	81.5	52.4	441	Group-1	11.0	38.0	4.35	5.70
8	81.5	83.5	52.3	332	Group-2	11.0	44.0	4.15	5.60
9	84.5	85.0	53.1	351	Group-2	12.0	41.4	4.30	5.90
10	86.5	88.5	59.2	382	Group-2	11.8	44.0	3.40	5.05
11	84.5	87.5	69.0	412	Group-2	11.0	44.0	3.15	4.26
12	88.5	91.5	71.2	405	Group-2	11.1	47.0	2.85	3.80
13	88.0	83.5	70.9	365	Group-2	11.0	43.5	3.10	4.07
14	84.5	86.5	72.1	419	Group-2	11.2	47.0	2.91	3.82
15	87.5	88.5	70.2	368	Group-2	11.0	43.3	3.00	3.96
16	74.5	82.5	62.3	447	Group-3	11.5	45.0	3.16	4.12
17	83.5	84.5	63.1	381	Group-3	11.8	45.3	3.18	4.30
18	85.0	85.0	62.8	367	Group-3	11.0	45.0	3.20	4.11
19	88.5	92.5	64.2	448	Group-3	11.2	46.0	2.80	3.95
20	93.5	94.0	65.3	366	Group-3	11.4	48.0	2.85	4.00
21	81.5	84.5	68.3	340	Group-3	10.2	39.8	2.87	3.68
22	85.5	86.5	67.8	357	Group-3	11.0	40.2	2.94	3.87
23	85.0	84.5	69.2	372	Group-3	10.0	42.0	2.90	4.00
24	83.5	81.5	70.1	339	Group-3	10.0	40.0	2.90	3.85
25	56.5	78.5	65.3	423	Group-3	9.2	36.8	3.12	4.00
26	88.5	85.5	67.2	415	Group-3	11.0	44.0	2.25	3.25

(Continued)

Continued

Sl No.	Temp <sub>i</sub>	Temp <sub>f</sub>	Temp <sub>om</sub>	t	Worker group	T <sub>min</sub>	T <sub>max</sub>	ST	OCT
27	84.5	81.5	68.7	390	Group-3	11.6	42.0	2.48	3.35
28	85.5	88.5	69.1	397	Group-3	11.0	45.0	2.26	3.20
29	88.5	91.0	70.0	375	Group-3	10.5	47.0	2.20	3.14
30	87.5	85.5	67.2	412	Group-3	10.2	45.5	2.56	3.58
31	82.5	84.5	71.9	391	Group-3	11.9	40.2	2.53	3.55
32	85.5	86.5	70.2	334	Group-3	12.2	43.6	2.48	3.48
33	67.5	78.5	68.4	408	Group-3	11.0	43.0	2.70	3.70
34	80.5	82.5	69.3	392	Group-3	11.7	41.6	2.71	3.72
35	83.5	85.0	68.2	412	Group-3	11.8	42.6	2.58	3.65
36	85.5	89.5	69.3	382	Group-3	11.9	42.4	2.31	3.35
37	90.5	92.5	65.1	352	Group-3	12.0	49.4	2.27	3.64
38	91.5	89.5	66.2	362	Group-3	12.0	45.2	2.25	3.39
39	89.5	86.5	67.8	378	Group-3	11.8	43.8	2.54	3.60
40	86.5	84.5	68.5	352	Group-3	12.0	49.0	2.55	3.60
41	63.5	72.5	62.8	512	Group-3	11.5	48.4	3.05	4.26
42	73.5	79.5	65.8	418	Group-3	12.2	42.0	3.12	4.30
43	79.5	82.5	63.7	389	Group-3	12.0	42.1	3.26	4.45
44	86.5	87.5	59.8	361	Group-4	10.1	44.0	3.40	4.46
45	88.0	88.5	60.1	376	Group-4	10.3	43.0	3.37	4.53
46	84.5	83.5	61.5	389	Group-4	9.8	41.0	3.45	4.70
47	82.5	81.5	63.5	334	Group-4	9.9	41.0	3.46	4.52
48	79.5	79.0	60.2	337	Group-4	11.5	38.0	3.85	4.95
49	76.5	78.0	58.3	392	Group-4	11.4	37.2	4.45	5.45
50	56.5	70.5	49.1	454	Group-4	10.4	40.2	3.75	4.82
51	74.5	86.5	48.4	406	Group-4	11.1	44.5	3.75	5.02
52	89.0	90.0	46.1	392	Group-4	11.3	40.5	3.85	5.50
53	91.5	91.5	53.2	408	Group-4	11.7	44.3	3.80	5.10
54	57.5	70.5	61.2	426	Group-4	11.5	42.0	3.83	5.00
55	74.5	81.5	62.1	372	Group-4	11.2	38.5	4.10	5.38
56	71.5	74.5	51.8	314	Group-4	11.0	39.3	4.20	5.40
57	75.0	78.5	50.2	324	Group-4	11.0	37.4	4.20	5.36
58	80.5	83.5	54.0	368	Group-4	10.5	40.2	3.60	4.82
59	82.5	78.5	51.2	354	Group-4	11.0	43.8	4.00	5.50

## Data on Rework Before Implementation

Date	No. of lots produced	Not released	Date	No. of lots produced	Not released
01.04.04	8	2	16.04.04	6	0
02.04.04	8	8	20.04.04	6	0
03.04.04	8	0	21.04.04	6	0
04.04.04	10	0	22.04.04	6	0
06.04.04	12	0	23.04.04	6	4
08.04.04	6	0	24.04.04	2	0
09.04.04	6	0	24.04.04	6	0
09.04.04	8	0	25.04.04	12	0
10.04.04	12	2	26.04.04	10	0
10.04.04	2	0	27.04.04	2	0
11.04.04	2	0	28.04.04	6	0
13.04.04	12	0	29.04.04	8	0
15.04.04	2	0	16.04.04	6	0
16.04.04	10	0			

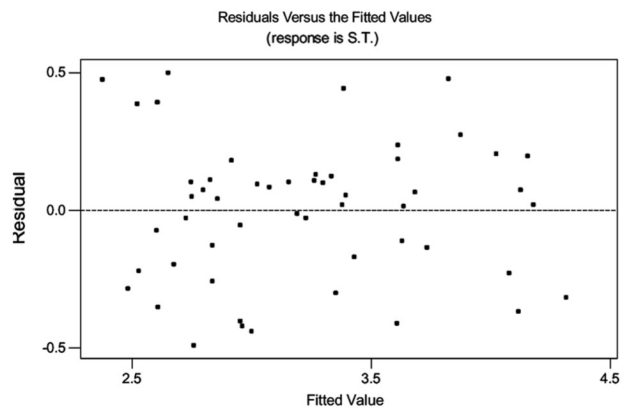
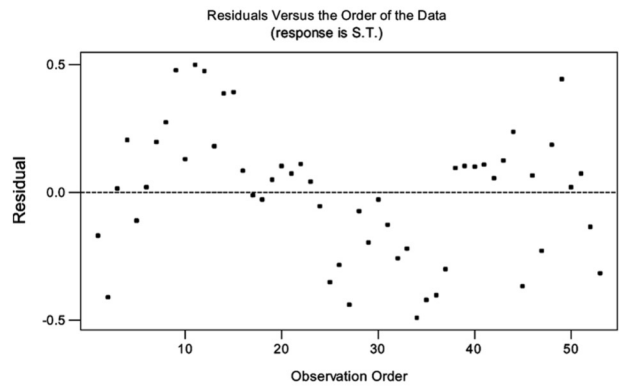
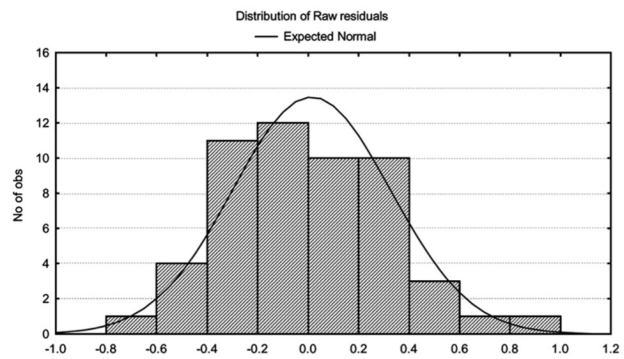
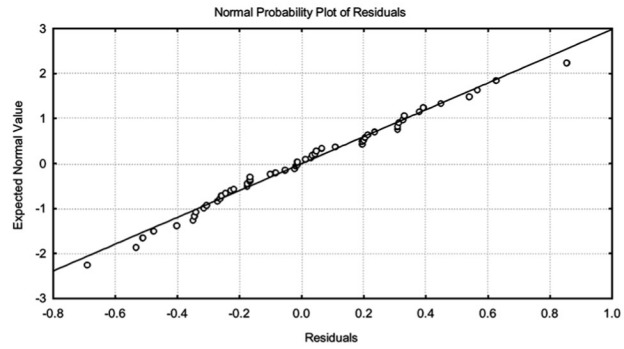
## Data on Rework After Implementation

Date	No. of lots produced	Not released	Date	No. of lots produced	Not released
26.06.04	10	2	07.07.04	8	0
27.06.04	10	0	08.07.04	8	0
29.06.04	6	0	09.07.04	8	0
01.07.04	8	0	10.07.04	10	0
02.07.04	10	0	13.07.04	10	0
03.07.04	12	0	14.07.04	6	0
04.07.04	6	0	16.07.04	6	0

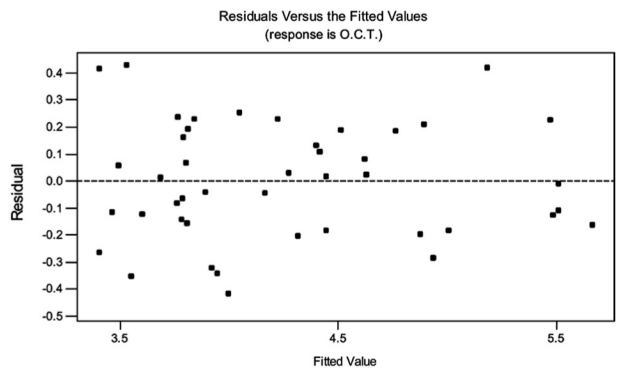
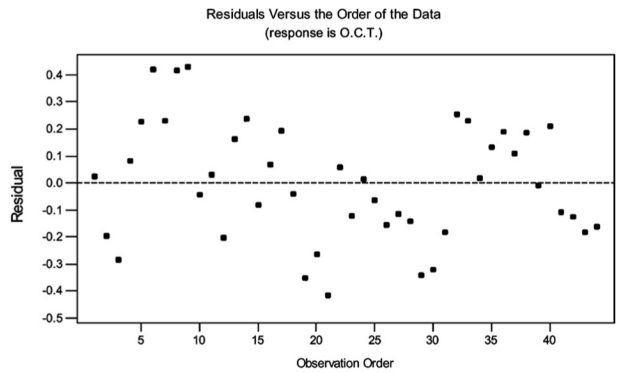
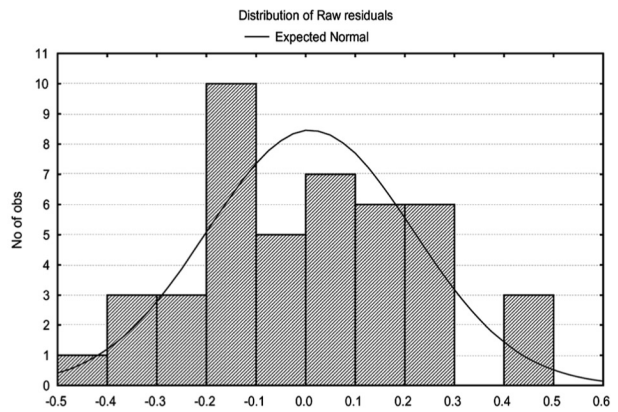
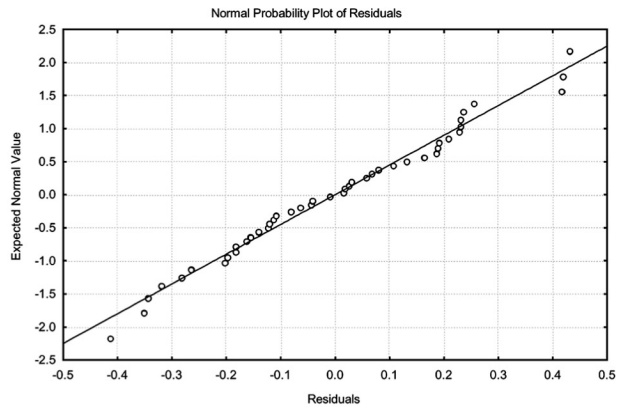
# APPENDIX 3

## Adequacy Checking for Regression Models

*Response: Scorch Time*



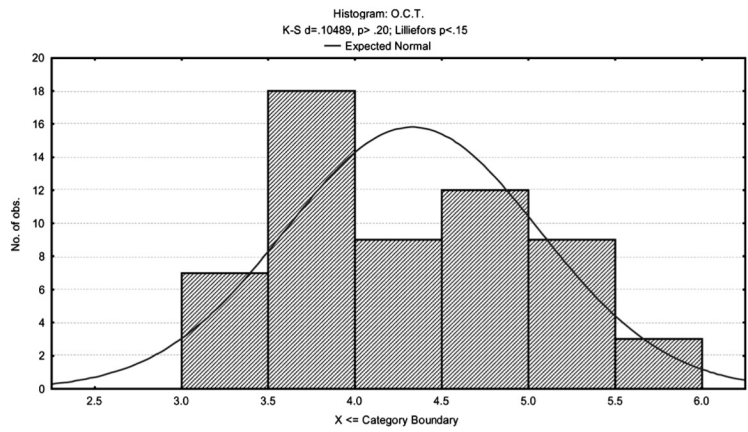
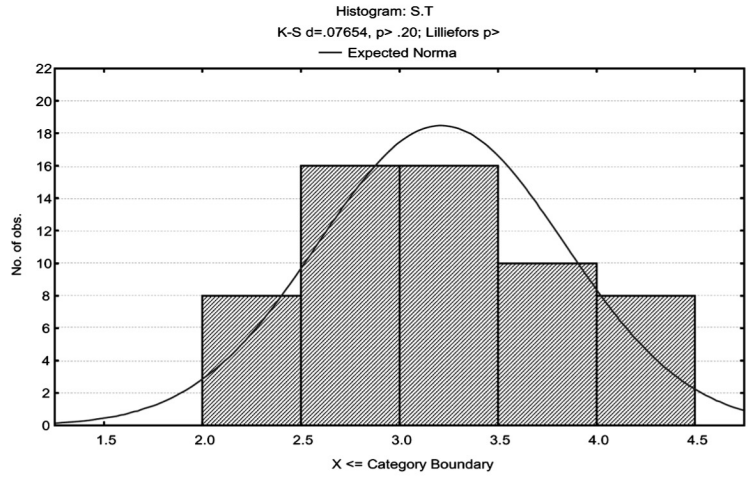
# Response: Optimum Cure Time





# APPENDIX 4

## Adequacy Checking for ANOVA



## Bartlett's Test

The hypotheses are

$$H_0: \sigma_1^2 = \sigma_2^2 = \dots = \sigma_a^2$$

$$H_1: \text{above not true for at least one } \sigma_i^2$$

The test involved computing a statistic whose sampling distribution is closely approximated by the Chi-square distribution with  $(a - 1)$  degrees of freedom when the 'a' random samples are from independent normal populations. The test statistic is

$$\chi_0^2 = 2.3026 \frac{q}{c}$$

where

$$q = (N - a) \log_{10} S_p^2 - \sum_{i=1}^a (n_i - 1) \log_{10} S_i^2$$

$$c = 1 + \frac{1}{3(a - 1)} \left( \sum_{i=1}^a (n_i - 1)^{-1} - (N - a)^{-1} \right)$$

$$S_p^2 = \frac{\sum_{i=1}^a (n_i - 1) S_i^2}{N - a}$$

and  $S_i^2$  is the sample variance of the  $i$ th population. The null hypothesis will be rejected if  $\chi_0^2 > \chi_{\alpha, a-1}^2$  or  $p$ -value is less than 0.05.

Results:

Response: Scorch Time

$p$ -value: 0.26

Response: Optimum cure time

$p$ -value: 0.009

## APPENDIX 5

### Abbreviation Glossary

$T_{\min}$ : minimum torque in pound-inch

$T_{\max}$ : maximum torque in pound-inch

$T_s$ : scorching torque in pound-inch

$T_o$ : optimum cure time torque in pound-inch

ST: scorch time in minutes

OCT: optimum cure time in minutes

$Temp_i$ : initial temperature of the dispersion kneader in degree Celsius

$Temp_f$ : final temperature of the dispersion kneader in degree Celsius

$Temp_{om}$ : open mill temperature in degree Celsius

DPU: defects per unit

ppm: parts per million

Yield:  $e^{-DPU}$

PPIV: potential process input variable

PPOV: potential process output variable

KPIV: key process input variable

KPOV: key process output variable

$Z_{ST}$ : short term sigma level

$Z_{LT}$ : long term sigma level