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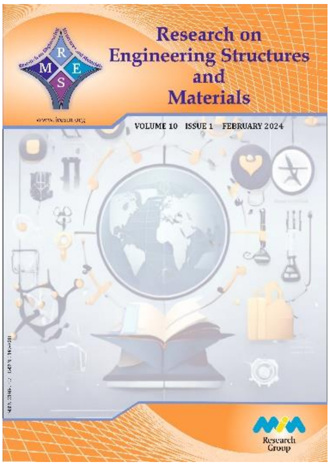

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S.S. Pachpore, Pradeep V. Jadhav

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Research Article

Endodontic treatment parameter optimization using central composite rotatable design

S.S.Pachpore *[1, a], Pradeep V. Jadhav[2, b]

[1]School of Mechanical Engineering, Dr. Vishwanatah Karad MIT World Peace University, Pune, India
[2]Department of Mechanical Engineering Bharati Vidyapeeth (Deemed to be) University, Pune, India

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Abstract

Endodontology referred to as Root Canal Treatment (RCT) is a field of science that deals with the entire chemo-mechanical cleaning and sealing of the root canal system by using restorative material used to rescue or repair severely decaying or diseased teeth. The success of the treatment depends on the seal formed between the filling material and the root cavity post-obturation. The crucial components include the energy used to clean and seal the root canal system, the material used to fill the root canal system, the process used to fill the root canal system, and the geometry of the root canal system. In the presented research, ideal operative parameters and their interaction were studied with 32 experimental trials for five operative parameters namely canal angle, canal operative length, compaction force, operative temperature, and operating frequency using central composite rotatable design (CCRD); a response optimization tool. The treatment was carried out on endo-training blocks prepared with a 6% uniform taper across the working length by using gutta-percha as filling material. A compaction force of 10N, operating temperature between 90-92° C, operating frequency in the range of 40-50 Hz, and operative length of 12mm results in maximum gutta percha compaction.

1. Introduction

RCT is a process of relieving dental pain that occurs due to inflammation or infection in the roots of a tooth. and saving the teeth. RCT is a dental operation that requires removing the pulp (root nerves and blood cells) from a tooth, cleaning and shaping the canal cavity, and then adding fillers to stop germs from re-entering the apical end of the root canal. In terms of medicine, the process of cleaning and sculpting the canal cavity is known as 'Biomedical Preparation', and the 3D filling and sealing of the canal to establish an undamaged seal is known as 'Obturation'(1). The purpose of obturation is to seal the cleaned, shaped, and disinfected root canal system and to prevent re-infection (2). The obturation without voids and to within 2.0 mm of the apex has a significant positive influence on the outcome of treatment which governs the success index of the treatment (3). The complete obturation process closely resembles mechanical subtractive and additive processes. Over the years, numerous studies have been published in estimating the success and failure of endodontic treatment (4), which lies between 46-93%, with few researchers/practising dentists reporting up to 98% (5). Variations in experimental designs and clinical practices, as well as in the standards for determining periapical healing and the duration of the postoperative observation period could be the reason for variation (4). From the theoretical point of view, the long-term persistence of microorganisms, chronic inflammation due to overfilling and constant trauma, and non-removal of irritant bodies

*Corresponding author: swanand.pachpore@mitwpu.edu.in
[a] orcid.org/0000-0002-7833-9560; [b] orcid.org/0000-0002-7167-2387
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affect the success whereas, from the clinical point of view, preoperative factors such as patient's age, sex, medical health, tooth type affects the most (6). Over the years i.e. between 1990-2023, maximum studies carried out by clinical researchers were more focused on identifying the preoperative factors and post-operative factors governing the success of treatment(7). In the present study, an attempt is being made to quantify the operative factors such as root canal filling volume and quality of coronal restoration which have not been addressed yet (8). There are several operative factors in root canal filling which affect the process and success index. They are classified into four groups Geometry, Process, Material, and Energy categories shown in Fig. 1 (9). The present study focuses on defining the interaction between operative parameters using Central Composite Rotatable Design (CCRD) with half replicate to enhance filling material compaction (10).

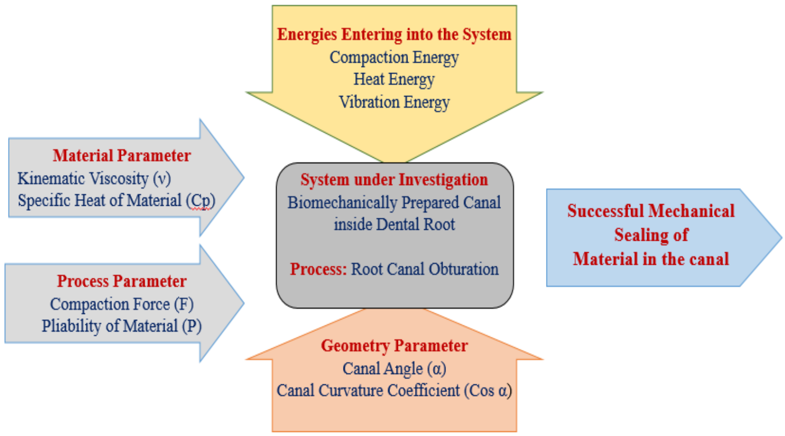

Fig. 1. Categorial factors affecting success index in terms of compaction [11]

2. Material and Method

Under the scope of the study, considering the complexity of root canals and following medical and ethical guidelines governed by the Indian Medical Association. The primary study was restricted to endo-training blocks shown in Fig. 2. Endo-training blocks are synthetic materials that are used to simulate the anatomy of a tooth root canal system. The tests were carried out on endo-training made up of acrylic material. The canal present inside the blocks was prepared using K-Type hand files made up of NiTi (nickel-titanium) material with a 6% uniform taper across the working length. K-file is the most commonly used instrument for root canal shaping (12), (13) as it has got positive rake angle which results in optimum cutting efficiency. The 6% uniform taper is preferred because of its several advantages such as it allows irrigation agents to work more efficiently and also provides the cleanest possible canal post biomechanical preparation to clear the debris. The success rate will be higher for the canal having less curvature than the canal having larger curvature, making the canal angle a crucial geometrical feature. The steeply curved canal is more challenging to instrument and fill than the canals with mild and moderate curvatures. There are few proven methods available to measure the canal curvatures namely Schneider's method and Weine's method which works on the same idealogy, but the error for Schneider's method is less as compared to the Weine's method (14). Thus, the canal morphology was examined using an optical comparator and geometry was verified using Schneider's method (15). The entire canal is divided into 3 major parts; Coronal, Middle and Apical (16). The coronal and Middle part are straight tapered and the apical region is curved. This method measures the canal angle between line 1 and line 2. Line 1 is nothing but the canal axis. Line 2 is the line drawn between point a and point b. Point A is marked on the axis of the traced profile at the end of the middle region and point b is marked where curvature ends as shown in Fig. 3 to measure the canal curvature.

Fig. 2. Endo training block prepared with uniform 6% taper under scope of study (17)

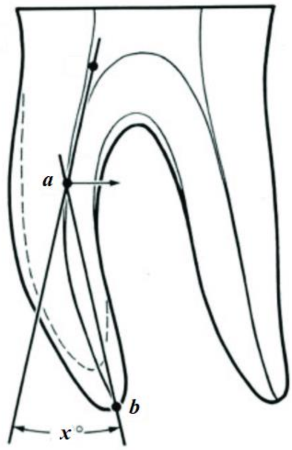

Fig. 3. Schneider's Method to Measure Canal Curvature (18)

Based on the studied literature, gutta-percha was found to be a promising material having superior properties such as thermo-plasticity, solubility with the organic solvent (19) and viscoelasticity and high-temperature susceptibility (20). The selected gutta-percha cones were found to be of pH7 because according to (21), water-stored gutta-percha cones are subjected to remain in a stable condition which enhances the compactibility during obturation.

3. Experimental Set-up

The experimental setup shown in Fig. 4 was developed to compact gutta-percha inside the prepared canal. The laboratory Experimental set-up to fill in gutta-percha inside the block consists of three major components namely a thermo-mechanical simulator, heat and vibration compactor, and connected to a data visualization system.

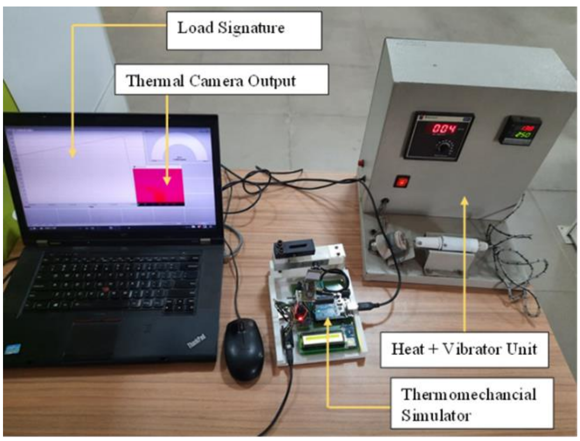

Fig. 4. Laboratory Experimental Setup

The experimental set-up measures the applied force, to compact gutta-percha and capture the heat signature of the subject and accordingly saves data to the data logger with time stamps. The heat and vibration compactor unit consists of a power supply which generates vibration of 0-50 Hz at 230AC supply. The vibration is supplied to an off-centric vibrator placed inside the holder made up of heat-resistant PTFE material and a plugger is attached to it. The plugger is made up of SS 304L material with a 0.7mm taper placed inside the holder that compacts gutta-percha with heat and vibration.

The volume of compacted gutta-percha inside the canal was measured using equation 1 which is the ratio of the increased mass of the block after compaction to density of gutta-percha. The increased mass of the block was recorded using an electronic weighing balance before and after obturation.

$$\text{Volume} = \frac{\text{Increased Mass of Block After Compaction}}{\text{Density of Gutta−Percha}} \tag{1}$$

4. Design of Experiment Using Central Composite Rotatable Design (CCRD)

Response Surface Methodology (RSM) is a set of mathematical and statistical approaches that analyse issues in which numerous independent variables factors impact a dependent variable or response, to optimize this response (22). The independent operative variables such as canal angle, operative length, compaction force, operating temperature, and frequency are quantitatively represented in the presented study, and have the following functional relationship with the response i.e. percentage mass of gutta-percha filling, which is analysed using a central composite rotatable design. The CCRD is a statistical experimental design used to optimise a system's response to many input factors. The central composite rotatable design approach is utilised in this work to anticipate the best values of operating parameters and their interactions (23), (24). Table 1 represents the lowest, central and highest levels of variables represented as (-2, -1, 0, 1, 2) with α = 2.00 i.e. the distance of the axial points from the centre. The range of values of star points for the rotatable design depends upon the number of points in the factorial section of the offered design, which is calculated as given in equation 2 (25) below.

$$\alpha = (F)^{0.25} \tag{2}$$

Table 1. Actual values of different parameters affecting gutta-percha filing

Abbreviation	Parameter	Unit	Levels				
			-2	-1	0	1	2
X_1	Canal Angle (α)	Deg.	12	24	36	48	60
X_2	Compaction Force (FT)	N	8	9	10	11	12
X_3	Operating Temperature (T)	°C	84	86	88	90	92
X_4	Operating Frequency (F)	Hz	10	20	30	40	50
X_5	Operating Length (L)	mm	10	11	12	13	14

Here, F is the determined no. of points in the cube section and represented as $F=2^k$, where k is the no. of independent parameters (26). A total of five parameters were considered under the scope of the study, i.e. k=5, the no. of points becomes 32 which represents no. of trials. Hence, 32 experimental trials were designed based on the number of considered parameters i.e. five operative parameters (25). Considerations of variables and their levels for 32 experiments have been shown in Table 2. The mass of compacted gutta-percha shown in Table 3 is arrived at using weight analysis before and after. A total of thirty-two tests were carried out at the values of five factors with various combinations listed by using the laboratory test setup described in the preceding section.

Table 2. Order of experiments and responses for gutta-percha compaction filling

Order of Expt.	Natural Values					Response
	(α)	(FT)	(T)	(F)	(L)	Mass of GP Compacted (* 10^{-2} gms)
1	24	9	86	20	13	12.75
2	48	9	86	20	11	16.19
3	24	11	86	20	11	16.69
4	48	11	86	20	13	15.61
5	24	9	90	20	11	20.88
6	48	9	90	20	13	20.33
7	24	11	90	20	13	19.86
8	48	11	90	20	11	19.26
9	24	9	86	40	11	22.67
10	48	9	86	40	13	22.62
11	24	11	86	40	13	25.32
12	48	11	86	40	11	29.42
13	24	9	90	40	13	33.24
14	48	9	90	40	11	27.46
15	24	11	90	40	11	35.47
16	48	11	90	40	13	29.43
17	12	10	88	30	12	19.34
18	60	10	88	30	12	19.76
19	36	8	88	30	12	24.43
20	36	12	88	30	12	29.91
21	36	10	84	30	12	24.55
22	36	10	92	30	12	36.42
23	36	10	88	10	12	16.38
24	36	10	88	50	12	37.89
25	36	10	88	30	10	27.46
26	36	10	88	30	14	24.63
27	36	10	88	30	12	32.89
28	36	10	88	30	12	32.45
29	36	10	88	30	12	34.25
30	36	10	88	30	12	31.25
31	36	10	88	30	12	32.40
32	36	10	88	30	12	33.19

5. Design of Experiment Using Central Composite Rotatable Design (CCRD)

The results were analyzed using a statistical tool namely MINITAB 19 software. The outcomes of the study were analyzed using ANOVA at a 5% level of significance using probability measures test (p-Test); and finally, predicting the response by RSM and a second-order polynomial mentioned in equation 3 was fitted to experimental data. As mentioned, the gutta-percha volume was recorded using weight analysis and volume measurement for five controllable parameters Canal Angle (α), Compaction Force (FT), Operating Temperature (T), Operating Frequency (F), and Operating Length (L). The detailed results of regression analysis and ANOVA are mentioned in Table 3. The obtained results show that the maximum mass of 0.03789 gms was recorded for experiment set no. 24 which is for combination of (X_1-X_2-X_3-X_4-X_5: 0-0-0-2-0: 36°-10 N-88 °C-50 Hz-12 mm). The regression model for gutta-percha-filled mass is within the significant level at α= 0.05. Furthermore, the probability measures i.e. p-values for the gutta-percha filled mass are less than α = 0.05, indicating that these models have strong significance and are sufficient within the 95 % confidence interval shown in Table 3. The probability measure values for mass of filled gutta-percha indicate that parameters such as X_2, X_3, X_4, and X_5: Compaction Force, Operating Temperature, Operating Frequency, and Operating Length have a significant effect on the Enhancement of GP Compaction along with the interaction terms such as $X_1* X_3$, $X_2* X_3$, $X_2* X_4$, and $X_2* X_5$ have significant contribution since the p-values are less than 0.05. But the closest value is taken into consideration i.e. X_2, X_3, $X_1* X_3$. and the gutta-percha enhancement can be obtained mathematically through the equation containing all the significant parameters affecting the mass of filled gutta-percha shown in Equation 3.

$$GP\ Enhancement = 0.32998 + 0.01079\,X_2 + 0.02850\,X_3 + 0.01212\,X_1 * X_3 \tag{3}$$

Table 3. Regression analysis and ANOVA for GP enhancement

Predictor	Coeff	P-Value	Predictor	Coeff	P-Value
Constant	0.32998	0.000*	-	-	-
X_1	-0.00239	0.366	$X_2* X_4$	0.00774	0.030*
X_2	0.01079	0.001*	$X_2* X_5$	-0.00773	0.030*
X_3	0.02850	0.000*	$X_3* X_4$	0.00405	0.219
X_4	0.05295	0.000*	$X_3* X_5$	0.00528	0.117
X_5	-0.00606	0.036*	$X_4* X_5$	0.00005	0.988
$X_1* X_2$	-0.00042	0.894			
$X_1* X_3$	-0.01212	0.002*			
$X_1* X_4$	-0.00561	0.099			
$X_1* X_5$	0.00012	0.969			
$X_2* X_3$	-0.00669	0.049*			

Regression Output

S	R-sq.	R-sq.(adj)	R-sq.(pred)
0.0124325	98.88%	96.85%	80.69%

ANOVA Output

Source	DF	SS	MS	F value	P value
Regression	20	0.150633	0.007532	48.73	0.000
Linear	5	0.090586	0.018117	117.21	0.000
Square	5	0.053851	0.010770	69.68	0.000
Interaction	10	0.006196	0.000620	4.01	0.016
Residual Error	11	0.001700	0.000155		
Lack of Fit	6	0.001208	0.000201	2.04	0.225
Pure Error	5	0.000492	0.000098		
Total	31	0.152333	* Indicates the Significant Terms		

5.1 Effect of Canal Length on Compaction

The canal operative length is the primary geometry parameter. The probability measure value indicates canal operative length was found to be superior to canal angle towards contributing to the success in terms of gutta-percha compaction enhancement. The behaviour of canal operative length on gutta-percha compaction is represented in Fig. 5 and has a p-value of 0.036. The filled quantity of gutta-percha shows a wavy trend throughout the bound of considered length. The maximum value of 0.24 gms was recorded for 12mm canal length in mild curvature i.e., canal angle between 20° - 40°. For the other two types of curvature, the trend remains the same and the maximum value is recorded at 12mm working length. Thus 12 mm length was found to be ideal.

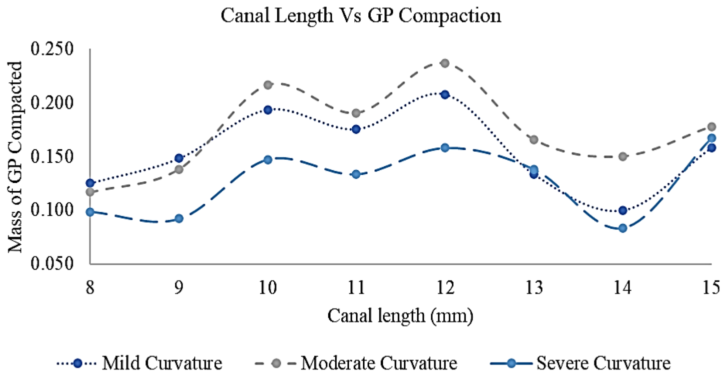

Fig. 5. Effect of canal length on GP compaction

5.2 Effect of Compaction Force on Compaction

The compaction force behaviour was recorded for all types of canal curvatures. In all the curvatures gutta percha were filled using Heat+ Vibration techniques. Fig 6 shows that with an increase in compaction force higher mass of gutta-percha gets compacted. At 12 N the maximum compaction was observed for all types of curvatures i.e., for mild curvature 0.7 gms mass was compacted. Thus, the compaction force of 12 N is considered to be the ideal force where maximum compaction was recorded and then the trend declined as shown in Fig 6. The compaction signature declines post 12 N due to changes in the canal geometry on account of excess loading. The ideal load range is between 5 to 15 N (27).

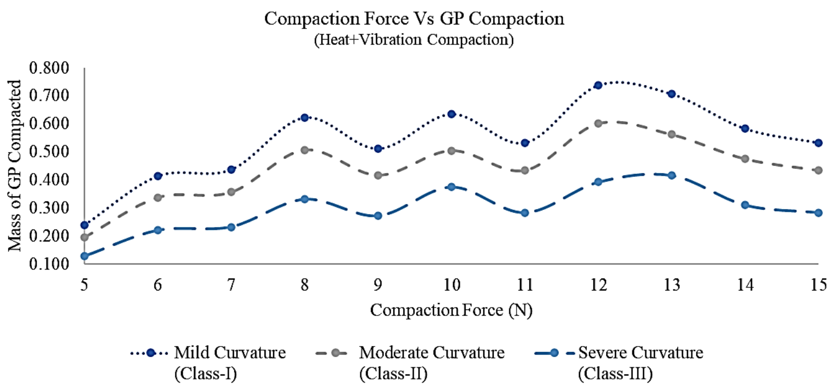

Fig 6: Effect of compaction force in compaction

5.3 Effect of Frequency on Compaction

The traditional obturation deals with single energy compaction i.e., heat compaction. Under the scope of the study, two types of energy are utilized in compaction gutta-percha i.e., heat energy in the form of temperature and vibration energy. The individual effect of heat and vibration on the mass of compacted gutta-percha was recorded. During pilot experimental trials with only vibration energy with varying frequencies between 10-50 Hz, it was observed that at 50 Hz, a significant rise in gutta-percha compaction was recorded as represented in Fig. 7. Also, the heat energy i.e., the temperature was varied between 80-100 °C. This range was selected from the primary data recorded from published literature and found that operating temperature in the range of 90°C to 96°C gives compaction in a higher range but at 92°C, compaction was found to be maximum as shown in Fig. 8.

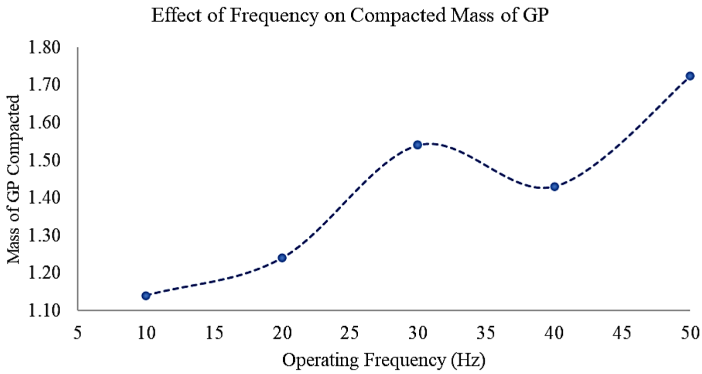

Fig. 7. Effect of frequency on the Compacted Mass of Gutta-percha

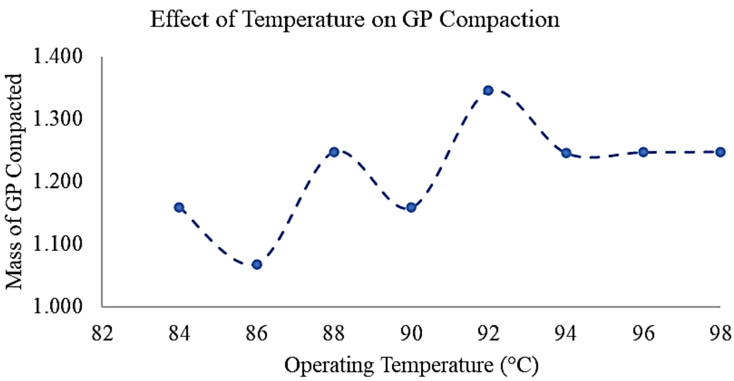

Fig. 8. Effect of Heat on the Compacted Mass of Gutta-percha

The effect of all the parameter was studied and the optimal operating parameter parameters range were determined and represented in Fig. 9, Fig. 10, and Fig. 11. This gives a clear guideline for designing a dual energy obturation device. The ideal operative range is seen in the highlighted area. The ideal force was found to be around 10-12 N and the operative frequency was towards 40-50 Hz. This result was found to be very much in line with numerical and mathematical studies.

Fig. 10 shows the interaction between force and temperature for enhancing GP compaction. The ideal parameter range was found to be in the range of 90 °C – 92 °C and an operating force of 10-11 N. Fig. 11 shows a contour plot for gutta-percha enhancement against Frequency and Temperature. The ideal temperature was found to be 90-92 °C at 40-50Hz Frequency.

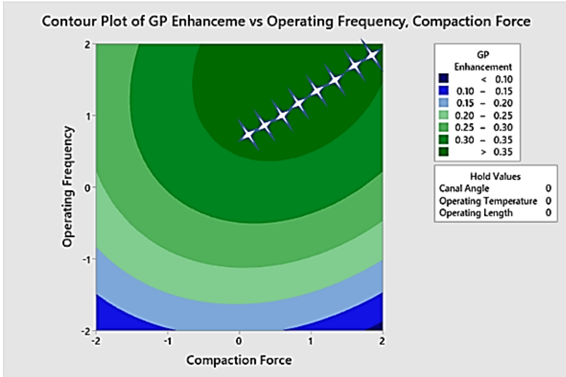

Fig. 9*.* Contour Plot for gutta-percha Enhancement VS Force and Frequency

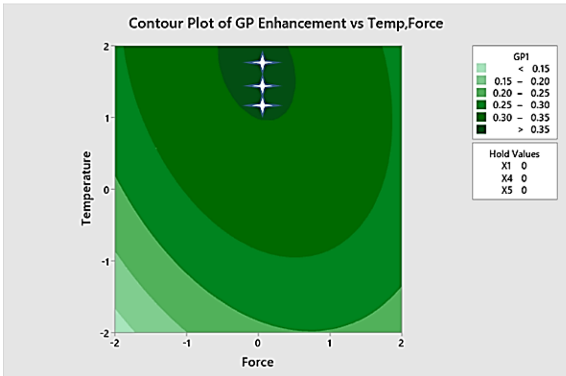

Fig. 10**.** Contour Plot for gutta-percha Enhancement VS Force and Temperature

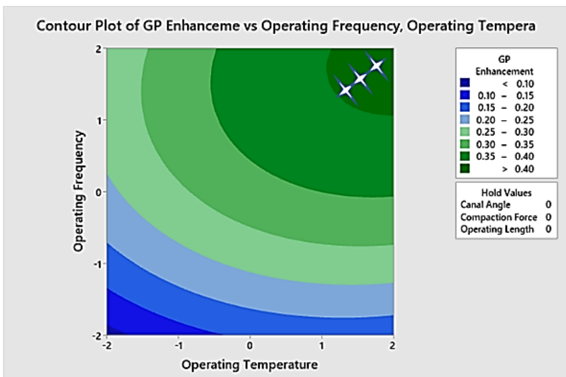

Fig. 11. Contour Plot for gutta-percha Enhancement VS Frequency and Temperature

6. Conclusion

The presented study was carried out to analyze the interaction effect of operative parameters on GP compaction enhancement and the following conclusions must be drawn-

- The regression analysis for GP Enhancement indicates that parameters such as X_2, X_3, X_4, and X_5: Compaction Force, Operating Temperature, Operating Frequency, and Operating Length have a significant effect on the Enhancement of GP Compaction along with higher order terms and interaction terms have significant contribution since the model values for P are less than 0.05.
- By implementing the Central Composite Rotatable Design and conducting 32 experimental trials for five operative parameters, the ideal operative parameters were determined. It was discovered that to achieve maximum gutta-percha compaction, the compaction force should be 10 N, the operating temperature should be between 90 and 92° C, the operating frequency should be between 40 and 50 Hz, and the operational length should be 12mm.

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