Modelling and Optimization of the Impact Resistance of Graphene Oxide Modified Crumb Rubber-ECC Using Response Surface Methodology

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Abstract. This paper presents the findings of an investigation on the impact resistance of graphene oxide (GO) modified rubberized engineered cementitious composite (GOCRECC) and the development of response-predictive models and optimization using response surface methodology (RSM). The input factors considered as the independent variables were the GO at 0, 0.02, 0.04, 0.06 and 0.08% addition by cement weight and crumb rubber (CR) at 1, 3 and 5% replacement of fine aggregate. Fifteen mixes having different quantities of input factors were used for the determination of the initial (E1) and ultimate (E2) impact energy using the ACI 544.R drop weight impact test method. The results showed that impact resistance of the GOCRECC mixes increased with increasing contents of the input factors. Response predictive models for E1 and E2 were developed and found to have high R² values of 78 and 93% respectively, after validation using the analysis of variance (ANOVA). The optimization performed yielded an optimal amounts of the input factors of 0.0347 and 5% for GO and CR respectively at a desirability value of 74%.

1. Introduction

As the world experiences rapid urbanization, there is an increasing demand for efficient, innovative and eco-friendly building materials to cope with the growing infrastructures. Cementitious composites are the most popular materials used for the construction of various structures. These structures are often subjected to extreme conditions of loading in static or dynamic manner. Many structures and structural elements may be subjected to impact loadings from different sources. For example, the impact on structures due to vehicular accidents, impact caused by falling objects on structures, impact of bullets and explosives due to war or terror incidents, impact of water on structures etc. [1]. Due to the brittle nature of cementitious composites, severe failure can occur owing to these loads [2]. Their low resistance to cracking and poor energy absorption ability make them susceptible to failure due to sudden impacts. It therefore became necessary to develop new innovative building materials with high damage tolerance, deformation capacity, ductility and energy absorption that could withstand the impact loads and prevent catastrophic failure [3].

The development and use of Engineered Cementitious Composite (ECC) have proven to be very useful as it resists impact loading much better than conventional and fiber reinforced concrete (FRC). ECC is able
to outperform FRC because of its superior ductility. It has a strain capacity of 3 to 7%, which is 300 to 700 times more than normal concrete [4]. In addition, it is capable of withstanding more load beyond the initial crack strength by exhibiting a pseudo-strain hardening behavior similar to steel. This behavior is achieved by applying the principles of micromechanics to tailor the matrix, the polymeric fiber; usually polyvinyl alcohol (PVA) fiber with a volume fraction less than or equal to 2%, and their interface. This allows the development and propagation of microcracks controlled at width of less than 100 μm. The use of only fine aggregates with no coarse aggregates in the mix also contributes to the ultra-high ductility of the ECC [5].

With the increasing use of ECC beyond repair and retrofit purposes and its high energy absorption properties due to its exceptional ductility and low elastic modulus, some researchers have investigated its behavior under impact load. The behavior of self-consolidating ECC (SCECC) under repeated impact was studied by Ismail et al. [6]. The result showed that the combination of slag, silica fume, or metakaolin with fly ash in SCECC could produce composites with improved mechanical properties, sufficient ductility, and increased impact strength. Moreover, increased impact resistance in SCECC has been reported to be much higher than that achievable with self-compacting concrete [6]. Similarly, the impact resistance of strain-hardening cementitious composite containing recycled fibers was investigated by Lo et al. [7]. It was reported that the use of polyethylene terephthalate (PET) fibers recycled from plastic waste as a substitute for PVA fibers in ECC could produce a PET-ECC with comparable energy absorption with PVA-ECC, thereby reducing the manufacturing cost of the composite. Similarly, Ali et al. [3] studied an ECC containing hybrid fibers. The results showed that the shape memory alloy (SMA) fibers considerably improved the ECC’s impact and tensile strengths. A similar conclusion on the improvement of impact strength of ECC by SMA was made by Mohammed et al. [8]. Soe et al. [9] also reported an improvement in the impact resistance of a hybrid-fiber ECC containing 1.75% and 0.58% PVA and steel fibers, respectively. Findings on the resistance of hybrid-fibers ECC to high-velocity impact were reported by Bell et al. [10], Li and Zhang [11] and Maalej et al. [12].

Hence, it is obvious that the resistance of ECC to impact load has been investigated with positive outcomes attributed to its ductility. However, there is still an ongoing debate on the negative influence of strain loading rate on the ductility of ECC. A reduction in the tensile capacity of ECC from 3% to 0.5% was reported with a strain range from 0.0001/s to 0.1/s [13]. A similar descending trend in the ductility of ECC was observed by Mechtcherine et al. [14] when the strain rate increased from 0.00001/s to 1/s. However, at 25/s and 50/s, the trend was observed to reverse. In the same vein, Douglas and Billington [15] reported an increase in the composite’s brittleness at higher loading rates. Similar findings were reported by Yu and Ranade et al. [16, 17]. Conversely, other researchers have reported no change in the ductility of the composite with an increase in the loading rate [12, 18, 19]. These discrepancies in the ductility of ECC with rate of strain rate prompted Zhang et al. [2] to investigate the effect of incorporating CR on the impact behavior of ECC. According to the findings, the CR considerably improved the damage tolerance of PVA-ECC and delayed the load-rate dependency in ductility [2].

This study aims to assess resistance of graphene oxide (GO) modified rubberized ECC (GOCRECC) subjected to drop-weight impact. Although previous studies have demonstrated an enhancement in the impact resistance of ECC with CR, the poor bonding between the cement matrix and the rubber particles led to lower compressive strength and the decline in the impact resistance of the composite with increased CR content [20]. The high reactivity of GO, which results from the abundance of oxygen functional groups on its basal planes, will be employed to improve the composite's performance by strengthening it at nanoscale level by improving the interfacial interaction between the CR and the hardened matrix within the composite.

The aim of the research is achieved through the use of response surface methodology (RSM), which is an experimental design method that uses statistical and mathematical analyses approaches for the development of empirical models known as response surface models. These models can also be graphically represented using response surface diagrams. This requires determining the influence of the interaction...
between various levels of input factors (independent variables) and the response (dependent variable). The response is determined empirically, and the data is fitted using a suitable model. The models are validated using analysis of variance (ANOVA). In addition, optimization is carried out to identify the optimal amounts of the input factors required to provide the most efficient response [21, 22].

2. Experimental Program

2.1 Materials

The cement used is type I Ordinary Portland cement (OPC) complying to ASTM C150 specifications. The fly ash (FA) used satisfied the ASTM C618 requirements and is classified as F based on the total SiO₂, Fe₂O₃ and Al₂O₃ contents of more than 70% as presented in Table 1 showing the chemical composition of the OPC and FA used. Fine aggregate with a specific gravity and fineness modulus of 2.65 and 2.5, respectively was used. The CR used has particle size passing 1.18 mm sieve as shown in the grading curve for the fine aggregate and CR in Figure 1. Highly concentrated GO dispersion (2.5 wt. %) having the properties shown in Table 2 was used. PVA fiber used is produced by Kuraray Company Japan having a length, diameter, aspect ratio, modulus of elasticity and tensile strength of 18 mm, 200 μm, 90, 27 GPa and 750 MPa, respectively. A high range water reducing admixture (polycarboxylate based) with brand name Sika-ViscoCrete 2044 was used to attain the required self-consolidating requirements of the composite in fresh state.

Table 1. Oxide composition and properties of the cement and FA used

| Oxide | OPC (%) | FA (%) |
|-------|---------|--------|
| SiO₂  | 8.59    | 62.4   |
| Al₂O₃ | 2.00    | 15.3   |
| Fe₂O₃ | 3.18    | 9.17   |
| CaO   | 81.10   | 6.57   |
| K₂O   | 0.72    | 1.49   |
| MgO   | 0.62    | 0.77   |
| SO₃   | 2.78    | 0.65   |
| P₂O₅  | 0.46    | 1.23   |
| TiO₂  | 0.17    | 1.32   |
| MnO   | 0.15    | 0.77   |
| Na₂O  | 0       | 0.385  |
| LOI   | 2.2     | 1.25   |
| Specific Gravity | 3.15 | 2.38 |
Figure 1. Grading curves of fine aggregate and CR.

Table 2. Properties and elemental analysis of GO.

| Element   | Concentration (%) | Form                  | Properties                        | Slurry          |
|-----------|-------------------|-----------------------|-----------------------------------|-----------------|
| Carbon    | 49 – 56           |                       | D90: 29 – 33                       |                 |
|           |                   |                       | D50: 14 – 17                       |                 |
| Hydrogen  | 0 – 1             |                       | D10: 6 – 7                         |                 |
| Nitrogen  | 0 – 1             | Color, Odor           | Dark brown, Odorless               |                 |
| Sulfur    | 2 – 4             | Dispersibility, pH    | Concentration (wt. %), pH (4mg/mL dispersion) | 2.5             |
| Oxygen    | 41 – 50           |                       | 1.8 – 2.0                          |                 |

2.2 RSM mix proportioning

The user defined option of the RSM was used to develop 15 distinct mixes having different levels of the GO addition and CR replacement of fine aggregate. The GO was added as a percentage weight of cement at 0, 0.02, 0.04, 0.06 and 0.08%. The CR replaced fine aggregate at 1, 3 and 5% by volume. The quantities of the ingredients were based on the mix proportion for standard ECC-M45 mix as presented in Table 3. Water binder ratio (W/B), FA/B and fine aggregate binder ratios of 0.25, 1.2 and 0.36 were used, respectively. Adequate amount of superplasticizer was used based on each mix requirement to achieve the desired self-compacting properties as recommended by European committee on self-compacting concrete (EFNARC 2002). Furthermore, a control mix of normal ECC (NECC) having 0% GO and 0% CR was produced for comparison.
Table 3. RSM variable proportioning and quantities of materials.

| Run (Mix) | Factor 1 | Factor 2 | PVA | FA | Quantities of Materials (Kg/m³) |
|-----------|----------|----------|-----|----|---------------------------------|
|           | A:GO %   | B:CR %   |     |    | GO  | CR  | PVA | FA  | Cement | Sand | Water |
| M1        | 0.02     | 3        | 1.75| 55 | 0.115| 3.9 | 22.75| 705.65| 577.35 | 463.1 | 320   |
| M2        | 0.08     | 3        | 1.75| 55 | 0.462| 3.9 | 22.75| 705.65| 577.35 | 463.1 | 320   |
| M3        | 0.08     | 1        | 1.75| 55 | 0.462| 3.9 | 22.75| 705.65| 577.35 | 463.1 | 320   |
| M4        | 0.04     | 5        | 1.75| 55 | 0.231| 6.5 | 22.75| 705.65| 577.35 | 460.5 | 320   |
| M5        | 0.02     | 5        | 1.75| 55 | 0.115| 6.5 | 22.75| 705.65| 577.35 | 460.5 | 320   |
| M6        | 0        | 3        | 1.75| 55 | 0    | 3.9 | 22.75| 705.65| 577.35 | 463.1 | 320   |
| M7        | 0.04     | 3        | 1.75| 55 | 0.231| 3.9 | 22.75| 705.65| 577.35 | 461.3 | 320   |
| M8        | 0.04     | 1        | 1.75| 55 | 0.231| 1.3 | 22.75| 705.65| 577.35 | 465.7 | 320   |
| M9        | 0        | 5        | 1.75| 55 | 0    | 6.5 | 22.75| 705.65| 577.35 | 460.5 | 320   |
| M10       | 0.06     | 5        | 1.75| 55 | 0.346| 6.5 | 22.75| 705.65| 577.35 | 460.5 | 320   |
| M11       | 0.06     | 3        | 1.75| 55 | 0.346| 3.9 | 22.75| 705.65| 577.35 | 463.1 | 320   |
| M12       | 0.02     | 1        | 1.75| 55 | 0.115| 1.3 | 22.75| 705.65| 577.35 | 465.7 | 320   |
| M13       | 0.08     | 5        | 1.75| 55 | 0.462| 6.5 | 22.75| 705.65| 577.35 | 460.5 | 320   |
| M14       | 0        | 1        | 1.75| 55 | 0    | 1.3 | 22.75| 705.65| 577.35 | 465.7 | 320   |
| M15       | 0.06     | 1        | 1.75| 55 | 0.346| 1.3 | 22.75| 705.65| 577.35 | 465.7 | 320   |
| NECC      | 0        | 0        | 1.75| 55 | 0    | 0   | 22.75| 705.65| 577.35 | 466.6 | 320   |

2.3 GOCRECC mixing and sample preparation

The dry components comprising the cement, FA, CR and fine aggregates were dry mixed in a pan mixer for 3 minutes. All the components were mixed for 5 minutes after the GO suspension, water, and SP (1 percent by cement weight as a starting amount) were added. To prevent clumping, the PVA fiber was carefully added to the mix while the mixer was running. Based on the mix demand, more SP is added (at 0.5% interval) to ensure that the self-consolidating requirements are attained. The mixing is continued for 10 minutes until when the fresh GOCRECC looks consistent without fiber balling.

For the impact test, 100 mm diameter and 50 mm thick cylinder samples were cast [3]. The samples were demoulded after 24 hours and placed in a curing tank at 20°C and 95 percent relative humidity for 28 days.

2.4 Drop weight impact test

An impact test using a drop weight was carried out in accordance with the American Concrete Institute (ACI) Committee 544.R recommendations. [3]. As suggested by Adamu et al. [23], using the manual impact test apparatus will be very tedious for a material expected to have high number of blows. Hence, an automatic Marshall compactor was used. The compactor has a sliding hammer of 4.5 kg and falling height of 457 mm. The test was set up by clamping 63.5 mm steel ball on the sample to receive the falling hammer and transfer the impact to the sample as depicted in Figure 2. The number of strikes required to induce the initial crack (N1) as shown in Figure 3 (a) was recorded. The test was continued by subjecting the samples to more blows of the impact hammer until it fails by exhibiting deep wide cracks as depicted in Figure 3 (b). The number of blows to cause failure was recorded as N2. The impact energy for both first and ultimate blows were calculated from Equation [1].
\[ E = N \cdot m \cdot g \cdot h \]  

(1)

Where the impact energy (in Joules) is represented by \( E \), \( N \) represents the number of the impact hammer blows, the mass of the drop hammer is given as \( m \), \( g \) is the acceleration due to gravity (10 m/s\(^2\)) and \( h \) is the height of drop.

**Figure 2.** Drop weight Impact test set up

**Figure 3.** Failure pattern of GOCRECC a (a) First rack (b) Ultimate crack
Results and Discussion

3.1 Impact resistance

The results of the impact test performed on the GOCRECC are presented in Table 4. Also, the result of initial (N1) and ultimate (N2) number of blows is graphically depicted in Figure 4. N1 is associated with the first sign of deterioration of the composite under repeated impact loading as shown in Figure 3 (a). More blows of the impact hammer were applied to the samples until large radial cracks extending through the samples were achieved, as illustrated in Figure 3 (b). A wide variation in the initial and ultimate energy absorptions of the composite was observed, similar to the findings of previous researchers [20, 23]. Despite the variability in the test results, the findings suggest that increased CR and GO content led to the greater capacity of the mixes to withstand more impacts, as seen in Figure 5 and hence increased energy absorption. For example, compared with the reference mix (NECC), M10 (the highest) has a 555% and 589% increase in the number of blows at 0.06% GO and 5% CR replacement for the first crack and ultimate crack, respectively. The positive influence of CR on the impact resistance of rubberized composites has been attributed to the lower elastic modulus of CR which reduced the brittle behavior of the composite and enhanced its ductility and energy absorption [23, 24].

On the other hand, the presence of GO in the mix is novel in this circumstance. The results support recent findings that GO increases the strength of cementitious composites [25, 26]. Because of the structure of the GO nano-sheets, they bridge across cracks at nano level within the matrix and prevent them from expanding further, increasing the composite's resilience to impact. Furthermore, because of the availability of oxygen-containing functional groups on the surface of the GO nanosheets, the bonding between CR and cement paste was enhanced, resulting in improved stress transfer at the interfacial transition zone (ITZ), with the CR acting as micro shock absorbers and mitigating the impact effect. This effect contrasts sharply with nano-silica, which has been found to reduce post-crack impact resistance due to the spherical shape of its particles. Unlike the GO nano-sheets, the nano silica particles only perform pore-filling effect thereby densifying the matrix but have no fiber bridging effect [23].

### Table 4. GOCRECC drop weight impact test result.

| Mix Number | A: GO (%) | B: CR (%) | N1 | N2 | E1 (J) | E2 (J) |
|------------|-----------|-----------|----|----|--------|--------|
| M1         | 0.02      | 3         | 35 | 462| 720    | 9501   |
| M2         | 0.08      | 3         | 68 | 698| 1398   | 14354  |
| M3         | 0.08      | 1         | 40 | 413| 823    | 8493   |
| M4         | 0.04      | 5         | 60 | 622| 1234   | 12791  |
| M5         | 0.02      | 5         | 46 | 560| 946    | 11516  |
| M6         | 0         | 3         | 38 | 246| 781    | 5059   |
| M7         | 0.04      | 3         | 56 | 501| 1152   | 10303  |
| M8         | 0.04      | 1         | 35 | 401| 720    | 8247   |
| M9         | 0         | 5         | 38 | 250| 781    | 5141   |
| M10        | 0.06      | 5         | 72 | 703| 1481   | 14457  |
| M11        | 0.06      | 3         | 61 | 654| 1254   | 13450  |
| M12        | 0.02      | 1         | 30 | 302| 617    | 6211   |
| M13        | 0.08      | 5         | 61 | 703| 1254   | 14457  |
| M14        | 0         | 1         | 26 | 162| 535    | 3332   |
| M15        | 0.06      | 1         | 30 | 385| 617    | 7918   |
| NECC       | 0         | 0         | 11 | 102| 226    | 2098   |
3.2 RSM Modelling and Optimization

3.2.1 Modelling and ANOVA validation

The impact resistance of the GOCRECC given by the initial (E1) and ultimate (E2) impact energy are the responses in this case. As shown in Equations (2) and (3), a linear and quadratic models were found more suitable to fit the empirical response data for E1 and E2 respectively.

\[
E1 = + 954.23 + 254.94 \times A + 238.45 \times B
\]  
(2)
\[
E2 = +11.68E3 +3.74E3 * A +2.42E3 * B +0.95E3 * AB - 2.29E3 * A^2 - 1.28E3 * B^2
\]

Where A represents the GO addition in percentage of binder weight and B is the CR replacement of fine aggregate by volume.

Table presents the ANOVA results of the developed models. The analysis was performed at 95% confidence level. Hence any model or model term with a probability of less than 0.05 (5%) is considered statistically significant. It can be seen here that all the models are significant having probabilities of less than 0.05 for both E1 and E2. Furthermore, for E1, both A, B were found to be significant model terms. While A, B, A^2 and B^2 model terms were found to be significant in the case of E2.

Model validation parameters are presented in Table 6. One of the important parameters is the coefficient of determination (R^2). High value of R^2 on a scale of 0 to 1 (0-100%) shows how well the selected model fits the data. High R^2 values of 78 and 93% were observed for E1 and E2 respectively. Similarly, for a good model, a difference of less than 0.2 is required between the adjusted (Adj.) R^2 and predicted (Pred.) R^2 (27). The difference between the Adj. R^2 and Pred. R^2 is in good agreement for both E1 and E2 with a difference of less than 0.2. For a model to be used to adequately navigate the design space, an adequate precision (Adeq. Precision) of 4 or more is desired as a measure of signal to noise ratio. In this case, an Adeq. Precision of 13.82 and 19.69 was obtained for both models.

**Table 5. ANOVA result**

| Response | Source | Sum of Squares | Df | Mean Square | F - Value | P - Value > F | Significance |
|----------|--------|----------------|----|-------------|-----------|---------------|--------------|
| E1 (J)   | Model  | 1056071        | 2  | 528035.5    | 20.724799 | 0.0001281     | Yes          |
|          | A – GO | 487463.13      | 1  | 487463.13   | 19.132379 | 0.0009057     | Yes          |
|          | B – CR | 568607.87      | 1  | 568607.87   | 22.317219 | 0.0004935     | Yes          |
|          | Residual | 305741.25    | 12 | 25478.437   |           |               |              |
|          | Cor Total | 1361812.2   | 14 |             |           |               |              |
| E2 (J)   | Model  | 1.87E+08       | 5  | 3.74E+07    | 3.83E+01  | 8.46E-06      | Yes          |
|          | A – GO | 1.05E+08       | 1  | 1.05E+08    | 1.07E+02  | 2.66E-06      | Yes          |
|          | B – CR | 5.84E+07       | 1  | 5.84E+07    | 5.96E+01  | 2.93E-05      | Yes          |
|          | AB     | 4.55E+06       | 1  | 4.55E+06    | 4.65E+00  | 5.94E-02      | No           |
|          | A^2    | 1.38E+07       | 1  | 1.38E+07    | 1.41E+01  | 4.54E-03      | Yes          |
|          | B^2    | 5.44E+06       | 1  | 5.44E+06    | 5.55E+00  | 4.28E-02      | Yes          |
|          | Residual | 8.81E+06    | 9  | 9.79E+05    |           |               |              |
|          | Cor Total | 1.96E+08   | 14 |             |           |               |              |

**Table 6. Model validation parameters**

| Model Validation Parameters | Std. Dev. | Mean | C.V. % | PRESS | -2Log Likelihood | R^2 | Adj . R^2 | Pred . R^2 | Adeq. Precision | AIC |
|---------------------------|-----------|------|--------|-------|-----------------|-----|-----------|-------------|-----------------|-----|
| Response                  |           |      |        |       |                 |     |           |             |                 |     |
| E1 (J)                    | 159.6     | 2    | 16.7   | 4.90E+0 | 191.40         | 0.7 | 0.7       | 0.64        | 13.82           | 199.5|
| E2 (J)                    | 989.4     | 2    | 10.2   | 2.64E+0 | 241.82         | 0.9 | 0.9       | 0.87        | 19.69           | 258.0|
A response surface model graph gives a visual depiction of the effect of the interaction of the independent variables on the response (dependent variables). This is achieved through the 2D contour plot and the 3D response surface diagram as shown in Figures 6 and 7 for E1 and E2, respectively. The graphs give information on the amount of the input variables that will interact to yield certain levels of the responses. The red regions depict areas of high response intensities, the intermediate intensities are represented by green regions while the blue regions are the lowest intensity values.

Similarly, among the most vital model diagnostic tools are the “Normal Plot of Residuals” and the plot of “Predicted versus Actual” values as shown in Figure 8 and 9 for E1 and E2, respectively. In both graphs, the linearity of the data points shows the strength of the developed model in predicting the responses [28].

Figure 6. Response surface plots for E1 (2D contour and 3D surface diagram)

Figure 7. Response surface plots for E2 (2D contour and 3D surface diagram)
3.2.2 Optimization

To obtain the optimal amounts of the input factors to produce a GOCRECC with the most desirable energy absorption (impact resistance), an optimization was performed. Optimization using RSM is accomplished by specifying a target for the variables (maximum, minimum, or in range) and the response (maximize or minimize) and letting the RSM execute the operation. The optimization result is assessed by a value known as “desirability”, based on a scale of 0 to 1 (0 to 100%). A value of desirability close to one indicates the high accuracy and relevance of the response model.

The Optimization criteria used is presented in Table 7. The objective was to maximize the responses at the minimum value of the GO and maximum value of the CR. The solution is shown by the optimization ramp diagram and the 3D response surface plot in Figure 13 (a) and (b), respectively. From the results, the desirability value of 0.739 (74%) was obtained showing the accuracy of the optimization. The proposed optimal amount of the input factors are 0.037% and 5% for the GO and CR respectively to achieve initial and ultimate impact energy (impact resistance) of 1177 J and 12512 J, respectively.

| Factors                  | Value Goal          | Minimum | Maximum | Goal  |
|--------------------------|---------------------|---------|---------|-------|
| Variable (input factors) | GO (%)              | 0       | 0.08    | Minimize |
|                          | CR (%)              | 1       | 5       | Maximize |
| Responses (output factors)| E1 (J)             | 535     | 1481    | Maximize |
Conclusion
This research was performed to investigate the impact resistance of GO modified rubberized ECC (GOCRECC) and develop response predictive models for the energy absorption (impact resistance) of the composite. The following conclusions were drawn:

1. The impact resistance of the composite increased with increasing CR replacement of fine aggregate. This is attributed to the reduction of the brittle behavior of the composite by the low elastic modulus CR.

2. An increase in the GO addition led to a corresponding increase in the energy absorption of the composite. This is due to the GO nano-sheet particles which intercept crack growth at nano level preventing them from propagating.

3. The combined effect of the GO and CR led to a high impact resistance of the composite. The GO enhanced the bonding between the CR and the cement paste and improved stress transfer between the hardened cement matrix and the CR at the ITZ.

4. Response predictive models were developed and validated using ANOVA and found to have high R^2 values of 78 and 93% for E1 and E2 respectively. An optimization was performed and yielded an optimum values of 0.037 and 5% for the GO and CR, respectively, to develop a GOCRECC with a predicted E1 and E2 values of 1177 J and 12512 J, respectively.

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