Taguchi Grey Relational Optimization of the Multi-mechanical Characteristics of Kaolin Reinforced Hydroxyapatite: Effect of Fabrication Parameters

Johnson Kehinde Abifarin¹, * | David Olubiyi Obada¹ | Emmanuel Toi Dauda² | Elijah Oyewusi Oyedeji³

¹Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria
²Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria
³National Space Research and Development Agency (NASRDA), Abuja, Nigeria

*Corresponding author: jkabifarin@abu.edu.ng

Received 5 August 2021; Revised 9 September 2021; Accepted 10 September 2021

Abstract: Comparative study of kaolin reinforced hydroxyapatite (KHAp) and pure HAp using different production parameters has been done through traditional experimentation. However, the quantitative effect, optimization of kaolin reinforcement and fabrication parameters have not been investigated. Hence, this study examines the effect of kaolin reinforcement, compaction pressure and sintering temperature on the experimental mechanical properties of HAp. Taguchi design assisted by grey relational analysis was employed with L36 (2**2 3**1) orthogonal array. The Minitab 16 software was used to analyze the Taguchi design. The result showed a disparity in kaolin reinforcement as the optimum condition for individual mechanical properties, but the grey relational analysis showed better mechanical properties with kaolin reinforcement, 500 Pa compaction pressure and 1100 °C sintering temperature. The obtained result further revealed kaolin reinforcement as a strong and promising reinforcing material for high strength clinical application, having a contribution of 93.16% on compressive strength of HAp. Therefore, future studies can be conducted in the use of different wt% of kaolin on the multi-response mechanical characteristics of HAp.

Keywords: Grey relational analysis; optimization; hydroxyapatite; kaolin; production parameters; mechanical properties

1. Introduction

Hydroxyapatite (HAp) with the chemical formula of Ca10(PO4)6(OH)2 is a calcium phosphate based bio-ceramic because it forms a mechanically strong bond to bone and typically no fibrous particles are found inherent on the implants’ surface. These attractive properties make HAp a good material in clinical applications such as bio-medical implants and substitutes for the repair of damaged bones (Caliman et al., 2017; Adeogun et al., 2018). The constant use of HAp is due to its unique chemical composition, in addition to its biological and crystallographic similarity with the
mineral portion of hard tissues, for instance, bones and teeth. HAp has received attention as a good candidate for biomedical application, due to its excellent biocompatibility and high rate of cell proliferation. Because of its poor mechanical strength, extensive research has been geared towards the improvement of HAp mechanical properties. The use of foreign material as a reinforcing agent has been reported in the literature (Santos et al., 1994; Lahiri et al., 2012; Zhao et al., 2018; Singh et al., 2020; Singh et al., 2021). Reinforcement is an action or process of reinforcing or strengthening a weak material.

Taguchi design of the experiment is a method of mitigating laboratory robustness and also a way of optimizing design parameters or process parameters of singular response of a product or system. The design was named after the Japanese quality guru Genichi Taguchi who invented it (Taguchi & Phadke, 1989; Taguchi, 1993; Taguchi et al., 2005). While Grey Relational Analysis (GRA) is employed when there is a need to optimize design parameters for multiple response characteristics. It is also used when a process or design is uncertain or complicated (Julong, 1989; Javed, 2019).

This study employed Taguchi design assisted by the GRA to mitigate the indecision on the best combination of fabrication parameters for better mechanical integrity of HAp. Taguchi-grey relational analysis has been used as follows: Sylajakumari et al. (2018) optimized production parameters on the multi-wear responses of a co-continuous composite with the help of Taguchi-grey relational analysis. Bademlioglu et al. (2020) employed Taguchi grey relational analysis to investigate and to optimize the working parameters affecting the multiple performance characteristics of an organic Rankine cycles. Almetwally (2020) carried out multi-objective optimization of woven fabric parameters using Taguchi-grey relational analysis.

In light of the synthesis and mechanical improvement of hydroxyapatite, Abifarin et al. (2019) synthesized and characterized pure HAp for biomedical application. The mechanical properties of the synthesized HAp were further worked upon by Obada et al. (2020) and Obada et al. (2021) using 15 wt% kaolin and different sintering parameters. Recently, Abifarin (2021) employed Taguchi grey relational analysis to determine and to optimize quantitatively the effect of sintering parameters on pure HAp. Kaolin was employed as a reinforcement in the bulk HAp because it is a silica based materials with excellent biocompatibility (Obada et al., 2021). The reinforcement of HAp with kaolin in this study is referred to as kaolin reinforced HAp. Having reported traditional experimentation of 15 wt% kaolin reinforcement and the effect of compaction pressure and sintering temperature on the mechanical properties of HAp, it is expedient to examine the quantitative effect and the optimization of fabrication parameters of kaolin reinforced HAp. Hence, this study employed Taguchi grey relational analysis as the statistical tool to investigate the optimum production parameters and its quantitative effect on the mechanical properties of HAp. Table 1 describes the employed based materials and its fabrication parameters.

| Variable                        | Definition                                                                 | Reference                        |
|---------------------------------|---------------------------------------------------------------------------|----------------------------------|
| Hydroxyapatite                  | Hydroxyapatite is a calcium phosphate based ceramic, having chemical formula of Ca_{10}(PO_4)_{6}(OH)_2 | Posnet et al. (1958); Orlovskii et al. (2002) |
| Kaolin                          | Kaolin is a silica based material with a chemical formula of Al_2O_3-2SiO_2 | Murray (1980); Chen et al. (1997); Schroeder and Erickson (2014) |
| Reinforcement                   | Reinforcement is an action or process of reinforcing or strengthening a weaker material. | Seward (1956); Byrne and Clore (1970) |
| Kaolin reinforced hydroxyapatite| Kaolin reinforced hydroxyapatite is a composite showing hydroxyapatite as the main matrix, strengthened by kaolin | The present work                  |
| Sintering temperature           | It is the annealing temperature at which material mechanical and microstructural properties are improved | Kuang et al. (1997); Abifarin (2021) |
| Compaction pressure             | It is the pressure at which a material scaffold is formed or made           | German (2010); Abifarin (2021)    |
2. Materials and Method

HAp/KHAp synthesis, characterization and mechanical properties evaluation have been reported in the previous study (Obada et al., 2021). This study employed statistical Taguchi grey relational analysis to examine the quantitative effect of kaolin reinforcement and production parameters (compaction pressure and sintering temperature) on the reported experimental hardness and compressive strength. Figure 1 shows the overall experimental procedure on how the mechanical properties were obtained in the study of Obada et al. (2021).

2.1 Taguchi experimental design

The factors and their respective levels were employed based on the design consideration based on the previous study (Obada et al., 2021), and was formulated using Taguchi design strategy as shown in Table 2. The suitable orthogonal array employed according to Minitab 16 software was \( L_36 (2^{**2} 3^{**1}) \), and it is displayed in Table 3. The corresponding experimental hardness, compressive strength and resultant grey relational grade were analyzed using Taguchi on Minitab. The steps for generating the resultant grey relational grade for the experimental mechanical properties are shown in section 2.2, and are similar to the work of Abifarin (2021) and Awodi et al. (2021). All the plotted graphs were obtained using Minitab. Figure 2 shows the overview of Taguchi-grey relational optimization analysis.

2.2 Grey relational analysis

Integration of GRA into the Taguchi method can improve the performance of Taguchi method for optimization (Chang et al., 2000). As it is impossible to directly average experimental hardness and compressive strength, grey relational analysis was employed to address the impossibility (Julong, 1989; Javed et al., 2019). First, hardness and compressive strength values were converted to grey relational generation (normalizing the sequence) using the larger-the-better consideration as shown in Equation 1. The larger-the-better was employed because high hardness and compressive strength is desired. After sequence normalization, deviation sequence of the reference sequence was computed using Equation 2. Next, grey relational coefficient was generated using Equation 3, and thereafter the resultant hardness and compressive strength grey relational coefficients were average to have grey relational grade (GRG) using Equation 4.

Figure 1. Mechanical synthesis of pure and kaolin reinforced hydroxyapatite
Note that $x_i(k)$ is the normalized data for the $i^{th}$ experiment, and $y_i(k)$ denotes the initial sequence of the mean of the responses

$$\Delta_0i(k) = |x_0(k) - x_i(k)|$$

Here, $\Delta_0i(k)$, $x_0(k)$, and $x_i(k)$ are the deviation, reference and comparability sequences respectively.

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_0i(k)} + \zeta$$

where $\xi_i(k)$ symbolizes GRC of individual response variables calculated as a function of $\Delta_{\min}$ and $\Delta_{\max}$, the minimum and maximum deviations of each response variable. $\zeta$ is the distinguishing coefficient (Mahmoudi et al., 2020) whose value was considered 0.5 in the current study.

$$\gamma_i = \frac{1}{n} \sum_{i=1}^{n} \xi_i(k)$$

where $\gamma_i$ is the GRG determined for the $i^{th}$ experiment, $n$ is the aggregate count of the performance characteristics. Since the Taguchi orthogonal array design displayed three replications for the experimental run, the average grey relational grade (AGRG) for each treatment (sample) was computed afterwards.

**Table 2. Factors and their levels**

| Fabrication parameter | Wt% kaolin | Compaction pressure(Pa) | Sintering temperature (°C) |
|-----------------------|------------|-------------------------|----------------------------|
| Level 1               | 0          | 0                       | 900                        |
| Level 2               | 15         | 500                     | 1000                       |
| Level 3               | -          | -                       | 1100                       |
3. Results and discussion

3.1 Effect of kaolin and production parameters on hardness

Figure 3 shows effect of kaolin, compaction pressure and sintering temperature on HAp hardness value. The result revealed that 15 wt% of kaolin dropped HAp hardness value, but 500 Pa compaction pressure had a little increasing effect on the hardness value. However, increase in sintering temperature had a significant increasing effect on HAp hardness value. Hence, the optimal factors levels for better hardness are HAp without kaolin reinforcement, 500 Pa compaction pressure and 1100 °C sintering temperature.

3.2 Quantitative effect of reinforcement and production parameters on HAp hardness

Statistical ANOVA data of the Taguchi result is highlighted in Table 4. As effect of the considered factors has been discussed in section 3.1, it is important to have their quantitative effect which is displayed in Table 3. The result revealed that when kaolin reinforcement was not employed, there was a significant contribution of 46.04%. The sintering temperature factor shows the most significant contribution of 50.76% on HAp hardness value. Even though, 500 Pa

| Experimental no. | Wt% kaolin | Compaction pressure (Pa) | Sintering temperature (°C) |
|------------------|------------|--------------------------|---------------------------|
| 1                | 0          | 0                        | 900                       |
| 2                | 0          | 0                        | 1000                      |
| 3                | 0          | 0                        | 1100                      |
| 4                | 0          | 0                        | 900                       |
| 5                | 0          | 0                        | 1000                      |
| 6                | 0          | 0                        | 1100                      |
| 7                | 0          | 0                        | 900                       |
| 8                | 0          | 0                        | 1000                      |
| 9                | 0          | 0                        | 1100                      |
| 10               | 0          | 500                      | 900                       |
| 11               | 0          | 500                      | 1000                      |
| 12               | 0          | 500                      | 1100                      |
| 13               | 0          | 500                      | 900                       |
| 14               | 0          | 500                      | 1000                      |
| 15               | 0          | 500                      | 1100                      |
| 16               | 0          | 500                      | 900                       |
| 17               | 0          | 500                      | 1000                      |
| 18               | 0          | 500                      | 1100                      |
| 19               | 15         | 0                        | 900                       |
| 20               | 15         | 0                        | 1000                      |
| 21               | 15         | 0                        | 1100                      |
| 22               | 15         | 0                        | 900                       |
| 23               | 15         | 0                        | 1000                      |
| 24               | 15         | 0                        | 1100                      |
| 25               | 15         | 0                        | 900                       |
| 26               | 15         | 0                        | 1000                      |
| 27               | 15         | 0                        | 1100                      |
| 28               | 15         | 500                      | 900                       |
| 29               | 15         | 500                      | 1000                      |
| 30               | 15         | 500                      | 1100                      |
| 31               | 15         | 500                      | 900                       |
| 32               | 15         | 500                      | 1000                      |
| 33               | 15         | 500                      | 1100                      |
| 34               | 15         | 500                      | 900                       |
| 35               | 15         | 500                      | 1000                      |
| 36               | 15         | 500                      | 1100                      |
Compaction pressure had a little increasing effect, its contribution (0.24%) and the contribution of residual error (2.96%) on HAp hardness are insignificant.

3.3 Effect of kaolin and production parameters on compressive strength

It is important to note from the compressive strength result revealed in Figure 4 was significantly increased with inclusion of kaolin. The reason for the increment has been discussed in the previous study (Obada et al., 2021). Equally, this result showed that the two production parameters considered in this study had an increasing effect on the compressive strength of HAp. Meaning, the optimal factors are 15 wt% of kaolin reinforcement, 500 Pa compaction pressure and 1100 °C sintering temperature.

| Fabrication parameter | DOF | Adj SS   | Adj MS   | F     | Contribution % | Remark   |
|-----------------------|-----|----------|----------|-------|----------------|----------|
| Wt% of kaolin         | 1   | 0.128133 | 0.128133 | 15.54 | 46.04          | Significant |
| Compaction pressure   | 1   | 0.000655 | 0.000655 | 0.08  | 0.24           | Insignificant |
| Sintering temperature | 2   | 0.282524 | 0.141262 | 17.13 | 50.76          | Significant |
| Residual error        | 7   | 0.057720 | 0.008246 |       | 2.96           | Insignificant |
| Total                 | 11  | 0.278296 |          | S = 0.09081 | R² = 87.7%     | R²Adj = 80.7% |

![Figure 3. Effect of factors on hardness](image1)

![Figure 4. Effect of factors on compressive strength](image2)

![Figure 5. Effect of factors on grey relational grade](image3)
3.4 Quantitative effect of reinforcement and production parameters on HAP compressive strength

The quantitative effect of addition of kaolin and production parameters are shown in Table 5. Interestingly, other factors did not have much significance on HAP compressive strength except kaolin reinforcement having contribution of 93.16%. Meaning, without the consideration of the production parameters, kaolin reinforcement has a robust increasing effect on the compressive strength of HAP.

3.5 Grey relational evaluation

It is essential to optimize input processing parameters of HAP for its multiple mechanical properties. Grey relational analysis gives conclusive input parameters for high strength HAP. Table 6 and Table 7 highlight the analysis of grey relational grade, while Figure 5 and Table 5 show the effect of kaolin reinforcement, compaction pressure and sintering temperature on the multi-response grey relational grade. It is important to note that, for the multi-response mechanical properties, kaolin reinforcement had an increasing effect on the mechanical properties. Also, compaction pressure, 500 Pa shows a higher increasing effect compared with the individual hardness and compressive strength properties. As the sintering temperature increased, the multi-response mechanical properties increased as it is on individual hardness and compressive strength. Hence, it can be conclusively said that, kaolin reinforcement had a positive impact on the overall mechanical properties of HAP, and the optimal conditions for high strength of HAP are 15 wt% kaolin reinforcement, 500 Pa compaction pressure and 1100 °C sintering temperature.

Table 7 and Figure 6 show the grey relational grade (GRG) result. The graph in Figure 6 displays experimental number 30, 33, and 36 as the highest GRG, which is also depicted in Table 8. Since the experimental numbers displaying the highest GRG, it was then average to have the mean value of GRG, which gave 0.7445 as the experimental optimum GRG value.

3.6 Quantitative effect of reinforcement and production parameters on HAP GRG

As the qualitative effect has been revealed above, Table 9 reveals the quantitative effect of the controlling factors on GRG values. The result revealed sintering temperature as the most significant production factor having a contribution of 60.21%, followed by kaolin reinforcement with a contribution of 29.72%, and compaction pressure with a contribution of 8.32%. Importantly, the result revealed that the residual error was insignificant on the HAP GRG.
3.7 Confirmation analysis

3.7.1 Confidence interval analysis: After determining the optimal fabrication parameters, its predicted grey relational grade was computed as 0.6911 using Table 5 and Equation 5 (Ross, 1996; Abifarin, 2021; Abifarin et al., 2021).

\[ \gamma_{\text{predicted}} = \gamma_m + \sum_{i=1}^{q} \gamma_0 - \gamma_m \] (5)

\[ \gamma_0 \] highlights the highest GRG response under each fabrication parameter, while \[ \gamma_m \] is the total average GRG value. \[ q \] is the number of fabrication parameters.

To investigate the authenticity of the predicted response and experimental response, confidence interval (CI) was calculated using Equation 6 (Taguchi & Phadke, 1989; Abifarin, 2021; Awodi et al., 2021):

| Experiment run | Reference Sequence \( x_i^* \) | Deviation Sequence \( \Delta x_i \) |
|---------------|-------------------------------|----------------------------------|
|               | HV                           | CS                              | HV       | CS      |
| 1             | 0.269663                     | 0.00515                         | 0.73034  | 0.99485 |
| 2             | 0.603371                     | 0.03995                         | 0.39663  | 0.96005 |
| 3             | 0.730337                     | 0.06443                         | 0.26966  | 0.93357 |
| 4             | 0.247191                     | 0.01418                         | 0.75281  | 0.98582 |
| 5             | 0.775281                     | 0.02706                         | 0.22472  | 0.97294 |
| 6             | 0.689888                     | 0.06959                         | 0.31011  | 0.93041 |
| 7             | 0.352843                     | 0.01933                         | 0.67416  | 0.98067 |
| 8             | 0.469663                     | 0.0451                          | 0.30304  | 0.9549  |
| 9             | 0.77191                      | 0.07861                         | 0.22809  | 0.92139 |
| 10            | 0.424719                     |                                 | 0.57528  | 1       |
| 11            | 0.755056                     | 0.02062                         | 0.24494  | 0.97938 |
| 12            | 1                            | 0.05284                         | 0       | 0.94716 |
| 13            | 0.451685                     | 0.01418                         | 0.54831  | 0.95852 |
| 14            | 0.746067                     | 0.03995                         | 0.25393  | 0.96005 |
| 15            | 0.88764                      | 0.0451                          | 0.11236  | 0.9549  |
| 16            | 0.358427                     | 0.00515                         | 0.64157  | 0.99485 |
| 17            | 0.651685                     | 0.02062                         | 0.34831  | 0.97938 |
| 18            | 0.853933                     | 0.0567                          | 0.14607  | 0.9433  |
| 19            | 0.258427                     | 0.37887                         | 0.74157  | 0.62113 |
| 20            | 0.541573                     | 0.5683                          | 0.45843  | 0.4317  |
| 21            | 0.396629                     | 0.82603                         | 0.60337  | 0.17397 |
| 22            | 0.348315                     | 0.38144                         | 0.65169  | 0.61856 |
| 23            | 0.477528                     | 0.67139                         | 0.52247  | 0.32861 |
| 24            | 0.5                          | 0.9317                          | 0.5      | 0.0683  |
| 25            | 0.255056                     | 0.34536                         | 0.74494  | 0.65464 |
| 26            | 0.460674                     | 0.65851                         | 0.53933  | 0.34149 |
| 27            | 0.651685                     | 0.82661                         | 0.34831  | 0.17139 |
| 28            | 0.105618                     | 0.54768                         | 0.89438  | 0.45232 |
| 29            | 0.364045                     | 0.86856                         | 0.63596  | 0.13144 |
| 30            | 0.006742                     | 0.9317                          | 0.39326  | 0.0683  |
| 31            | 0                            | 0.47552                         | 1        | 0.52448 |
| 32            | 0.320225                     | 0.71005                         | 0.67978  | 0.28995 |
| 33            | 0.503371                     | 0.9884                          | 0.49663  | 0.0116  |
| 34            | 0.149438                     | 0.55799                         | 0.85056  | 0.44201 |
| 35            | 0.304494                     | 0.72552                         | 0.69551  | 0.27448 |
| 36            | 0.588764                     | 1                               | 0.41124  | 0      |
\[ CI = \sqrt{F_{\alpha}(1,f_e)V_e \left[ \frac{1}{\eta_{eff}} + \frac{1}{R} \right]} \] (6)

\( F_{\alpha}(1,f_e) \) is the required F ratio for risk, \( \alpha \); \( f_e \) is the degree of freedom (DOF) of error; \( V_e \) is variance of error; \( \eta_{eff} \) is effective number of replications. If \( R \) represents the number of experimental repetitions when the investigation is done for affirmation and \( N \) represents all the experiments carried out then \( \eta_{eff} \) is given by:

\[ \eta_{eff} = \frac{N}{1 + \text{(total DOF of control factors)}} \] (7)

Therefore, if \( V_e = 0.001372; f_e = 7; \) DOF of all the control factors is 4; \( R = 1; N = 36; \alpha = 0.5 \) under 95% confidence interval (CI), then \( F_{0.5}(1,7) = 5.59 \) based on the F-statistical table. Consequently, \( \eta_{eff} = \frac{36}{1+4} = 7.2 \) and \( CI = \sqrt{5.59 \times 0.001372 \left[ \frac{1}{7.2} + \frac{1}{1} \right]} = \pm 0.0935 \). 95% of confidence interval for the optimal grey relational grade predicted is given in Equation 8 (Abifarin, 2021),

| Experiment run | Grey relational coefficient, \( \varepsilon_i(k) \) | GRG \( \gamma_i \) |
|----------------|----------------------|------------------|
| 1              | 0.40639              | 0.33448          | 0.37044 |
| 2              | 0.55764              | 0.34245          | 0.45005 |
| 3              | 0.64964              | 0.34829          | 0.49896 |
| 4              | 0.3991               | 0.33651          | 0.36781 |
| 5              | 0.68992              | 0.33946          | 0.51469 |
| 6              | 0.6172               | 0.34955          | 0.48337 |
| 7              | 0.42584              | 0.33768          | 0.38176 |
| 8              | 0.48528              | 0.34367          | 0.41447 |
| 9              | 0.68673              | 0.35177          | 0.51925 |
| 10             | 0.46499              | 0.33333          | 0.39916 |
| 11             | 0.67119              | 0.33798          | 0.50459 |
| 12             | 1                    | 0.3455           | 0.67275 |
| 13             | 0.47696              | 0.33651          | 0.40673 |
| 14             | 0.66319              | 0.34245          | 0.50282 |
| 15             | 0.81651              | 0.34367          | 0.58009 |
| 16             | 0.43799              | 0.33448          | 0.38624 |
| 17             | 0.5894               | 0.33798          | 0.46369 |
| 18             | 0.77391              | 0.34643          | 0.56017 |
| 19             | 0.40271              | 0.44598          | 0.42435 |
| 20             | 0.52169              | 0.53665          | 0.52917 |
| 21             | 0.45316              | 0.74187          | 0.59752 |
| 22             | 0.43415              | 0.447            | 0.44058 |
| 23             | 0.48901              | 0.60342          | 0.54622 |
| 24             | 0.5                  | 0.87982          | 0.68991 |
| 25             | 0.40162              | 0.43304          | 0.41733 |
| 26             | 0.48108              | 0.59418          | 0.53763 |
| 27             | 0.5894               | 0.74472          | 0.66706 |
| 28             | 0.35858              | 0.52503          | 0.44181 |
| 29             | 0.44016              | 0.79184          | 0.616  |
| 30             | 0.55975              | 0.87982          | 0.71978 |
| 31             | 0.33333              | 0.48805          | 0.41069 |
| 32             | 0.42381              | 0.63295          | 0.52838 |
| 33             | 0.50169              | 0.97733          | 0.73951 |
| 34             | 0.37022              | 0.53078          | 0.4505  |
| 35             | 0.41823              | 0.64559          | 0.53191 |
| 36             | 0.54871              | 1                | 0.77435 |
Table 9. Grey relational grade (GRG), and average grey relational grade (AGRG)

| Sample | Experiment run | GRG  | AGRG | Sample | Experiment run | GRG  | AGRG |
|--------|----------------|------|------|--------|----------------|------|------|
| 1      | 1              | 0.370| 0.373| 7      | 19             | 0.424| 0.427|
|        | 4              | 0.368|      |        | 22             | 0.441|      |
|        | 7              | 0.382|      |        | 25             | 0.417|      |
| 2      | 2              | 0.450| 0.460| 5      | 20             | 0.529| 0.538|
|        | 5              | 0.515|      |        | 23             | 0.546|      |
|        | 8              | 0.414|      |        | 26             | 0.538|      |
| 3      | 3              | 0.499| 0.501| 9      | 21             | 0.598| 0.652|
|        | 6              | 0.483|      |        | 24             | 0.690|      |
|        | 9              | 0.519|      |        | 27             | 0.667|      |
| 4      | 10             | 0.399| 0.397| 13     | 28             | 0.442| 0.434|
|        | 13             | 0.407|      |        | 31             | 0.411|      |
|        | 16             | 0.386|      |        | 34             | 0.451|      |
| 5      | 11             | 0.505| 0.490| 14     | 29             | 0.616| 0.559|
|        | 14             | 0.503|      |        | 32             | 0.528|      |
|        | 17             | 0.464|      |        | 35             | 0.532|      |
| 6      | 12             | 0.673| 0.604| 15     | 30             | 0.720| 0.745|
|        | 15             | 0.580|      |        | 33             | 0.740|      |
|        | 18             | 0.560|      |        | 36             | 0.774|      |

Table 10. ANOVA for HAp GRG

| Fabrication parameter | DOF | Adj SS   | Adj MS   | F        | Contribution % | Remark         |
|-----------------------|-----|----------|----------|----------|----------------|----------------|
| Wt% of kaolin         | 1   | 0.023324 | 0.023324 | 17.00    | 29.72          | Significant    |
| Compaction pressure   | 1   | 0.006530 | 0.006530 | 4.76     | 8.32           | Significant    |
| Sintering temperature | 2   | 0.094503 | 0.047252 | 34.43    | 60.21          | Significant    |
| Residual error        | 7   | 0.009607 | 0.001372 |          | 1.75           | Insignificant  |
| Total                 | 11  | 0.078478 | 0.03705  |          |                |                |

\[
\gamma_{\text{predicted}} - CI \leq \gamma_{\text{experimental}} \leq \gamma_{\text{predicted}} + CI
\]  

(8)

\[
0.5976 < \gamma_{\text{experimental}} < 0.7846
\]  

(9)

The CI findings showed that the experimental GRG value of 0.6911 correlates with the predicted optimal GRG value. This affirms the efficacy of the optimal fabrication parameters on the multi-mechanical characteristics of kaolin reinforced hydroxyapatite.

Figure 6. Grey relational grades
3.7.2 Probability distribution analysis: Figure 7 shows the probability plot and the statistical information of the multi-mechanical response of kaolin reinforced hydroxyapatite. The plot shows that all the GRG values except one are within the 95% confidence interval, which is supported by the confirmation analysis.

4. Conclusion

The quantitative effect of kaolin reinforcement, compaction pressure and sintering temperature has been examined with the help of statistical analysis technique assisted by grey relational analysis. It was noted that there was disparity in kaolin reinforcement as the optimum condition for individual mechanical properties, showing better hardness but poorer compressive strength when HAp was not reinforced. However, the grey relational analysis showed better mechanical properties with kaolin reinforcement. 500 Pa compaction pressure and 1100 °C sintering temperature are the optimum fabrication parameters for better mechanical properties, and was the same for individual mechanical properties. It is interesting to note that kaolin reinforcement significantly increased the compressive strength of HAp with a contribution of 93.16%. This influenced GRG values, resulting to 15 wt% kaolin as the optimum with 500 Pa and 1100 °C sintering temperature as the optimal fabrication parameters for high strength of HAp. The confirmation analysis also revealed that the experimental multi-mechanical response is within the 95% confidence interval.

These findings are useful in orthopedics industry in order to produce a mechanically fitted HAp for load bearing clinical application. These findings recommend fabrication parameters at which mechanically improved clinical hydroxyapatite would be achieved. Further studies are also recommended conducted investigate the use of different wt% of kaolin on the multiple mechanical characteristics of HAp.

Acknowledgement

The authors want to thank the Department of Mechanical Engineering and the Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, for their support.

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