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Analysis of Linear Regression to Predict Abrasive Water Jet Marble Drilling Quality

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Abstract:- Marble material is characterised by its high fragility and heterogeneousness, which directly depend on two main aspects: the origin and nature. Marble manufacturing for commercial and industrial uses involves many processes, such as the machining process, which requires detailed knowledge of marble characteristics and features. One of these important characteristics is the stone cutter point, an essential input to identify the marble machining parameters. In this study, an examination was achieved to optimise the marble drilling industry quality process. The main objective is to achieve high-quality marble drilling without fracturing. White Carrara marble was used to examine its drilling process. The utilised drilling method was the Abrasive-Water-Jet (AWJ); unlike conventional drilling methods, such as rotating abrasive can achieve better drilling quality. The performance and quality of the AWJ process depend on several considerations, including jet pressure, the nozzle Traverse-Speed (TS), hole diameter, Stand-Off-Distance (SOD) as well as Abrasive-Flow-Rate (AFR). All these parameters were studied and modelled, besides the most common defect types. The studied defect types involve hole location error and circularity, hole location error, surface roughness, and hole cylindricity. Variance analysis of artificial neural networks, as well as linear regression were utilised for modelling these types of defects. Accordingly, marble stone cutters can be effectively determined and utilised in configuring marble machining parameters, hence optimising its manufacturing process.

Keywords:- *Marble Material, Abrasive-Water-Jet, Get Pressure, Nozzle Traverse-Speed, Hole Diameter, Stand-Off-Distance, Abrasive-Flow-Rate, Marble Stone Cutters.*

I. INTRODUCTION

Marble is commonly used type of rock that is used in several applications. Marble is generated from the metamorphosing of the carbonate sediments entailing calcite CaCO3 and dolomite crystals. Furthermore, marble is considered a compacted limestone that is challenging to cut, has a beautiful polish, and coloured veins that are caused by the high pressure and temperature that occur through metamorphism [1].

Marble has several classifications, for example mono-mineral marbles is the marble type that involves pure calcite. Another classification is the poly-mineral marble, which is called the marble that involve minerals other than calcite. Furthermore, marble classification can be achieved depending on its attribution by executing petrographic and mineralogical annotations about the thin marble that is utilised in the flooring, buildings, sculptured and architectural statues in order to identify the origin quarry. The marble provenance influences the marble marketing and processing. Nevertheless, the marble microstructure influences its machining process [2] [3].

Carrara marble is characterised by its anisotropic structure, the greater calcite solubility can enable the micro cracks expansion and the formation of further crystalline salts after the water evaporation. Also, Carrara is considered a heterogeneous type of marble, which comprises various sedimentation layers, various particle sizes, imperfections, which is known as a heterogeneous calcific marble [4] [5].

The material anisotropy and heterogeneity infers that the even the similar material acts in a different way in the case of machining in various situations. Internal flaws eventually consolidate due to the rock's calcite composition. Each of these elements contribute to marble's fragility and the fracturing process. As a result, digital machining effectiveness is constrained [6]. In general, there are a number of variables that affect how marble is machined, including cutting tool characteristics, machining parameters, cutting phenomena, as well as work piece material characteristics. In addition to the working machines, which have two main types: conventional machines that depends on utilising rotating tools for removing materials. The second common type is the non-conventional machines that utilise non-sheer cutting machines, including laser, electro erosion, as well as AWJ [7].

An example of conventional machines is tested in [8], in this study, continuum mechanics, as well as discrete modelling were used to examine numerically the outcomes of rotary drill cutting experiments on four types of marbles. Rock-cutting experiments were carried out using a novel transportable rotational micro drilling instrument that is now in use for the semi assessment of rock strength parameters. The assumptions of a continuum model were found to be completely consistent with the observed forces while drilling. According to the plasticity limit analysis theory, the cohesiveness and frictional resistance angle were the most essential characteristics influencing rock drilling resistance.

The literature mentions various examples of investigations about the surfaces machined quality by using conventional machines, including geometric as well as form tolerances relating to the rotating tool settings utilized. Nevertheless, one significant disadvantage of traditional machinery seems to be that the tested marble can be badly damaged while handling [9].

On the other hand, according to [10] a research was achieved to study the effect of cutting restrictions of marble, specifically Traverse-Speed (TS), SOF, the type of material, (AFR) on cutting quality of Carrara white. Furthermore, the impact of cutting settings regarding surface waviness, surface roughness, as well as Kerf taper ratios were studied statistically. The findings revealed the type of material and TS were the most important parameters influencing both Kerf tapering ratio, as well as surface roughness. Furthermore, whereas AFR was shown to have a considerable impact on the surface waviness, there was no discernible impact on roughness and Kerf tapering ratio.

In addition to that, the percentage of rock breaking rises with particle sizes, indicating the increasing in the irregularity of particle size, increase overall resulted damage. As a result, the interaction among the marble and the rotating tool, as well as the latter fragility, contribute to the limitation of the standard drilling process. On the other hand, there are several non-conventional marble drilling tools, such as the AWJ. This tool help avoids the marble fracture during the drilling process. Furthermore, in comparison to many non-traditional cutting tools, including Electrical-Discharge-Machining (EDM) as well as laser milling, AWJ is more effectual and can cut all types of materials like metals, non-metallic, polymer blends, and ceramics without causing thermal distortion and requiring minimal cutting force applied at the work materials [11] [12].

Additional advantage of the AWJ jets is its ability to be simply linked with current CAM and CAD systems, considerably streamlining the shape cutting, eliminating dust, and assuring acceptable working situations and sustainability performance. The AWJ technique eliminates the chance of marble slab fracture, although it has certain limitations [13]. Furthermore, according to the AWJ machine leads the cut-side wall to incline between the bottom and surface of the component, as well as the striations appearance depending on the material thickness [14].

The quality of the AWJ is considered an important issue to be considered in marble manufacturing process. The AWJ's quality can be monitored and controlled by utilising several performance indicators that are provided in Table 1.

Table 1 The Performance Indicators

KW	Kerf width
CD	Cutting Depth
KA	Kerf Angle
Ra	Surface Roughness
d	Straition Free-surface depth
Wa	Surface Waviness
P	Jet Pressure
SOD	Stand-off-distance
AFR	Abrasive flow Rate
TS	Nozzel Treverse speed

Also, the marble mechanical properties effect the AWJ's quality, including marble porosity, the Uniaxial-Compressive-Strength (UCS), marble density, shore hardness, as well as the abrasion resistance. Furthermore, there are several metaheuristics and statistical modelling methods for achieving a high accurate prediction of the marble machining process performance.

The quality of marble machining based on utilising the AWJM (Abrasive-Water-Jet-Machining), as well as the conventional processes based on the predictors performance indicators through different models are summarized on Table 2. However, there are different phases in the machining of marble, including straight cutting, drilling of marble, and polishing with a range of various properties, in different thicknesses which were studied by several researchers. A critical Analysis for the recent studies is shown in Table 2.

Table 2 Critical Analysis for the Recent Studies

Reference	Input	Results	Method of obtaining results	Similarity	Dissimilarity
[15]	Several sorts of marbles. The cutting edge diameter is 6-mm.	Signal-To-Noise (S/N) ratio. Ra factor	Computer Machine Controlled (CNC)	This work study and analyse the marbles surface roughness.	To determine machining settings for improving the quality of product surface by using CNC approach.
[16]	The studied marble type is: Crema Eda. The marble chemical characteristics: CaO concentration equals 55.50%, ignition loss concentration equals 41.75%, MgO concentration equals 2.20%, SiO2 concentration equals 0.24%, and F2O3 concentration equals 0.21%. The tested marble specimen's dimensions were: 3 cm, 20 cm length, as well as 10 cm width.	Surface roughness. Kerf angles. Cutting depths. Cutting wear zone. Cutting widths.	Experimental Method	The abrasives cutting quality are examined depending on several outputs, including (surface roughness)	There are several abrasives studied in this work, which are white-fused-alumina garnet, silicon carbide brown-fused-alumina, glass beads, as well as emery powder.
[17]	An L25 Orthogonal array is used in the experimental work. The Transverse-Speed (TS) = 60mm/min, The SOD was 4mm. The AFR was 200gm/min.	The effect of several process factors, including: TS, AFR, as well as SOD on the kerf taverns and width kerf.	Experimental method	This work depends on experimental investigation and regression analysis to study the INCONEL-825 effective machining by AWJM.	This work involved studying the process parameter significance on taperness and Kerf Width by performing Grey-Taguchi analysis.
[18]	Two marble specimen's types were used: Indian green and Carrara white. The specimen's dimensions were: length = 70 mm, width = 30 mm, as well as thickness = 20 mm. SOD. AFR	The cutting performance, including Surface roughness, Surface waviness, as well as Kerf taper ratio.	Experimental Approach and Statistical analysis	This work involves assessing the cutting parameter impact on the marble machining quality regarding surface roughness, as well as Kerf taper ratio.	This work utilises ANOVA Analysis of waviness mechanism
[19]	The marble tested specimen has a rectangular shape with the following dimensions: (100 × 7 × 18) mm. The abrasives Garnet Types. The Abrasive size was 80 mesh. The angle of jet impact was 90°. The orifice diameter was 0.25 mm. The nozzle length was 76.2 mm. The nozzle diameter was	Kerf Width (W). Kerf Taper Angle (θ)°. The free surface depth in (D)	Multi-artificial bee-colony algorithm, as well as effect matrix.	This work was conducted to minimise the kerf width, reduce the kerf taper, as well as increase the striation free surface depth in the AWJ process.	This work involves using response surface modelling in order obtain the relationship among different input parameters.

	0.762 mm. The passes number was 1. The AFR was 2.3 L/min.				
[20]	The input parameters for the abrasive water jet, including: Pump pressure in (MPa), TS (mm/min), Abrasive mass rate in (g/min), The mixing tube diameter (mm), SOF	SEM images. Removal mechanisms. The cutting efficiency.	Experimental approaches, as well as SEM analysis.	This work involves examining the impact of the AWJ on the cutting of several types of rocks, including marble.	This work involves SEM analysis
[21]	The pumping pressure was 380 MPa. The diameter of water orifice was 0.25 mm. SOD was 2 mm. The focusing tube diameter was 1.02 mm. The focusing tube length was 76 mm. The grain size of the abrasive material was 0.27 mm. The impact angle was 0 rad.	The outputs of this study involve the relationships between the kerf taper angle and the TS of the granites walls, as well as between the kerf taper angle and the TS of the kerf walls.	Experimental approaches.	This study involves investigating the influence of AWJ on the hole taper.	This work involves utilising two various kerf widths measurement approaches, including the direct measurement using the Digital-Vernier calliper.

The inputs of this study are AFR, P, and SOD. This study focus in analysing the macroscopic defects caused by marble drilling process, which is roughness depending on several parameters, including the AWJ's drilled cylindricity, depth, iconicity, localization error, as well as circularity. Furthermore, this study helps model the holes dimensional and geometrical tolerances regarding the AWJM parameters. In addition to the quality improvement of the process of marble drilling.

After reviewing the recent studies in Literature and determining the current gap. The experimental method that will be followed in this study is explained in the following section.

II. METHODOLOGY

A. *Experimental Procedure*

The primary purpose of this work is to investigate and analyse the impact of the cutting circumstances of the Carrara white marble on the holes' quality by using an AWJ. This will be achieved depending on experimental testing method. The most important experimental steps to achieve this aim are summarised in Figure 1.

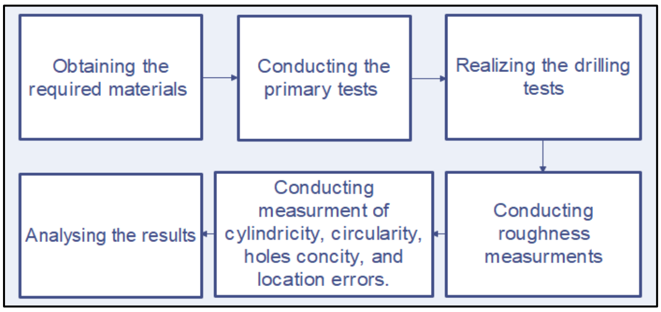

Fig 1 The Experimental Steps of this Work

- *Figure 1 clarifies the applied experimental approach that has been followed. In this work, the standardised failures to assess the quality of the hole are:*

- *The roughness of the hole for three plate thickness depths (Ra_1, Ra_2, and Ra_3),*
- *The Hole-Taper (HT) that is an important function of some conditions, including (cutting situations), which are (D, AFR, TS, SOD, P), the hole localisation error (HLE), the hole circularity (HC_i), hole cylindricity (HC_y).*
- *Both of the outputs and the inputs of the employed AWJ machine is provided in Figure 2.*

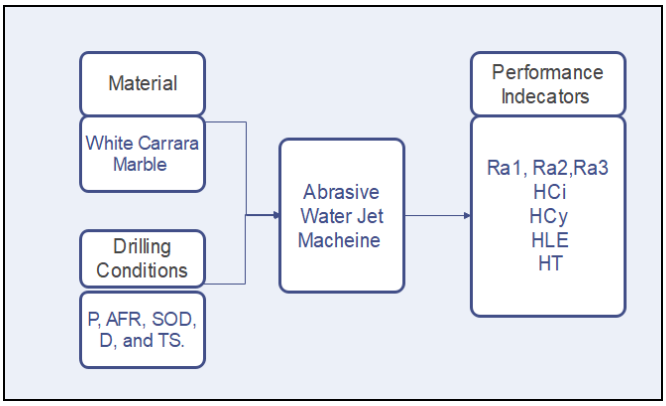

Fig 2 The Main Parameters of Drilling Process

B. *The Specifications of the Utilised Materials*

This study will clarify the conditions of drilling for the marble slab. In addition to provide several details of the most important performance indicators depending on the artificial intelligence techniques, as well as a statistical model. Firstly, a microstructure of white Carrara that is used in this study is presented in Figure 3 was obtained by the Scanning-Electron-

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Microscopy (SEM). This images showed that the utilised marble specimen is heterogeneous since it contains impurities and some grain widths with several sizes like the micro cracks and voids.

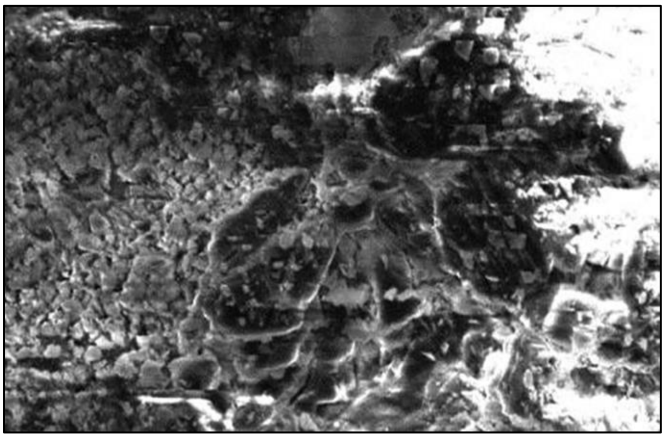

Fig 3 The Microstructure of White Carrara

Furthermore, the physical and mechanical properties of the tested marble specimen are listed in Table 3, and the used tests are clarified in Figure 4.

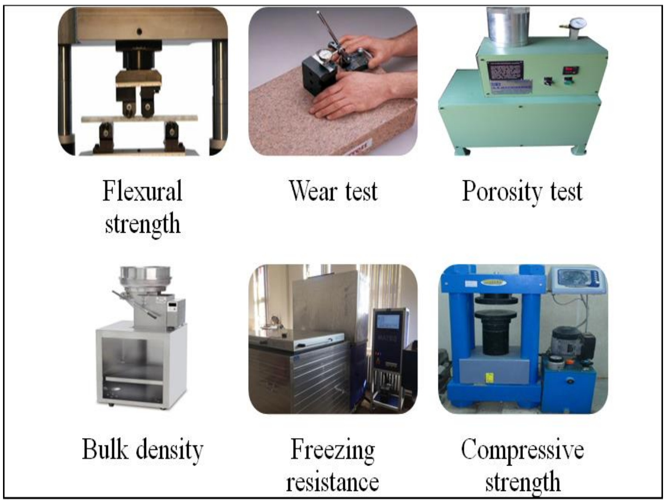

Fig 4 The Tests Conducted for Obtaining the Physical Parameters of the White Carrara Marble

Table 3 Mechanical and Physical Characteristics of the White Carrara Marble

Text Name	Resulted Value	Followed Standard
Flexural strength	19.2	EN-12372
Wear test	4.1	NBN-B15-223
Porosity test	0.14	EN-1936
Bulk Density	2706	EN-1936
Freezing Resistance	240	EN-12371
Compressive strength	142.6	EN-1926

It is notable that the resistance of the white Carrara marble is relatively high. Additionally, two specimens marble have been drilled through an AWJ machine in this work. The specifications of these two specimens are: 0.3 m length, 0.03 m thickness, and 0.3m width.

C. Design of Experiments

In this work, five inputs of machining were included which are D that is the hole diameter, AFR, the SOD, TS, P which is the pressure of the jet. Any input has two various levels, which have been chosen depending on the primary tests that are typically divided into two different variables which are variable and constant parameters. However, these parameters involve the D, AFR, TS, SOD, and P with two stages have been used for any parameter as represented in Table 4, while the constant parameters are the length of the abrasive, diameter of the orifice, the abrasive size, the type of the abrasive, the focusing tube diameter as clarified in Table 4.

Table 4 The Constant Parameters for the Drilling Process

The Abrasive Material Type	Garnet Abrasive
The abrasive mesh size	#80
The diameter of orifice	0.127
The length of nozzle	76.20
The diameter of nozzle	0.889

The drilling holes' order has been fixed based on the replicated of fractional factorial of 1/2. Furthermore, a number of runs has been carried out for the tested marble specimens, which are sixteen as clarified in Table 5 with a total number of tests that is equal to 32 tests.

Although the quality of marble cutting is influenced by the jet diameter and the garnet type, different drilling tests were implemented for the same abrasive material type with the same available nozzle within the workshop.

A series of preliminary tests were implemented to specify the variation range in the cutting condition, including AFR, pressure, SOD, advanced velocity, and hole diameter) for the white marble samples (Carrara). However, the peak pressure values have the ability to completely drill the tested marble samples. The applied pressure values were ranged from 2000 bar to 4000 bar. Further, the SOD varies between (10-20) mm, which causes the removal of undesirable materials when the drilled hole diameter is larger than necessary diameter.

In contrast, [22] stated that the optimal distance of SOD of the AWJ is 0.005 m, since when the distance gap is below 5 mm, there will be a notable increase in the cutting depth. Further, a damage of the nozzle as well as the rock sample is likelihood to occur because of the obstruction or back pressure. Accordingly, in this study two SOD have been chosen, which are 0.005 m and 0.007 m. Finally, when the speed of the transverse has been set to be between 0.4 m per minute and 0.4 m per minute, the marble cut will not be completed. The reason of that is these speeds are considered as high speed and therefore, the jet will not have plenty time in order to perforate the whole material.

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When the TS becomes less than 300 mm per min, all thicknesses will be cut; as a result, the chosen TS were 240 mm per min as well as 300 mm per min. The range of the selected hole diameter was in a range between (15-20) mm. Further, the AFR was selected to be 150g/min, which was selected to guarantee the cutting of the material. Hence, the AFR was selected to be 300 g/min and 150g/m to prevent the clogging of the Focal Canon higher than this specific value. The used machining parameters with the coding levels is summarized in Table 5.

Table 5 The Range of the Selected Machining Parameters

Parameters	Unit	Levels		The levels of coding	
Pressure	Bar	4000	2000	|	-|
Abrasive flow rate	g/min	300	150	|	-|
Standoff distance	Mm	7	5	|	-|
Traverse Speed	mm/min	300	240	|	-|
Diameter	mm	20	15	|	-|

D. The Assessment of Testing Performance

The resulted hole quality that is produced from drilling Carrara marble significantly depends on the Key Performance Indicators, which can be measured using the Surftest SJ-201P. This is a device used for obtaining the value of the surface roughness, in which the roughness of the surface will be calculated regarding the standards.

Then, the results will be displayed. The machining quality is checked by the Surftest SJ-201P device by determining the arithmetic mean roughness (R_a in mm) that presents the average roughness of the surface. To measure the roughness of the surface, the device must be calibrated and then the stylus will be moved on the surface by a transducer.

The transducer is used for digitally producing the signal from the movement. Striations might appear on the bottom side of the hole by some drilling test types. The hole's roughness will be measured for all holes by choosing three successive depths of 7 mm with a total depth of 21 mm. At each one of these three depths, four roughness values are measured from the angles at $(0, \frac{P}{2}, P, \frac{3P}{2})$ from the hole center. Accordingly, the average of these values will be calculated. R_{a1}, R_{a2}, and R_{a3} are measured for every hole at the depths (0-7) mm, (7-14) mm, and (14-21) mm. A 3D measuring machine that is denoted by CMM, is used for determining the hole cylindricity, circularity, and localization error. Table 6 represents the measurements regarding 0.5 fraction.

III. RESULTS AND DISCUSSION

This section emphasized getting benefits from the experimental data which are provided by the suggested 2521 experiments design. For the prediction of the performance of the essential indicator, a linear regression was suggested if the model was efficiently linear based on the conditions of the cuttings. Otherwise, nonlinear and a more general models by using ANN has been adapted.

A. Results of Regression Analysis

When the AWJ is used, the drilling quality for the Carrara marble can be controlled by the indicator's performance, specifically the dimensional hole tolerance and the hole geometry. In this investigation, MINITAB 19 software utilised to achieve a full analysis using the experimental data and a multi-regression analysis used for forecasting the main indicator's performance.

The experimental data were analysed through the (ANOVA). The ANOVA was defined by [23] as a specific tool for testing the statistical hypothesis based on analysing the experimental data. There are four graphs for the residual values are represented by the ANOVA diagrams:

- *The Henry's line of the residual is utilised to check if the suggested residual values follow the normal distribution.*
- *The relationship between the residual values and the fitted values are utilised in the process of testing the hypothesis when there is constant variance for the residual values.*
- *The histogram of the residuals helps in determining if there is a symmetrically in the data.*
- *The fitting of the residual data with the data order are utilised to check if there is a correlation between the residual values.*

In each output in this work, the variation of the errors should be fixed and the average of the error should be zero. Otherwise, the proposed model will be no longer valid.

B. The Parameters Impact on the Surface Roughness

This section is to discover the model of regression between the cutting process for the AWJ machine and the roughness surface of holes. Hence, this part offers the outcomes of model prediction as an ANOVA algorithm on several roughness surfaces such as Ra1, Ra2, as well as Ra3. Figures 5-8 display the results of the ANOVA model prediction, and proposed plots for Ra1 that are divided into four plots normal probability plot, versus fits and order, as well as histogram. Also, it offered the model of regression. Equation 1 represents the surface roughness of Ra_1 based on the condition of cutting.

$$Ra_1 = 3.036 - .000475(P) + 0.1269(SOD) + 0.000983(AFR) + 0.00459(D) + 0.008601(TS) \quad Eq.1$$

Likewise, both of Table 9 and Table 10 clarifies the models of regression for both of Kp_1 Ra_2 and Ra_3 sequentially.

$$Ra_2 = 3.378 - .000496(P) + 0.1038(SOD) + 0.000609(AFR) + 0.0006(D) + 0.00769(TS) \quad Eq.2$$

$$Ra_3 = 3.801 - .000607(P) + 0.1214(SOD) + 0.000833(AFR) + 0.0030(D) + 0.00806(TS) \quad Eq.3$$

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- *Ra1 Regression Model Results*

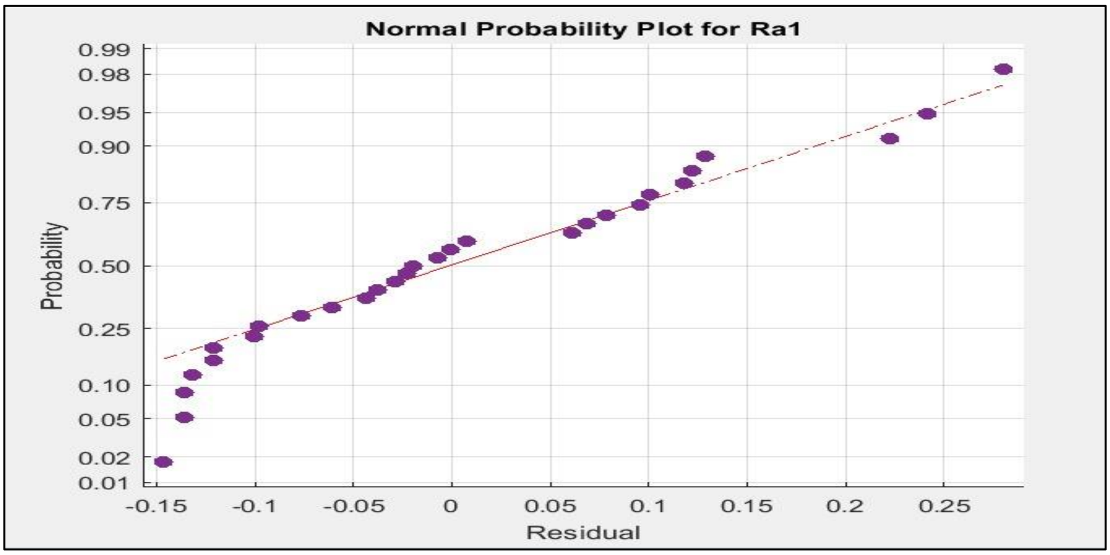

Fig 5 Ra1 Regression Model Results (Normal Probability Plot Results)

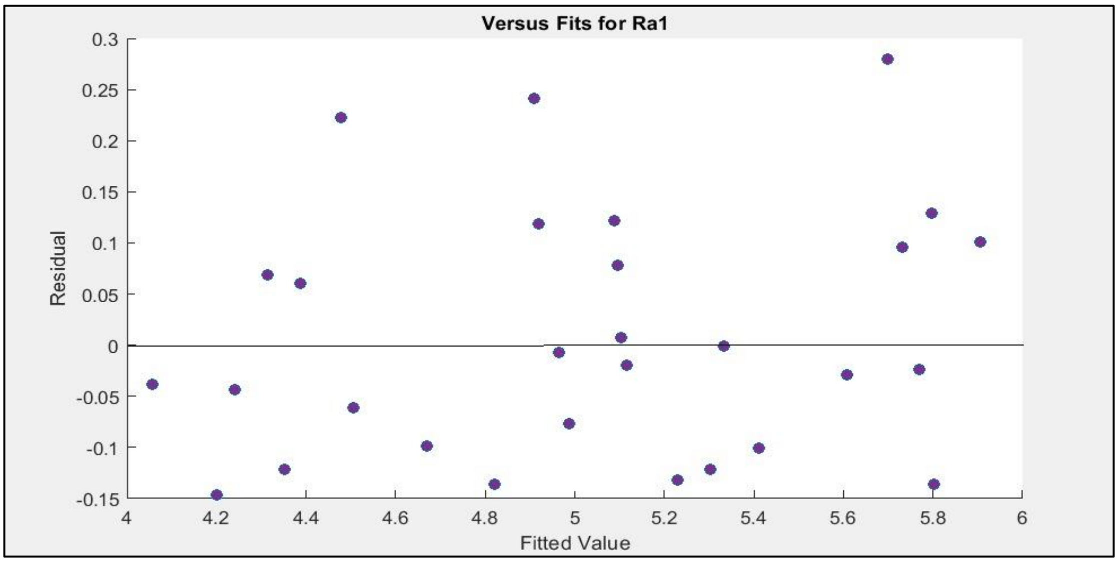

Fig 6 Ra1 Regression Model Results (Verses Fits Results)

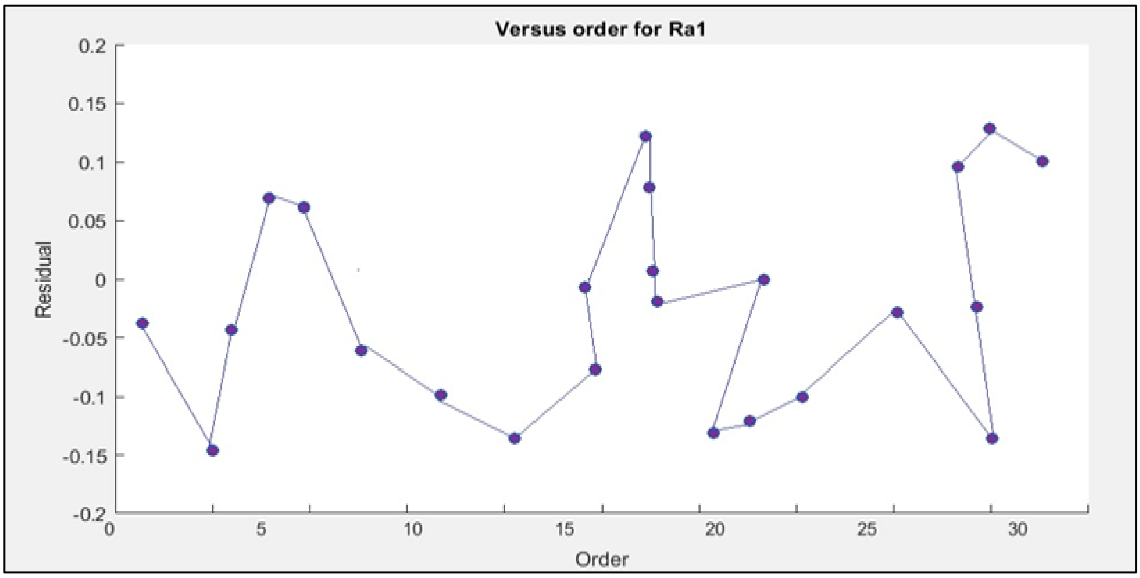

Fig 7 Ra1 Regression Model Results (Verses Order Results)

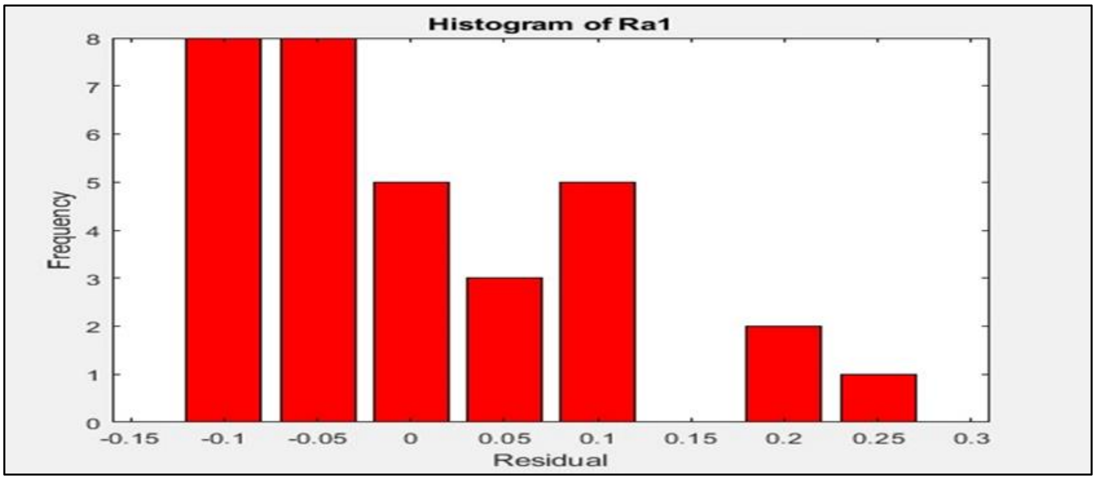

Fig 8 Ra1 Regression Model Results (Histogram Results).

Table 6 Ra_1 Model Performance

S	0102168
R-sq	97.37%
R-sq (adj)	96.86%
R-sq (pred)	96.01%

- *Ra_2 Regression Model.*

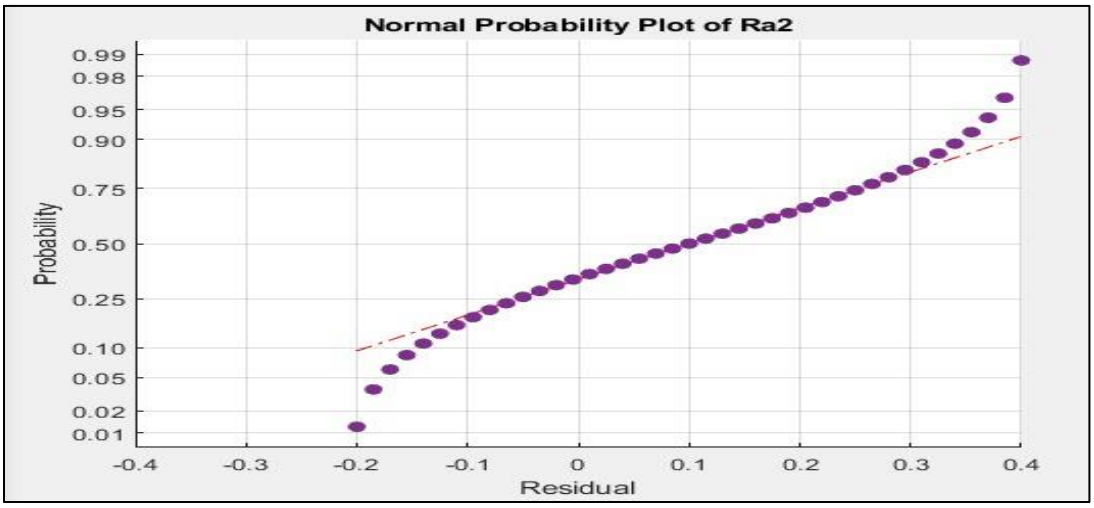

Fig 9 Ra2 Regression Model Normal Probability Plot Results

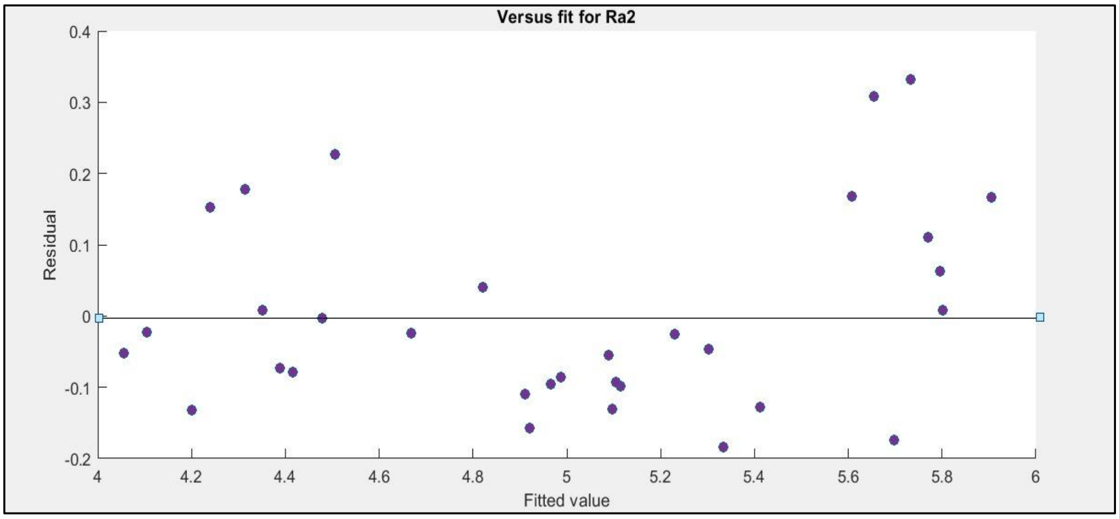

Fig 10 Ra2 Regression Model (Verses Fits Result)

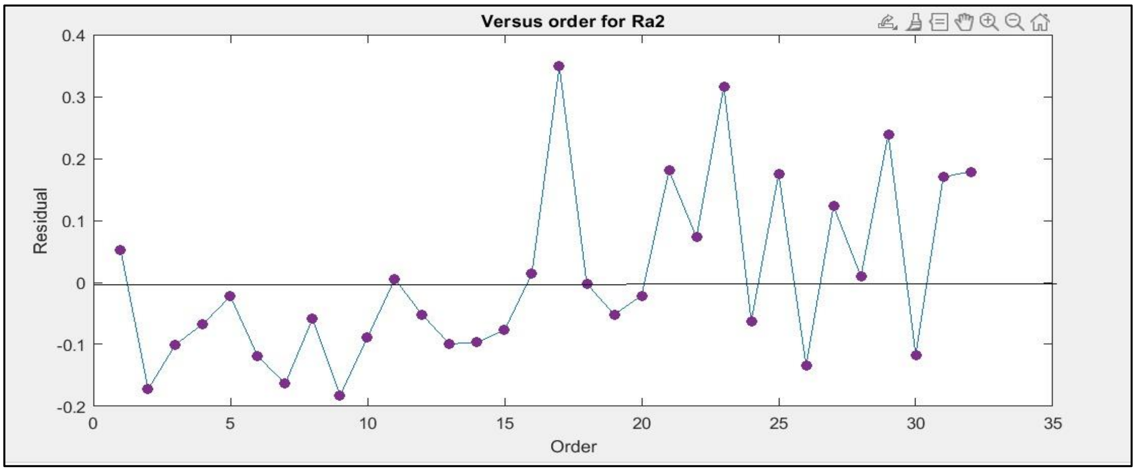

Fig 11 Ra2 Regression Model (Verses Order Results)

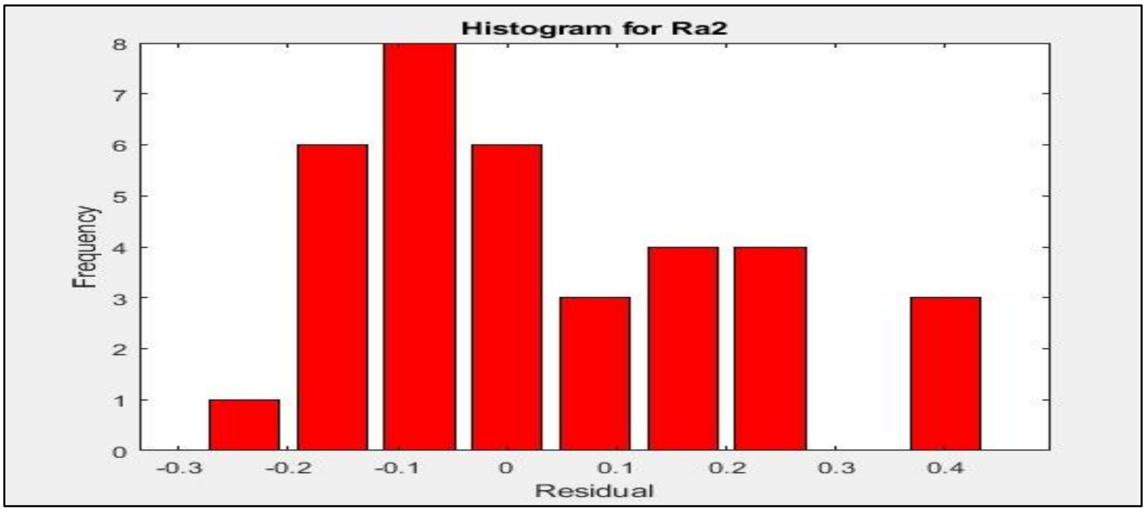

Fig 12 Ra2 Regression Model (Histogram Results)

Table 7 Ra_2 Model Performance

S	**0177147**
R-sq	92.45%
R-sq (adj)	91.00%
R-sq (pred)	88.57%

➢ *Results of Ra_3 Regression Model*

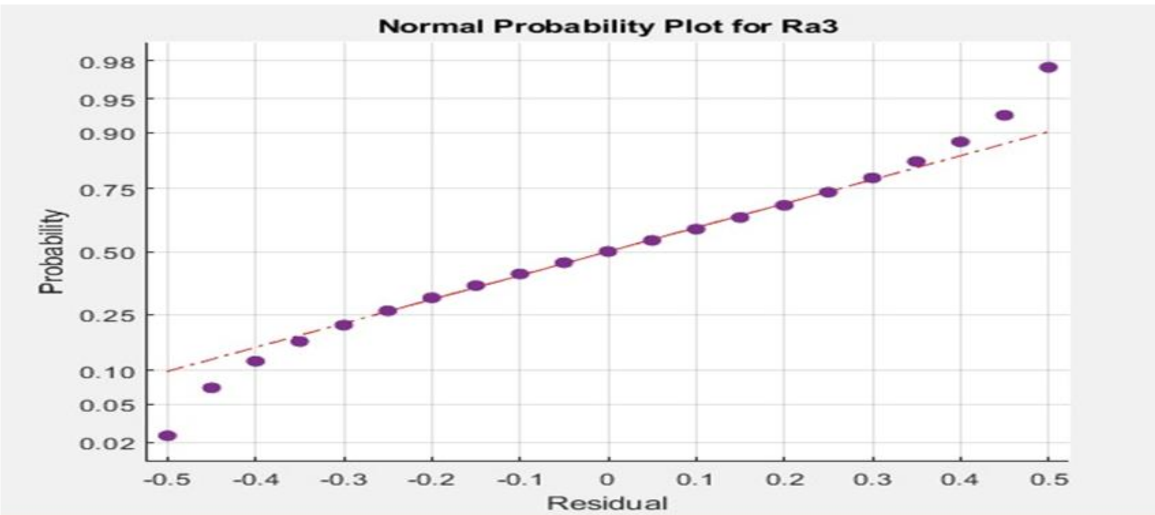

Fig 13 Ra3 Regression Model (Normal Probability Plot Results)

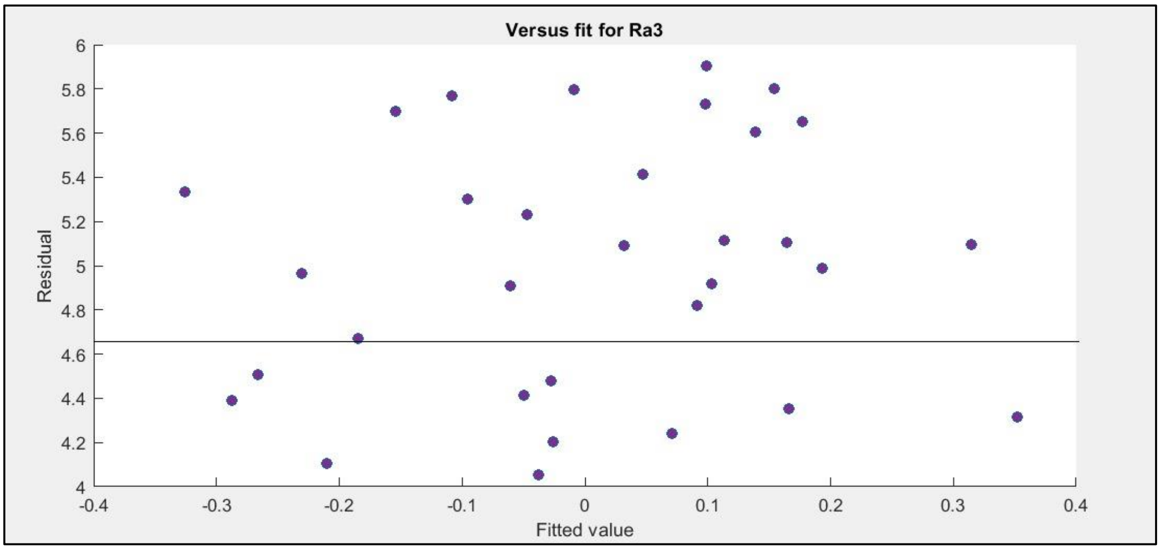

Fig 14 Ra3 Regression Model (Verses Fits Results)

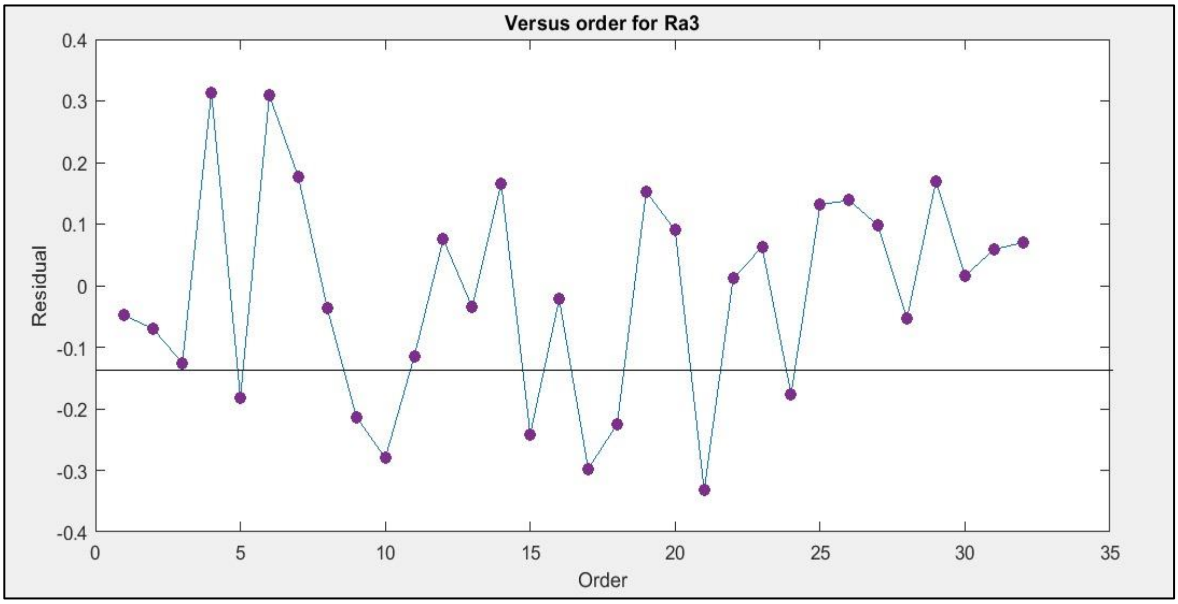

Fig 15 Ra3 Regression Model (Verses Order Results)

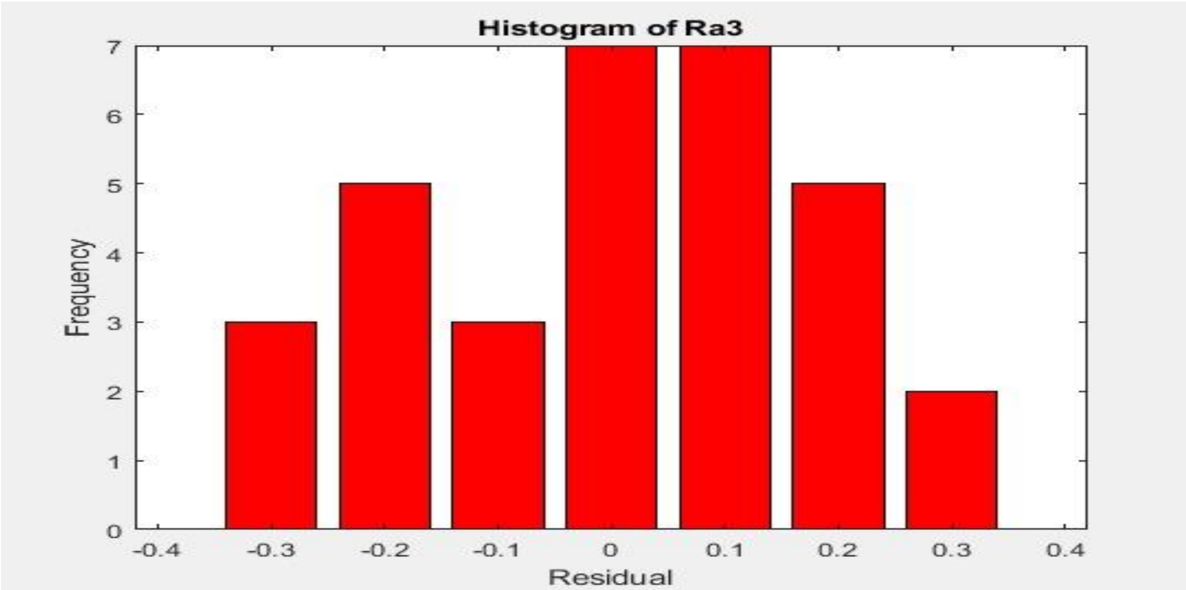

Fig 16 Ra3 Regression Model (Histogram Results)

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Table 8 Ra_3 Model Performance

S	0188415
R-sq	93.93%
R-sq (adj)	92.76%
R-sq (pred)	90.8%

Based on the obtained results, it can be concluded that the probability based on normal distribution for Ra_3, Ra_2, Ra_1 are linear while the versus fits variances are kept constant. Furthermore, it is clear that the dispersion vertical width does not decrease or increase for the modified values. In terms of Ra_1, it ranges between two values -0.1 and 0.1. Regarding Ra_2, it modifies between two values -0.2 and 0.2. As well, Ra_3 varies between two values -0.4 and 0.4.

Additionally, regarding the error variance terms are constant for three proposed surface roughness Ra1, Ra2, as well as Ra3. Also, the residuals of error take the average range at 0. Hence, the performance values of the model were mentioned as follows:

- *S: denotes the standard deviation.*
- *R-sq (adj): denotes adjusted R-squared.*
- *R-sq: refers to R-squared*
- *R-sq (pred): denotes R-squared*

Thus, all performance values demonstrate the models of linear regression suit the data of three surface roughness, which are Ra1, Ra2, as well as Ra3 very agreeably. The hole roughness information might be extracted as these holes are produced using a water jet. The hole roughness is significantly affected by the jet pressure (P) as it is considered the most critical factor, with a contribution percentage of 75%. The second contributing factor is the (TS) with a percentage equals 16.5%. The last contributing factors the (SOD), with a contribution percentage of 3.5%. However, AFR and the diameter of the hole (D) have a minimum contribution to the hole's roughness.

This work demonstrates the association between SOD and the roughness terminated in the current work. Also, this work demonstrates the impact of the nozzle speed the on the surface roughness of the outlet from the nozzle. After the implementation of the experimental work, it was noticed that if four factors or parameters, such as SOD, D, AFR, and P, are constant, the TS parameter was raised. In this work, the speed ranged from (240-300) mm/min, thus, raising the machined surface's roughness. Based on [18], it proved this statement on two kinds of marble such as green Indian and white Carrara marble.

Consequently, by corresponding to the roughness supplied, rotating tools and an AWJ. It is observed that the rough surface of the outlet of the nozzle drilled in the marble of white Carrara with the AWJ is not transcended 6mm while the surface roughness of identical holes, which means the exact dimensions that drilled with traditional instruments arrived 11mm.

In any case of the selected input factor, the AWJ went the smoother surface into the outlet of the drilled nozzle than conventional rotary machines. Hence, to reduce the hole's roughness, the essential rule of the cutting process regarding material that has to be cut at a few SOD s, safe, and high pressure, as well as with moderate and adequate TS. Additional experimental remarks were acquired from the marble outlet of the nozzle or the holes of roughness created by AWJ that described the variations between the values of roughness on both axis radial and vertical of the nozzle outlet.

Several observations that occurred after the implementation of the experimental work were noticed. In the first, it was observed that the angular location at the hole roughness is impacted by internal surface ranged based on the angular location. Figure 17 shows the distribution of the hole roughness that was drilled with AWJ. The dependence was explained by the travel speed concerned with the machined surface in terms of the roughness factor and connected to the machining exposition time of white marble.

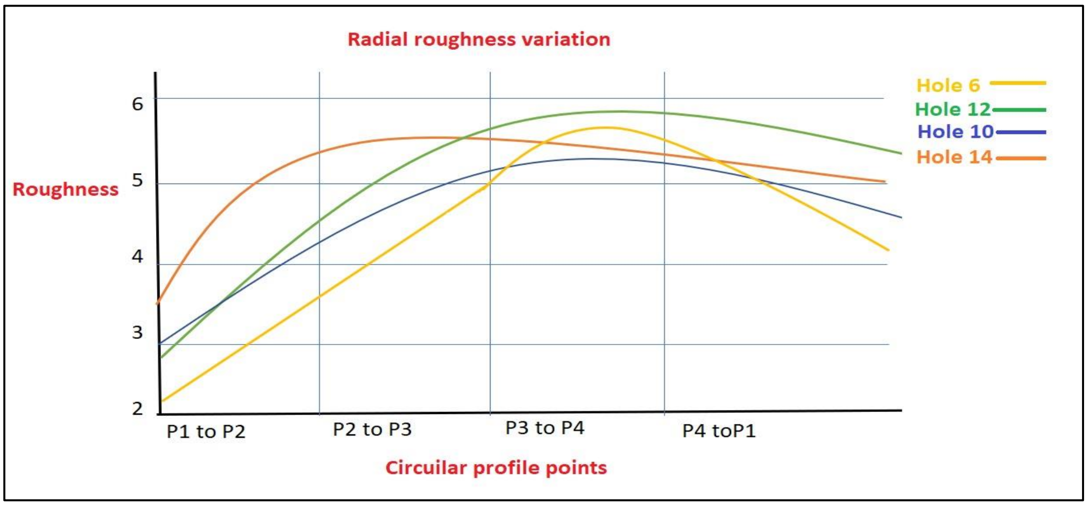

Fig 17 The Distribution of the Hole Roughness

Consequently, at increased velocity, the time will be met was more straightforward, in addition to that, the surface is rougher. Thus, the machining jet began from the middle of the nozzle outlet to the exterior from P1 to P4. As the remark, the machining jet in terms of fluid trajectory from start to the end was slower comparing the average speed set. Therefore, the roughness factor in these zones, such as P1 to P2 as well as P4 to P1 was more down than in the rest of the holes. An illustration of these three zones is provided in Figure 18.

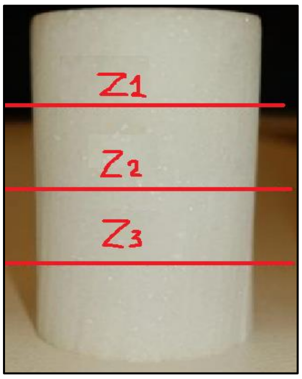

Fig 18 An Illustration of these Three Zones of the Marble Samples

The observed results could be clarified by the energy loss in the proposed jet based on the depth of the material. The variation that is between the zone 2 roughness and the roughness of zone 3 is the minor difference since Zone 1 involves the first interaction between the material as well as the jet. Hence, more disturbance is likelihood to happen to the material than Zone 2. While the third zone (Zone 3) represents the starting of the material patterns because of the jet divergence of zone 3 which is more asymmetrical in comparison with the divergence of jet of the zone 2 and zone 1.

Similarly, [24] found that the typical machine surface of aluminium owns three different areas along with the kerf wall, which is known as (IDR) that denotes Initial-Damage-Region. In addition to Rough-Cutting-Region (RCR) as well as the Smooth-Cutting-Region (SCR) from a jet entry into the specimen end. The SCR locates between the RCR and the IDR with the existence of small area and shaped by a relatively large attack angle, The IDR is known as a dark wear track which is achieved by the shallow attack angles. The roughness of the surface worsens by the RCP due to the jet upward deflection. In case of RCR the surface exhibits wavy or striations characteristics.

C. *The Process Parameters Effect on the Hole Taper*

At the end, the angle of Kerf is examined. Based on Table 15, it offers several residual plots, model equation, and model performances. The equation of the hole taper is given by:

$$HT = 2{,}359 - 0.000875(P) + 0.3199SOD\ (mm) + 0.000424\ (AFR) + 0.0108(D) - 0.003186\ (TS) \qquad \text{Eq.4}$$

The dispersion's vertical width is not increasing or even decreasing for the HT-adjusted values. Also, the HT values range within the interval (0.2-20.2). Accordingly, constant error variance is achieved with an error mean equal to zero. These observations with the performance parameters for the model, including the standard deviation, R^2, adjusted R^2, and the predicted R^2 are represented in Table 9 and Figure 19 (ANOVA of HT). According to the observations, the HT data values are met well by the proposed model and the linear regression model is applicable within the test's limits. With an 85% contribution percentage, the jet pressure was noticed to be the main parameter that affect the difference of the hole taper in the AWJ drilling process. The SOD, is the second influencing parameter with a contribution percentage equals to 11.4%.

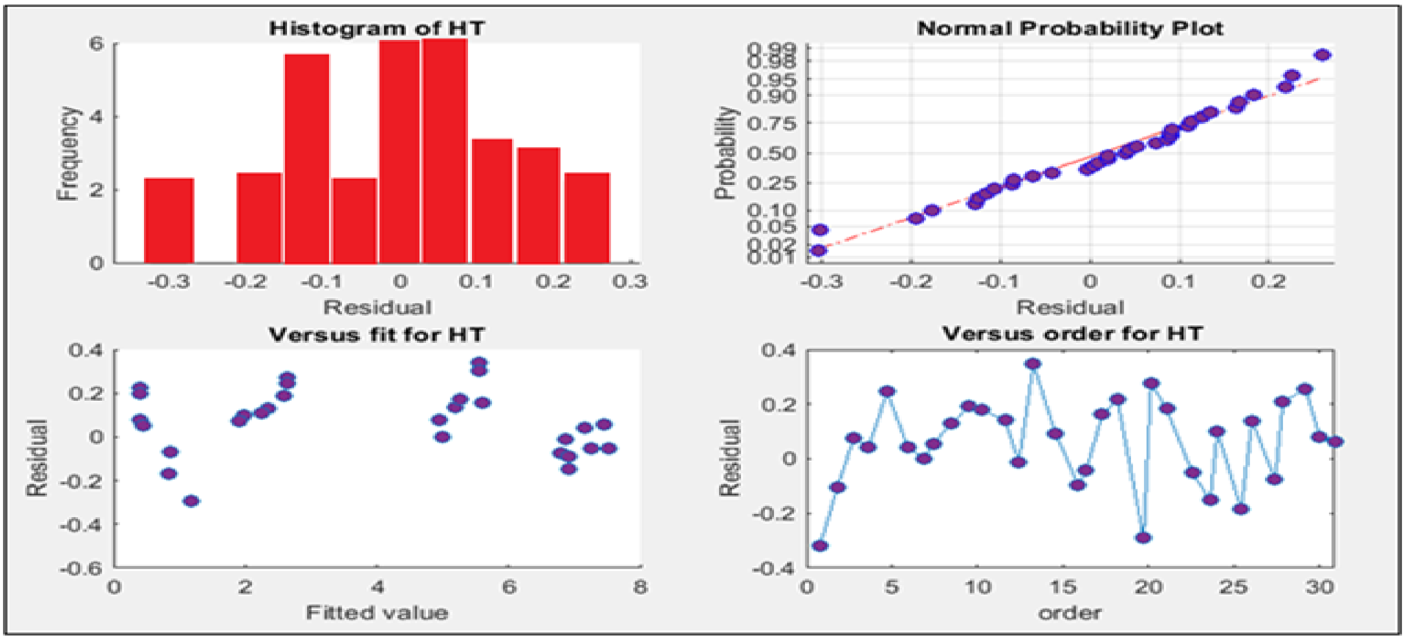

Fig 19 ANOVA for HT

Table 9 HT Model Performance

S	0153650
R-sq	97.86%
R-sq (adj)	97.45%
R-sq (pred)	96.76%

However, the effect of other parameters was neglected such as the AFR, the diameter of the hole, the hole taper, and the TS. A 97.86% accuracy is achieved between the hole taper and all the cutting parameters. Different values of jet pressure with SOD values were applied. The higher the pressure jet with 5 mm SOD, the minimum iconicity will be achieved. Increasing SOD will initiate the slug and the null angle of the hole iconicity is approximately reached. However, more noticeable iconicity is obtained by minimizing the pressure and the drilling is defective.

A high accuracy prediction of the hole taper is achieved by the regression models. Moreover, the hole taper depends on the pressure in a higher level than its dependence on the SOD and the TS. Accordingly, the pressure dramatically impacts on the striations formation and the increment in the hole taper.No linear regression models where used for modelling HCy, HCi, as well as HLE, which are functions of drilling parameters. Consequently, the later section presented a different regression model that can predict the key performance indicators.

D. Estimation of HLE, HCy, and HCi by using Artificial Neural Network.

The invention of the formal neuron has been widely discussed in several studies. For instance, a study defined the ANN as a flexible model tool that is able to learn the relationship between the output and the input as a map [25]. In general, the ANN has been used in order to the non-linear relationship between the input as well as the output of drilling process. Several methods can be utilised can be used to expect the roughness of the surface and to predict the geometric defects such as the localisations, cylindricity, and the circularity. Further, these methods are proposed to assess the roughness tolerance and the cylindricity of the holes which are drilled within the Carrara marble in conjunction with the diamond cutting bit.

This part concentrates on the model of ANN that used in predicting the performance of HLE, HCy, as well as HCi as a cutting condition function for the AWJ. The toolbox of neural network, in MATLAB, consists of different models. In this paper, multi layers are proposed due to the adaptability of several engineering issues.

Table 10 Optimal Number of Hidden Layers based on the Model Performance

Output	HLE	HCy	HCi
RMSE	3.13 E-12	1E-6	1.21 E-4
R-Sq %	99.72	97.89	98.91
Optimum NN	6	20	4

Five inputs and only one output were considered in this research with a trained one model for the localization error, circularity, and the cylindricity. Several sizes of hidden layer have been tested in this paper that varies from two to twenty hidden neurons. The optimum number of hidden layers has been selected such that the root mean square error is subjected to be as minimum as possible. In addition, the coefficient of determination (which is denoted by R-sq) that are defined in the following equations:

$$RMSE = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(Y_i - Y_i^{\wedge}\right)^2}. \qquad Eq.5$$

$$R_{Sq} = 1 - \left(\frac{\frac{1}{k}\sum_{i=1}^{k}\left(Y_i - Y_i^{\wedge}\right)^2}{\sum_{i=1}^{k}\left(Y_i - Y_i'\right)^2}\right) \qquad \text{Eq.6}$$

- k: is the overall measurements number.
- Yi: the value that has been measured.
- y^: is the value that has been predicted.
- y': the average of the values that were measured.

Once the RMSE value become around zero and the value of the R-Sq will be equal to one, the model of ANN is efficient. The R-Sq estimates the variable magnitude that is modelled by the ANN in the required output. Similarly, MSE determines the changing between the real value and the target value. In [27] the value of R-sq has been considered as the first criterion while the RMSE has been set to be the second criteria to evaluate the trained algorithms prformance. Furthermore, in the input layer, the five nodes represent the corresponding 5 decision values, which are TS, D, AFR, SOD, and P that were mentioned previously.

IV. CONCLUSION

The drilling process was conducted for white Carrara marble in presence of an AWJ machine. The impact of the characteristics of AWJ on the dimensional and geometric tolerances regarding holes such as taper angle, roughness, location error, cylindricity, and circularity were studied. The models of regression depended on ANN and linear regression models were suggested to accurately and easily estimate hole tolerances like a process of machining parameters for water jet.

The models that are used in the drilling process can be utilised through marble workers to determine the parameters of cutting that is used for white Carrara marble panels and to attain tolerances proposed by customer desired. These computationally and accurately efficient models might be utilized in the enhancement process to discover the ideal parameters of machining to reduce one or multiple machining defects. On the other hand, the models of ANN and linear regression assist comprehend the conduct of white marble as the friable material through non-traditional AWJ machining.

Thus, the AWJ conducts thermal stress and low mechanical on the marble. This process was applied to guarantee the surface of smoother marble than another drilling tools for instance high-speed steel (HSS), masonry drills, score drills, and diamond drills. Therefore, the drilling instrument is not essential to replace at each time when changing the dimensions of the hole.

Regarding the analysis of the regression model, it explained the taper angle and difference of surface roughness like a function to describe the cutting conditions of an abrasive jet, and their accuracy reached greater than or equal 92.46%. The mathematical patterns are highlighted in this work on two drilling parameters as the Kerf angle and roughness. These parameters help to link drilling process. Therefore, after applying these models to the process, it is concluded and observed that the pressure parameter is deemed the most crucial parameter at two values reach 75% as well as 85%. Also, the maximization conditions regarding jet pressure that reduces both parameters as a taper angle and the surface roughness.

The most important effect that is impacted the surface roughness at a ratio of 15% is called TS. Also, higher speed influences a rougher internal hole surface. The SOD impacted the taper of the hole at a ratio reaching 11%. On the other hand, the slight raise of minimal millimetres of SOD caused an expansion of the taper process by minimal degrees, and variation of a jet.

Both parameters as AFR and D diameter for the hole had minimal impact on all proposed outcomes. The model of ANN anticipated hole cylindricity and circularity, as well as localization error of holes that are characterized by high precision at 97.89%, 98.91%, as well as 99.72%, respectively. In this work, the drilling process was highlighted with high pressure that reaches 4000 bar, with two parameters as few and safe SOD and moderate TS able to penetrate whole material. Hence, this work confirms the local drilling process without the happening striations.

High quality of drilling process that permits for averting the finishing operations. Concerning the viewpoint of this project especially experimental design, it can be integrated several input parameters for instance the state of marble damage and plate thickness to achieve the generalization of drilling quality.

The studies of pattern recognition have been created and begun to detect brittle and crack spots that are presented in marble surfaces by utilizing different tools such as signal and images processing, thus, the type and position of weakness detected would be an extra input factor in whole reconfiguration system especially the machine of AWJ.

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