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Prediction of efficient fragmentation in a typical crystalline limestone quarry

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Abstract

Purpose. Rock fragmentation is the first result of blasting, and is directly related to the costs of mining. It is therefore imperative to predict the best possible way to achieve more economic and efficient fragmentation by blasting.

Methods. The study was carried out on two pits of Dangote crystalline limestone quarry at Obajana, Kogi State, Nigeria. The average uniaxial compressive strength (UCS) obtained from the rock samples from both pits of the quarry (i.e. OP1 and OP2) was determined in accordance to the international standard. The in-situ block sizes of the rock mass distribution were determined using AutoCAD, while the average percentage values of F50 was obtained from the Split-Desktop analyses. The total charge of explosive was obtained at each location. All these variables were used to develop a model for prediction of effective fragmentation.

Findings. With the aid of artificial neural network (ANN), the proposed model was found to be suitable for prediction of blast efficiency. Interestingly, the model uses pre-blasting parameter of in-situ block size which can be determined using AutoCAD and post blasting parameter of fragmentation size distribution that can be determined using Split-Desktop.

Originality. The findings compared the predicted value obtained with the measured efficiency, and the value of coefficient of determination, R^2 obtained is 0.9733, which makes it suitable.

Practical implications. The outcomes of the investigation have significant implications for the practical application. The model was used at the Freedom quarry, and it predicts good fragmentation during blasting. However, it does not consider the timing effect on the mining operation.

Keywords: *crystalline limestone deposit, rock fragmentation, Split-Desktop software, AutoCAD, ANN*

1. Introduction

Fragmentation is a critical process in quarrying and mining operations, as it directly affects the efficiency and cost of subsequent processing stages [1], [2]. In limestone quarries, efficient fragmentation is particularly important due to the increasing demand for high-quality aggregates and cement raw materials [3]. However, achieving optimal fragmentation in limestone quarries remains a challenging task due to the inherent heterogeneity of the rock mass and the complex interactions between blasting parameters, rock properties, and fragmentation outcomes.

The efficiency of a blast in fracturing a rock mass depends on the block size and the size distribution of the block [4]. The strengths of the joint sets generally are so small compared to the intact rock strength that most of the fracturing occurs along the joints rather than through the rock [5]. A realistic mechanical understanding of fundamental rock fracture modes is necessary in the search for greater efficiency and effectiveness of excavation techniques, particularly relevant in cases of rock fragmentation by blasting [6]. Blasting operations involve breaking or loosening the rock, ore and waste into minimum size and extracting the largest possible size at minimum cost. Drilling and blasting are essential to penetrate and fragment the rock mass [7].

Mining and its derivatives are very essential to our everyday lives. The challenges faced by Nigeria mining industry include not just finding enough mineral resources to meet demand, but also producing these minerals in a way that causes least harm, and conveys maximum advantage to the environment and society.

As a result of the growing concern about the effect of air pollution released into the environment, flyrock and excessive ground vibration after blasting, and cost of explosives used for blasting, there is need to identify, characterize, evaluate and possibly specify control measures for effective blast design to aid maximum recovery in the mining industry [8]-[11].

Several factors can influence the fragmentation process, including blasting parameters, rock properties, and joint orientation. Blasting parameters such as burden, spacing, and charge concentration, can significantly affect the fragmentation outcomes [7], [12]. For instance, increasing the burden can lead to larger fragment sizes, while increasing the charge concentration can lead to smaller fragment sizes [13]. Rock

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properties, such as rock type, texture, and strength, can also influence the fragmentation process [14]. For example, rocks with higher strength and lower porosity tend to produce larger fragment sizes. Additionally, joint orientation can also play a significant role in the fragmentation process [15]. For example, the orientation of the joints perpendicular to the blasting can lead to smaller fragment sizes.

Blasting is carried out in mining to reduce the *in-situ* rocks to smaller size fragments that can be easily handled by loading and haulage equipment [2], [3]. The process involves breaking or loosening the rock to extract largest possible tonnage of smaller size fragments at a reduced cost. To achieve this objective, quantitative and qualitative requirements of blast fragmentation are essential conditions that must be met [3], [16].

The primary purpose of blasting is rock fragmentation and displacement of the broken rock. Blasting operations may cause excessive noise and vibration in communities. The levels of structural vibration caused by ground vibration from blasting can result in damage to, or failure of, structures. The intensity of ground vibration depends on various parameters which can be categorized into two; controllable parameters and uncontrollable parameters [1]-[3].

Controllable parameters are mainly related to explosive characteristics (initiation system, initiation sequence, number of free faces, buffers, explosives energy, charge geometry, loading method) and blast hole design parameter (hole diameter, hole depth, subdrill depth, hole inclination, collar height, stemming, blast pattern, the burden to spacing ratio, blast size and configuration, blasting direction, initiating system, initiating sequence, number of free faces, explosive types, explosive energy, charge geometry, loading method), while others are uncontrollable parameters, which are natural and related to geological conditions and lithology of the rock mass [1]-[3].

Blasting operations are usually accompanied by various unwanted phenomena such as flyrocks, back-break and vibration. Meanwhile, some proposed mathematical models for blast fragmentation have failed [2], [16]. The ambiguity therefore triggers the question: how consistent can the fragmentation arising from rock blasting be improved optimally? The magnitude of the anticipated benefits can be varied, especially given the different types of rocks.

Recent research has focused on developing predictive models for fragmentation of various rock types, including limestone [17], [18]. These models often rely on empirical correlations between blasting parameters, such as burden, spacing, charge concentration, fragmentation outcomes, such as mean fragment size and fragmentation uniformity [12].

Numerous fragmentation prediction models have been developed to estimate the size distribution of fragments resulting from blasting. These models can be broadly classified into three categories: empirical, analytical, and numerical models. Empirical models are based on statistical relationships between blasting parameters and fragmentation outcomes. Examples of empirical models include the Kuz-Ram model [19] and the Cunningham model [20]. However, these models are often site-specific and may not account for the unique geological and geotechnical characteristics of the limestone [13], [21].

Analytical models, on the other hand, are based on the principles of rock mechanics and blasting dynamics. Examples of analytical models include the model developed by [22] and the model developed by [15]. These models can provide valuable insights into the underlying mechanisms of fragmentation, but may require complex mathematical formulations and extensive computational resources.

Numerical models, such as discrete element modelling (DEM) and finite element modelling (FEM), have also been used to simulate the fragmentation process. Examples of numerical models include the DEM model developed by [23] and FEM model developed by [15]. These models provide detailed information on the fragmentation process, but may require significant computational resources and expertise.

In effect, the process of objectively analyzing the effective relationship between the blast results and adopted models, and the overall economics of the mining operation is often far from the obscurities to provide conclusive results [3], [24]. Despite the progress made in understanding the factors influencing fragmentation in limestone quarries, several unresolved aspects remain, such as; the effects of joint orientation, rock texture, and moisture content on fragmentation outcomes are not well understood; the development of predictive models that can account for the variability in limestone properties and blasting conditions is still a topic of ongoing research; and the majority of existing fragmentation models are based on 2D analysis, which may not accurately represent the complex 3D rock mass nature [12], [14], [15].

This research is aimed to address these knowledge gaps by investigating the factors influencing efficient fragmentation in a typical crystalline limestone quarry. The research objectives were to analyze the effects of blasting parameters, rock properties, and joint orientation on fragmentation outcomes in limestone quarry, develop a predictive model for fragmentation in the limestone quarry that accounts for the variability in rock properties and blasting conditions, and evaluate the performance of the developed model using field data from a limestone quarry.

2. Study area

The study area is located within the Guinea Plain of Nigeria, characterised by sedimentary and metamorphic rocks. The dominant geological formation is the Anambra Basin, which comprises shale, limestone, and sandstone. The rock composition of the area is primarily sedimentary and metamorphic in nature. The region geology is characterised by crystalline limestone, primarily composed of calcium carbonate ($CaCO_3$) from ancient marine organisms. This makes the rock composition of the area crucial for mining and construction activities, as well as for environmental assessments.

Dangote cement quarry in Obajana, Kogi State, Nigeria is an open pit mine, operating in three different pits code-named OP1, OP2 and OP3. Dangote quarrying operations involve the extraction of limestone, granite and other minerals, which are used in various industries, including construction and manufacturing. The quarrying operations are a significant part of its business, with a focus on sustainability and environmental responsibility. The company emphasizes health and safety in its operations, and ensures a safe working environment for better performance and efficiency.

The study was carried out in two of the three pits (OP1 and OP2). The two mine pits produce crystalline limestone aggregates, and both are in operation. Figure 1 shows the Map of Dangote cement quarry in Kogi State as extracted from the Geological Map of Nigeria.

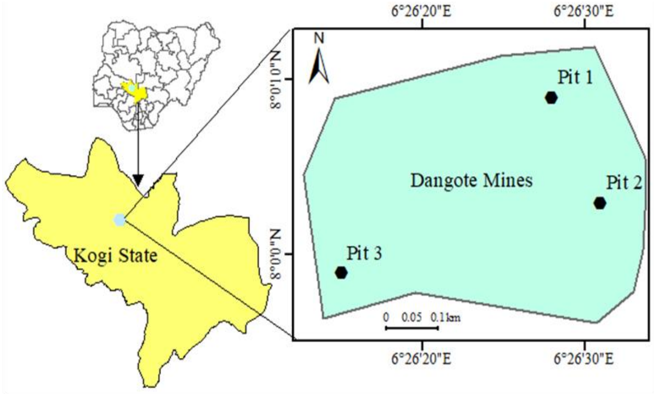

Figure 1. Location Map of the Study Area Showing the Pits [25]

Dangote cement quarry is located geographically between the latitude 06°30′55″N – 08°06′10″N and longitude 06°20′10″E – 07°10′00″E at 230 m above the sea level and it is approximately about 200 km southwest of Abuja, the capital of Nigeria.

3. Methods

3.1. Uniaxial compressive strength

The uniaxial compressive strength test is typically characterized and determined by loading a cylindrical rock sample with a diameter of approximately 50 mm and length to diameter ratio of 2.5:1 axially until the sample fails. It was carried out in accordance with international standards [26], [27]. The test is mainly intended for dynamic strength classification and characterization of intact rocks [28].

3.2. In-situ block size distribution

The in-situ rock block sizes are determined with the use of AutoCAD tool. AutoCAD has become a standard program for producing technical drawings of all types [29]. This may be used for structural or non-structural model. The required geotechnical data for the model include the relative position of the outcrop on the earth's surface, the spacing of joints, the persistence of fracture and the orientation of joint sets.

The individual blocks generated by the intercept of the joints are banded together and extruded to the required height based on the distance between sub-vertical features. Based on the model created, the surface area and the volume of each block is estimated to generate in-situ block size distribution within the required outcrop.

3.3. Fragment size distribution analysis of blasted rocks at OP1 and OP2

Split-Desktop digital image analysis was used to determine the rock fragmentation gradation distribution of average 50% passing of fragment sizes. High precision camera was used to capture the accurate images of the blasted muckpiles. This involves five phases for each image captured, and at the fifth stage, the size distribution results are displayed in the form of diagrams [30].

The blast design parameters for the blast operations carried out at OP1 and OP2 are presented in Table 1.

However, the only difference between the two pits is the burden value, which is reduced by 1 m, bench height is reduced by 5 m, and powder factor is reduced by 0.7 kg/ton in OP2.

Table 1. Data for drilling and blasting of OP1 and OP2

S/N	Parameter	Value for OP1	Value for OP2
1	Burden, m	5	4
2	Spacing, m	3	3
3	Bench height, m	14.5	9.5
4	Hole diameter, mm	125	125
5	Stemming, m	3	2.5
6	Sub-drill, m	1	1
7	Powder factor, kg/tons	3.2	2.5
8	Quantity of explosive per meter, kg	ANFO = 16	ANFO = 16
9	Explosive type: Low explosive, kg Bulk emulsion, kg	 18 22	 18 22
10	Delay time/ interval, ms	17 25	17 25

4. Results and discussion

4.1. The average uniaxial compressive strength of rock samples

The average uniaxial compressive strength (UCS) obtained from five samples, each from OP1 and OP2 of Dangote Obajana quarry, is 68.20 MPa and 76. 74 MPa, respectively, as shown in Tables 2 and 3.

Table 2. Uniaxial compressive strength of rock samples from OP1

Sample No.	Failure load, KN	Cross-sectional area, mm^2	Mass before rest, g	Comp. strength, MPa
OP1 A	155	22.8	136	68.06
OP1 B	150	22.8	132	66.61
OP1 C	170	22.8	149	74.57
OP1 D	145	22.8	127	62.99
OP1 E	160	22.8	140	68.78
		Average		68.20

Mean = 68.202; Standard Deviation = 25.100

Table 3. Uniaxial compressive strength of rock samples from OP2

Sample No.	Failure load, KN	Cross-sectional area, mm^2	Mass before rest, g	Comp. strength, MPa
OP2 A	170	22.8	149	73.85
OP2 B	210	22.8	184	92.67
OP2 C	140	22.8	123	62.26
OP2 D	170	22.8	149	75.30
OP2 E	180	22.8	158	79.64
		Average		76.74

Mean = 76.744; and Standard Deviation = 9.618

The UCS of rock samples from the crystalline limestone quarry of OP1 and OP2 vary from 62.99 to 74.57 MPa and from 62.26 to 92.67 MPa, respectively. The variation in the UCS of the rock type is basically due to their mineralogical compositions. According to [31] and [32], the UCS classification of the rocks is of moderate strength.

4.2. In-situ block size distribution of rock mass

For the in-situ block size distribution of the rock type, AutoCAD software was used. In each of the two locations for the study, the in-situ rock mass conditions for the five different blasts with similar dimensions were modeled and their cumulative graph curves were plotted to obtain the average in-situ block size distribution.

The AutoCAD block size distribution for ten different blasts, five at OP1 and five at OP2, are shown in Figures 2 and 3. The AutoCAD model dimension of the in-situ rock mass for each blast at OP1 is 90×50 m with a bench height of 14.5 m, and for OP2, it is 75×50 m with a bench height of 9.5 m.

Figure 2 reveals the average in-situ block size distribution for the five blasts at OP1, with A having the least block size distribution of 4.07 m^2 and D with the highest block size distribution of 5.62 m^2. Figure 3 reveals the average in-situ block size distribution for the five blasts at OP2, with C having the least block size distribution of 3.07 m^2 and B with the highest block size distribution of 5.41 m^2.

This actually helps in assessing the rock mechanical properties, such as strength, stiffness and stability of the rock mass as it affects the fragmentation process.

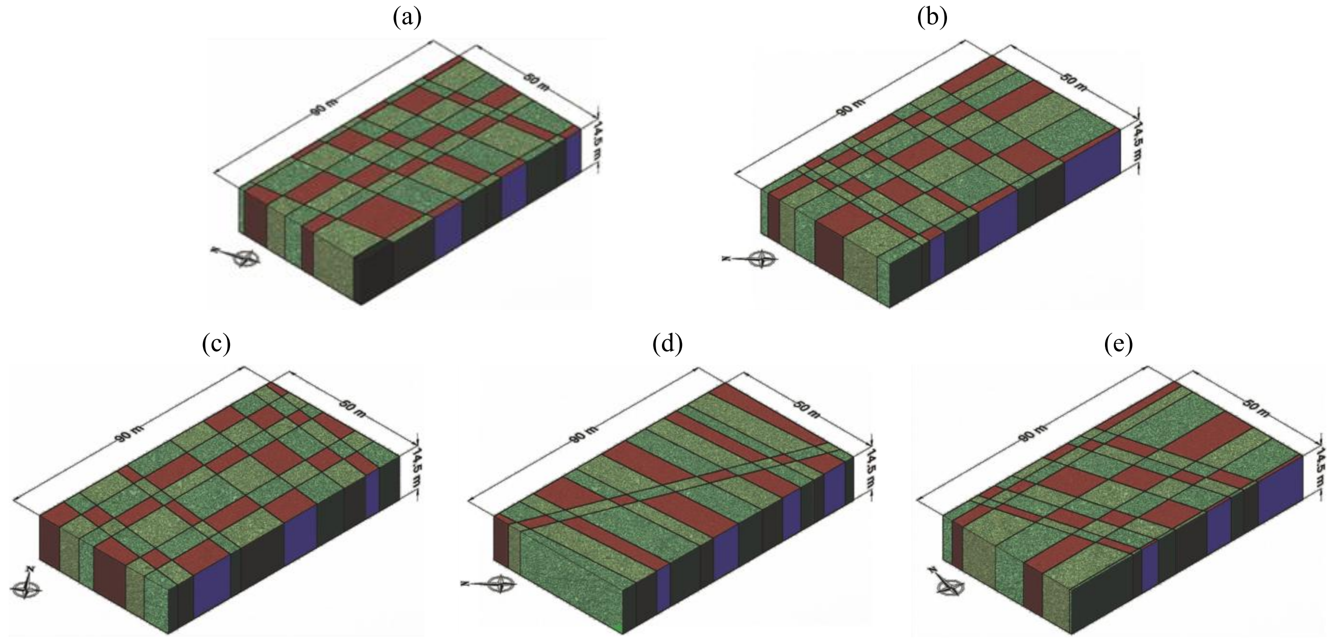

Figure 2. AutoCAD Block Size Distribution of Blasts A – E at OP1

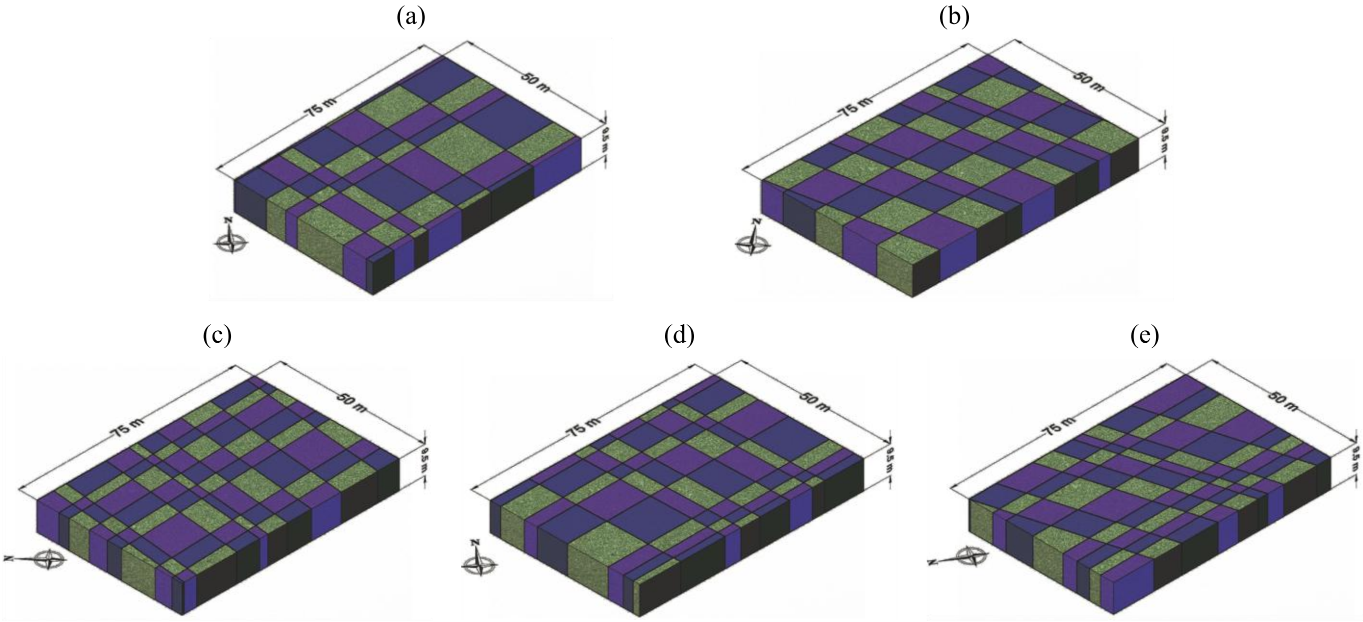

Figure 3. AutoCAD Block Size Distribution of Blasts A – E at OP2

The cumulative graph curves of the in-situ block size distributions for each of the five blasts A to E at OP1 and OP2 are presented in Figures 4 and 5. These cumulative curves help in better understanding the distribution of block sizes, which is very important in assessment of rock fragmentation characteristics. Figure 4 shows the cumulative graph curves at OP1 with block sizes varying from 4.07 to 5.62 m^2, where A is the lowest and D is the highest, respectively.

Figure 5 shows the cumulative graph curves at OP2 with block sizes varying from 3.07 to 5.41 m^2, in which C is the lowest and B is the highest, respectively.

The cumulative curves, as shown in both Figures 4 and 5, provide a visual representation of the block size distribution, making it easier to interpret the data. Additionally, the curves help to compare the block size distribution with other data, such as rock strength and image analyses.

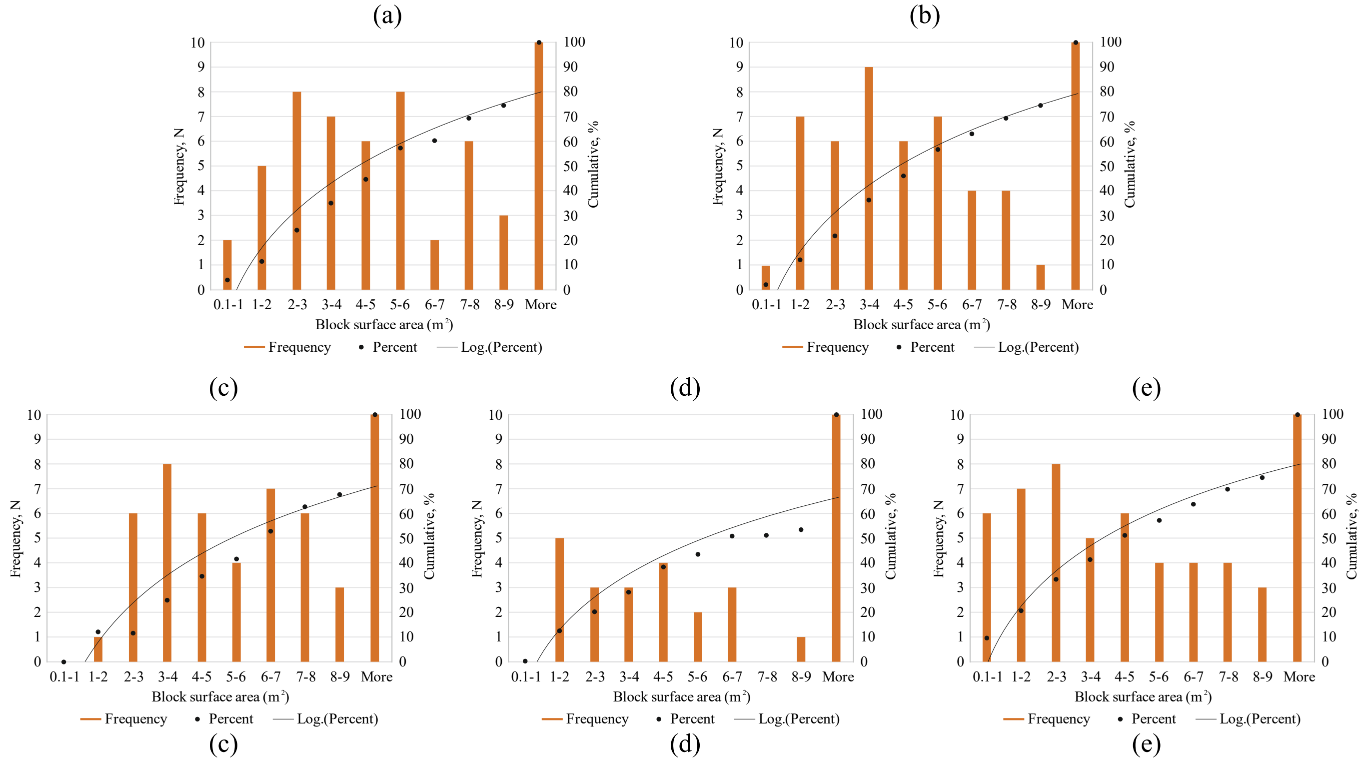

Figure 4. Cumulative graph of in-situ block size distribution for blasts A – E at OP1: (a) block A; (b) block B; (c) block C; (d) block D; (e) block E

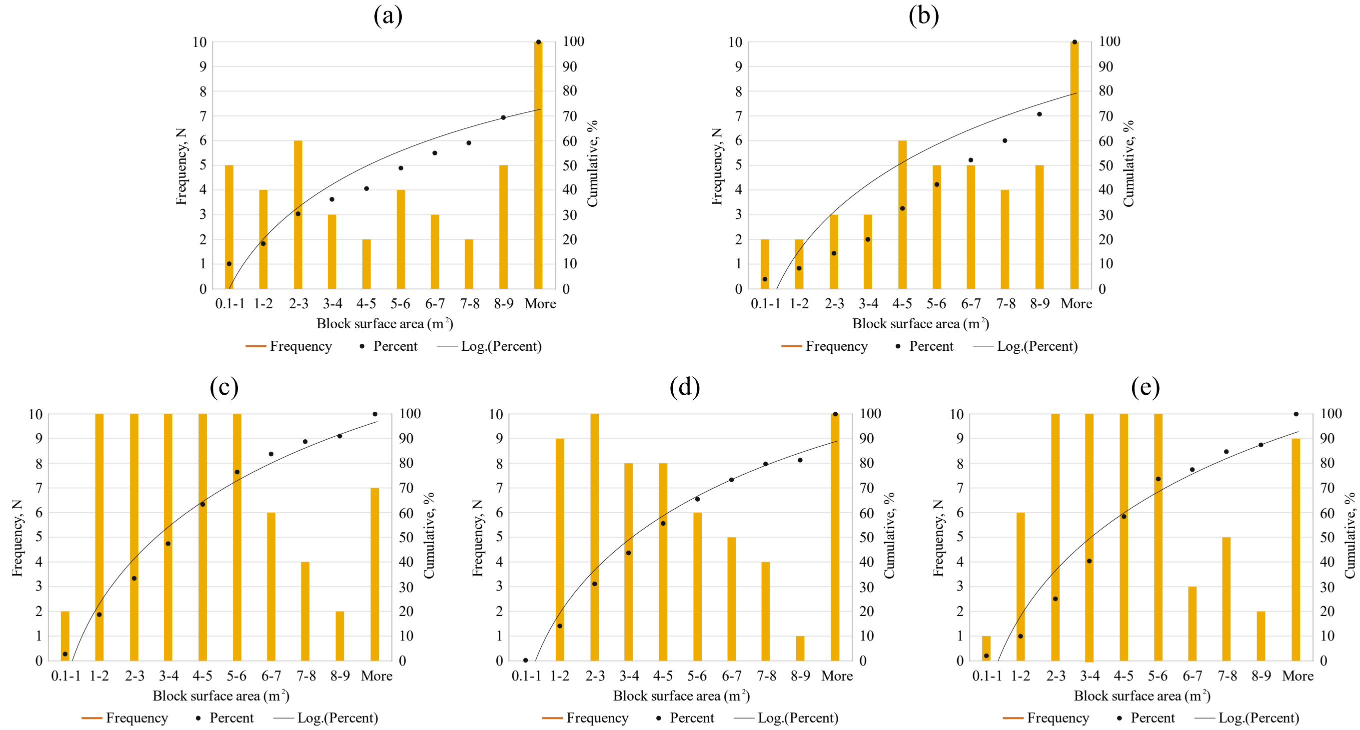

Figure 5. Cumulative graph of in-situ block size distribution for blasts A – E at OP2: (a) block A; (b) block B; (c) block C; (d) block D; (e) block E

4.3. Image analysis

The particle size distribution curve analyses of the muckpiles obtained from the ten different blasts of both OP1 and OP2 using Split Desktop model are shown in Figures 6 and 7. The results of the Split-Desktop processing of the blasted rock fragments are recorded in all the blasts.

The Split-Desktop analyses in Figure 6 show a very closely related particle size distribution for the five blasts at OP1 with uniformity index of 1.26. The average values of F_{50} obtained from the Split-Desktop analyses of OP1, as presented in Table 4, are approximately 67.38 cm.

The Split-Desktop analyses in Figure 7 show different particle size distribution for the five blasts at OP2 with uniformity index of 1.38. The average values of F_{50} obtained from the Split-Desktop analyses of OP2, as presented in Table 4, are approximately 69.40 cm.

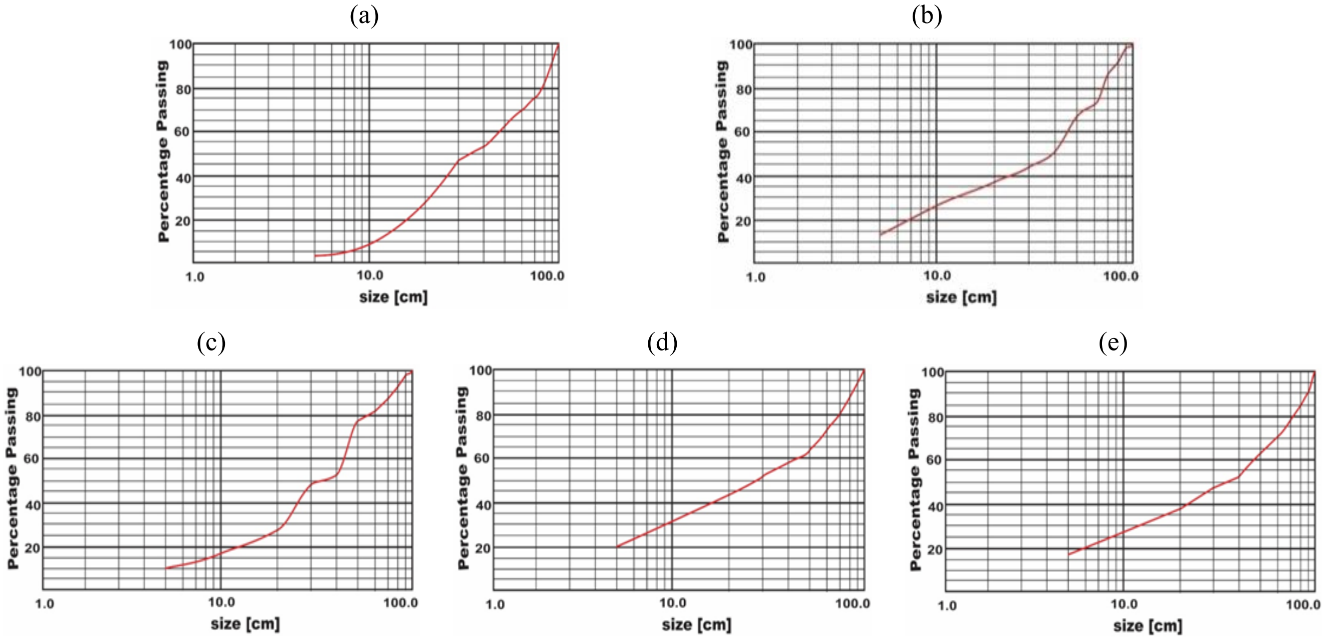

Figure 6. Cumulative grain size curves of image analysis of blasts A – E at OP1

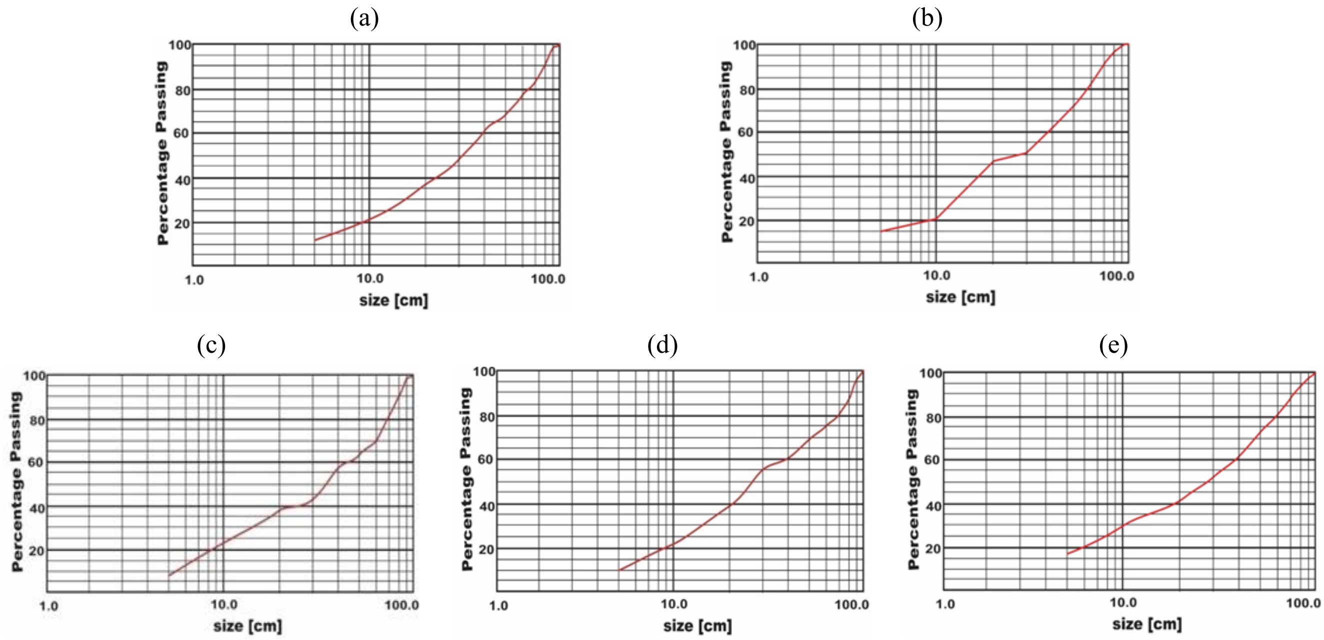

Figure 7. Cumulative grain size curves of image analysis of blasts A – E at OP2

Table 4. Average 50% passing of fragment sizes for blasts A – E at OP1 and OP2

Blast	OP1, cm	OP2, cm
A	64.8	67.1
B	62.9	69.8
C	66.9	73.5
D	63.8	73.7
E	78.5	62.9
Average	67.38	69.40

4.4. Model development

Table 5 shows the variables used for the blast prediction model development.

The ANN model is developed for predicting the blasting efficiency. The numbers of input and hidden neurons are three, while the neuron in the output layer is one.

Table 5. Variables for the blast prediction model development

S/N	Blast	Total charge, kg $[(i + ii)\cdot n]$	Average size of fragment 50% passing, cm	UCS, MPa	In-situ block size, m^2
1	OP1 Blast A	5600	64.8	68.06	4.07
2	OP1 Blast B	5750	62.9	66.61	4.12
3	OP1 Blast C	6720	66.9	74.57	5.26
4	OP1 Blast D	4940	63.8	62.99	5.62
5	OP1 Blast E	6900	78.5	68.78	4.60
6	OP2 Blast A	4800	67.1	73.85	4.53
7	OP2 Blast B	4500	69.8	92.67	5.41
8	OP2 Blast C	6160	73.5	62.26	3.07
9	OP2 Blast D	4940	73.7	75.30	3.92
10	OP2 Blast E	5880	62.9	79.64	3.84

The feed forward back propagation training algorithm was used. The obtained weights and biases were extracted from the ANN and then used to formulate mathematical model for predicting the blast efficiency, as presented in Equation (1).

The prediction of the proposed model in Equation (1) is compared with the measured efficiency, as presented in Figure 8.

$$\%Eff = 7.8\tan h\left(\sum_{i=1}^{3} x_i + 30.3384\right) + 70.7, \quad (1)$$

where:

$\% Eff$ – the blast efficiency;

x_i in Equation (1) is as listed in Equations (2)-(4):

$$x_1 = 30.0798\tan h\cdot(0.012237TC - \\ -0.4495UCS + 4.73568IB - 76.5322); \quad (2)$$

$$x_2 = 30.4429\tan h\cdot(0.00438TC - \\ -0.5088UCS + 0.82539IB + 6.140406); \quad (3)$$

$$x_3 = 30.30669\tan h\cdot(-0.01582TC + \\ +0.96968UCS - 13.89014IB + 69.52566). \quad (4)$$

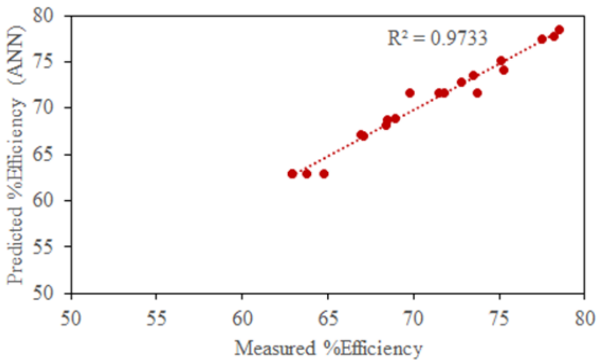

Figure 8. Comparison of the measured and predicted blasting efficiency using ANN

The prediction of the proposed model using ANN is compared with the measured efficiency and the value of the coefficient of determination, R^2 obtained is 0.9733.

5. Conclusions

Rock mass is composed of two parts of in-situ rock and discontinuities. Discontinuities include structures in rock mass such as joints, faults, fractures, bedding and other weakness surfaces that significantly influence the engineering and mechanical properties of rock mass.

The results of average UCS obtained from the rock samples of OP1 and OP2 are 68.20 and 76.74 MPa, respectively. This shows that the strengths of the rock types considered in the study area are moderate rock strength classes.

For the in-situ block size distributions of rocks using AutoCAD, the dimensions for the in-situ rock masses of each pit vary from each other. The allowable and acceptable block sizes of 50% frequencies of the cumulative graphs of the in-situ block size distributions were recorded for each location.

The research also investigated the particle size distribution of blast-induced fragmentation of two pits (OP1 and OP2) of Dangote Obajana Quarry using the digital image processing of Split-Desktop to evaluate the degree of fragmentation of muckpiles produced from the blasting operations.

The Split-Desktop analyses show that different rock masses subjected to similar blast design will produce varied degrees of fragmentation as a result of inherent resistances of the rock mass during blasting.

These average values of F_{50} percentage passing of the muckpiles produced are considered suitable for the quarry operations in the study area as a result of close values to the allowable value of 100 cm of the crusher.

The results obtained from the findings were used to develop a model for prediction of blast efficiency. The prediction of the proposed model using ANN is compared with the measured efficiency and the value of R^2 obtained is 0.9733, which is suitable for prediction of blast efficiency.

Author contributions

Conceptualization: KI; Data curation: GD, ZA; Formal analysis: DS, MS; Funding acquisition: HK; Methodology: KI; Project administration: KI; Resources: GD, DS, ZA, MS, HK; Software: DS; Supervision: KI; Validation: GD; Visualization: DS; Writing – original draft: KI; Writing – review & editing: KI. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Прогнозування ефективної фрагментації в типовому кар'єрі з видобутку кристалічного вапняку

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Мета. Дослідження фрагментації гірських порід при здійсненні вибухових робіт у вапняковому кар'єрі для прогнозування їх найкращих економічних показників.

Методика. Дослідження проводилося на двох шахтах кар'єру кристалічних вапняків Данготе в Обаджані, штат Когі, Нігерія. Середня межа міцності на одноосьовий стиск (UCS), отримана зі зразків породи з обох шахт кар'єру (тобто OP1 і OP2), була встановлена у відповідності з міжнародним стандартом. Розміри блоків розподілу гірничої маси на місці видобутку визначені за допомогою AutoCAD, тоді як середні відсоткові значення F50 були отримані за допомогою аналізу Split-Desktop. На кожній локації отримано загальний заряд вибухівки. Зазначені змінні були використані для розробки моделі прогнозування ефективної фрагментації.

Результати. Визначено, що за допомогою штучної нейронної мережі (ШНМ) розроблена модель виявилася придатною для прогнозування ефективності підривних робіт. Результати порівняння отриманого прогнозованого значення з виміряною ефективністю показали, що отримане значення коефіцієнта детермінації становить 0.9733, що є прийнятним. Зазначено, що ефективність фрагментації у розробленій моделі прогнозується на основі двох основних параметрів, а саме, попереднього до вибуху розміру блоків гірничої маси, який визначається за допомогою AutoCAD, та розподілу розмірів фракцій після вибуху, що аналізується у програмному середовищі Split-Desktop.

Наукова новизна. Створено прогнозну модель ефективності вибухових робіт в умовах вапнякових кар'єрів, яка вперше поєднує характеристики гірського масиву до вибуху та ступінь фрагментації після вибуху на основі штучної нейронної мережі.

Практична значимість. Створена модель була використана на кар'єрі Freedom й продемонструвала високий рівень прогнозу фрагментації гірських порід під час вибухових робіт, проте, не враховує вплив часу на видобування корисних копалин.

Ключові слова: *родовище кристалічних вапняків, фрагментація породи, програмне забезпечення Split-Desktop, AutoCAD, Artificial Neural Network*

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