Evaluating Blast Fragmentation: A Comparative Study of Electronic and Shock-Tube Initiation Systems in a Limestone Mine

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Abstract

Explosive energy is the most widely used method for fragmenting rock masses and mineral deposits in mining operations. The fragmentation achieved during blasting significantly impacts downstream operations including loading, transportation, crushing and processing costs. Among the various factors affecting blast fragmentation, the initiation system plays a crucial role. A study was carried out to compare the performance of electronic detonators with shock-tube detonators, in terms of fragmentation in a limestone mine. Field experiments were conducted to assess the fragment size using digital image analysis technique (DIAT).

The results indicated that electronic initiated blasts produced finer average fragment sizes (k_{50}) ranging from 0.31- 0.44 m, while as in non-electric shock-tube (NeSt) initiated blasts produced larger fragmentation with k_{50} values between 0.39 - 0.51 m. The analysis revealed that average k_{50} values of blasts initiated with electronic detonator were 20% less than that of non-electric shock tube (NeSt) initiated blasts. This is primarily due to precise delays planned and executed for the rock mass that aid in proper fragmentation.

Keywords: Electronic initiation, Fragmentation, Limestone, Non-electric shock-tube initiation.

Introduction

Fragmentation refers to the post-blast size distribution of the rock mass, a critical outcome of blasting operations. It is widely regarded as one of the most optimized outputs of blasting due to its significant influence on downstream processes in the Mine-Mill Fragmentation System (MMFS). Key factors affecting fragmentation include rock properties, explosive characteristics, blast geometry and initiation systems[2]. From an economic perspective, the integration of mine and mill systems emphasizes achieving a fragmentation degree that minimizes the combined costs of drilling, blasting, loading, hauling and crushing[6,9]. This balance ensures that the size and volume of fragmented rock are economically viable. Optimal fragmentation not only reduces costs but also minimizes environmental impacts, as stated by Da Gama et al[3].

Hustrulid[6] concluded that fragmentation size directly impacts loading efficiency and crushing rates, both of which are pivotal in maximizing production rates. Therefore, aligning fragmentation strategies with operational and economic objectives is essential for sustainable and efficient mining operations. Hence, explosive initiation systems such as non-electric shock tube (*NeSt*) detonator and electronic detonators are critical to this process, influencing blast outcomes such as fragmentation, muck pile geometry and vibration control[12]. Recently, electronic detonators have gained attention for their ability to deliver precise delay timing, offering enhanced control over the blast sequence[10].

Electronic detonators are designed to improve the accuracy of blast timing, which can significantly influence the fragmentation process. Precise timing reduces the risk of misfires and minimizes the fragmentation, resulting in improved uniformity and optimal particle size distribution[11]. This is particularly critical, where mining operations often face challenges related to diverse geological conditions and stringent regulatory frameworks. On the other hand, while cost-effective and widely adopted, *NeSt* have limitations in their ability to offer precise delay timing due to inherent variability in the manufacturing process of shock tubes and delay elements. As a result, these systems may lead to suboptimal fragmentation and increased costs associated with secondary blasting or crushing[4].

Himanshu et al[5] stated that electronic detonators offer precise control over the timing of explosions, which leads to more efficient use of explosive energy. This precision helps in achieving better fragmentation of the rock, reducing the size of the muck pile and improving overall excavation productivity. The electronic detonators allow for better control over the blast sequence. Iwano et al[7] investigated the use of advanced electronic detonators in tunnel blasting and construction, for minimizing ground vibrations and air blast, that are crucial for operations near populated areas or sensitive structures.

The accuracy of delay timing, blast sequence control and safety of electronic detonators is studied by Kalyan et al[8] who stated that electronic detonators provide more precision delay timings compared to *NeSt* initiation systems, which rely on pyrotechnic delays. They also offer better control over blast sequence, consenting for larger blasts with minimal vibration and optimal fragmentation.

In this context, a case study was taken up to assess the role of electronic detonators in rock fragmentation and to quantify their effectiveness by comparing the results with those obtained using *NeSt* with similar delay timings. In this study, the fragmentation analysis using digital images was carried out to provide insights into the advantages associated with adopting electronic detonators, thereby aiding in the selection of appropriate blasting techniques for demanding mining production. Also, in this case study, investigations were carried out with conventional *NeSt* system and electronic detonators in a limestone mine.

Material and Methods

Non-electric Shock-tube (*NeSt*) Detonator: The shock-tube initiating system is made of a hollow polymer tube with an internal diameter of 1.5 mm and an outer diameter of about 3 mm. The inner surface of the tube has a very thin layer of reactive material or low explosive[13]. The tube is crimped on one end and the other end is inserted with a non-electric detonator that has a specified time delay element of pyrotechnic nature. The shock tube is initiated with an ordinary detonator. The shock wave with a VOD of 1800-2000 m/s travels within the hollow tube. The shock is carried to the detonator where a delay element holds it for designated time. The end of delay element carries the shock to main charge of the detonator. That in turn initiates the explosive for detonation. A schematic diagram of a non-electric shock-tube detonator is shown in figure 1.

Electronic Detonator: The operation of electronic detonators involves a series of precise, programmable steps to ensure safe and efficient blasting. First, the detonator is connected to a logger via wires and assigned a unique ID for identification. The delay timings are programmed into the detonator's microchip to control the exact sequence and intervals of detonations. When the blasting machine sends encoded signals, the microchip within each detonator verifies the signal to ensure correctness, preventing unauthorized or accidental activation. Once verified, the internal power source (capacitor) charges and provides energy to heat a bridge wire or semiconductor igniter, which ignites the primary explosive (lead azide).

The primary explosive generates a shock wave that activates the secondary explosive (PETN), amplifying the detonation force and triggering the main explosive charge in the blast hole. This sequence ensures controlled and efficient fragmentation of material while minimizing ground vibrations and fly rock. Electronic initiation system gives an accurate delay time with $\pm$ 1 ms accuracy and precision in blasting operation. A schematic diagram of an electronic detonator is shown in figure 2.

Electronic detonator – design aspects: The electronic detonator system has three closely interacting main components, namely, the detonator, the logger and the blasting machine which are necessary for the proper functioning of the system as shown in figure 3.

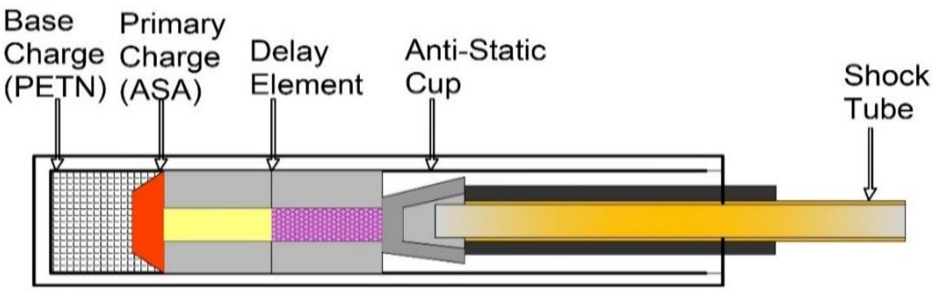

Figure 1: A schematic diagram of a non-electric shock-tube *(NeSt)* detonator

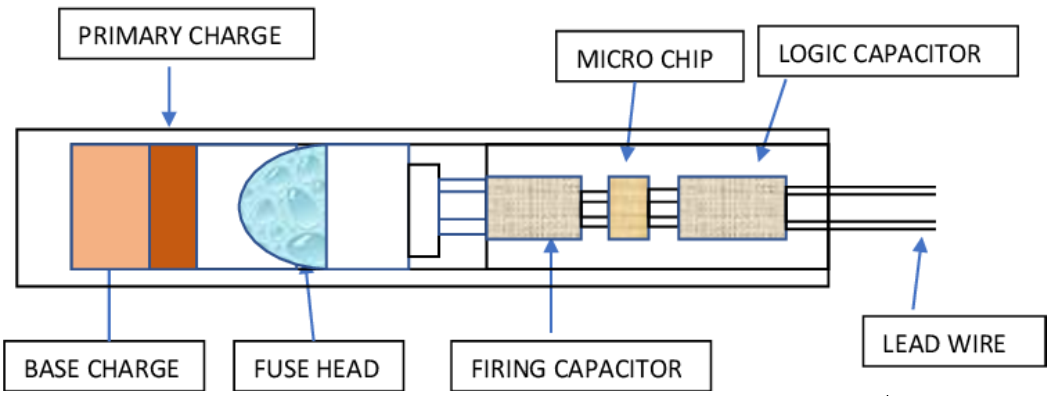

Figure 2: A schematic diagram of an electronic detonator[1]

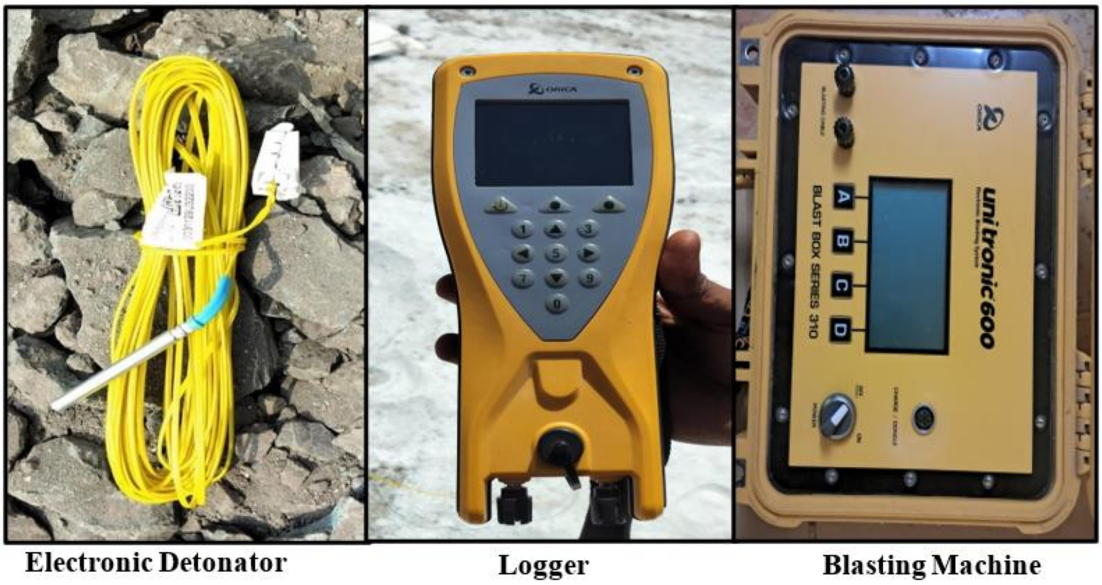

Figure 3: A view of components of electronic detonator

Electronic detonators blasting system consists of following elements:

- Programmable electronic detonator
- Micro logger- for assigning delay timing to detonator
- Bus wire - for connecting all the holes in the shot
- Micro tester - for checking the circuit once the holes are connected
- Micro blaster - device for firing the holes charged with detonator

Micro logger: To assign delay timing to the detonator, the micro logger is used to set the delay time. It has the capability to store information such as hole numbers, detonator IDs and delay timings. During logging, one end of the logging cable is connected to the logger and the other end is attached to the detonator via a connector. All the logging data from the micro logger is transferred to the micro tester for circuit testing. The logging data is also transferred to the micro blaster before firing the shot. For assigning delay timing to detonator, the micro logger is used to set the delay time.

Micro tester: To check the circuit once the holes are connected, the micro tester is used. It has the capacity to test up to 500 detonators. The data from the micro logger is transferred to the micro tester via a transfer cable. The micro network tester communicates with all detonator units and shows the connection status for each. At this stage, the delay timing of any detonator unit can be edited. The tester also measures the total resistance and displays 'Short Circuit' if any issue is detected. It can handle up to 500 detonator units. After checking the circuit with the micro tester, the data from the logger is transferred to the blaster before firing.

Micro blaster: Device for firing the holes charged with detonator again checks the integrity and continuity of the circuit. Once the Blaster ARM key is turned on, all the detonators will be armed within 1 minute and will be previously assigned delay timing. The firing at this stage can be aborted by pressing "ABORT" button. All the detonators receive fire signal at the same time but fired according to the delay time given to them.

Study area: The limestone mine is located in southern India. The mining area is generally flat with an elevation of about 59 m above MSL. The mine is being operated with a daily production capacity of about 2800 tonnes in two shifts. Conventional benching method is adopted to mine out the limestone deposit. An overview of the limestone mine is shown in figure 4. The entire area comprises of Archean formations completely covered by 1-2 m thick black cotton soil. Below this soil cover, the Archean rocks, namely, charnockite, granite, granulite, limestone, pink granitic gneiss and pegmatite occur. The charnockite and pyroxene granulite occur as hang wall and footwall of the limestone band as depicted in figure 5.

In general, the cycle of operations in the mine consists of drilling, blasting, loading and transporting. Wagon drills are used to drill blast holes of 115 mm diameter. Depth of the blast holes in general is about 9 m for the 8.5 m height bench, including a sub grade drilling of about 0.5 m. A burden to spacing pattern of 3 m × 4 m is being used in this mine. Approximately 1600-1800 kg of explosives are used regularly for blasting in the limestone benches. Cap-sensitive and non-cap sensitive cartridges of 83 mm diameter and ANFO are commonly used as explosive charges in the blast holes. Exact length of the charge column is normally calculated before each blast and the explosives are charged as per the requirement. Drill-cuttings are used as stemming material.

Methodology: To analyse the influence of initiation system on blast fragmentation, field studies were conducted in one of the lime stone mines in Southern India. Blasts were

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conducted with conventional non-electric based shock-tube (*NeSt)* initiation system and electronic detonators. All the blasts muckpile images were captured to assess the influence of initiation system on blast fragmentation. For fragmentation analysis, digital image analysis technique (DIAT) methods were selected. The complete methodology for fragmentation analysis using DIAT is provided in figure 6.

Digital image analysis technique (DIAT): Digital image analysis technique (DIAT) was used to determine the fragmentation sizes of blasts. In this method, an image of the muckpile was captured using a high-definition camera keeping known dimension objects for calibration. Care was taken to see that different exposed layers of muckpile were photographed to represent the entire material. These images were processed using the Fragalyst software. Using this software, it is possible to take different sizes of fragments i.e. k_{25}, k_{60}, k_{70}, k_{80}…., k_{100}, but as a standard practice only, the average values (k_{50}) were considered for analysis purposes.

Digital image analysis technique involves the following steps:

a) Capturing of representative images of fragmented rock with a known scale at various intervals of mucking
b) Compilations of the images for different blast
c) Importing of the images to a digital image analysis software and
d) Calibration of the images
e) Edge detection
f) Fragment size determination
g) Distribution fitting and mean fragment size
h) Storing of data and further analysis.

Figure 4: An overview of the limestone mine

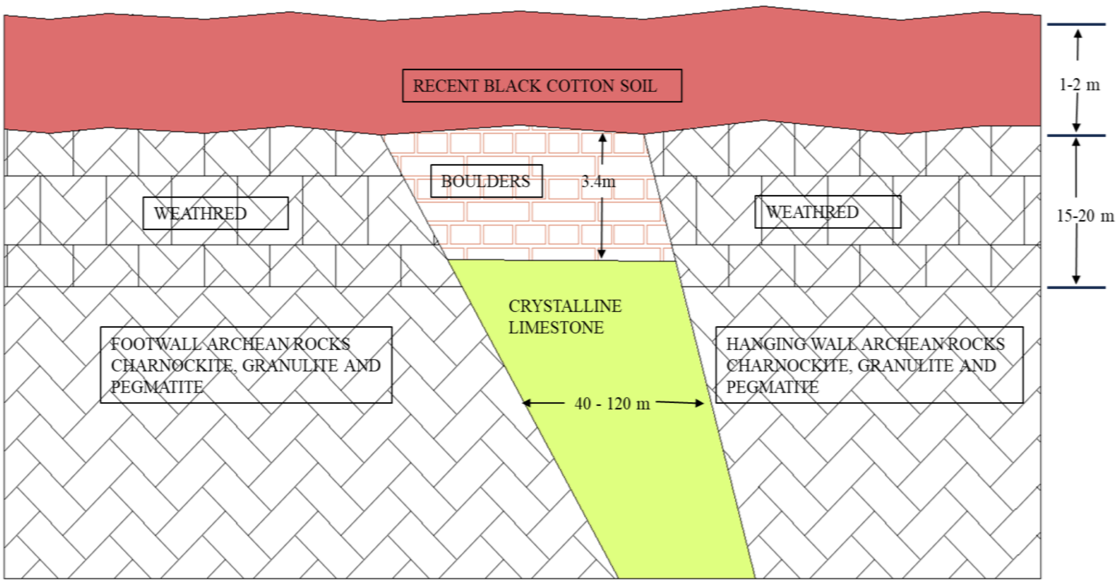


Figure 5: A view of the geological formations of the limestone mine and lithological setup

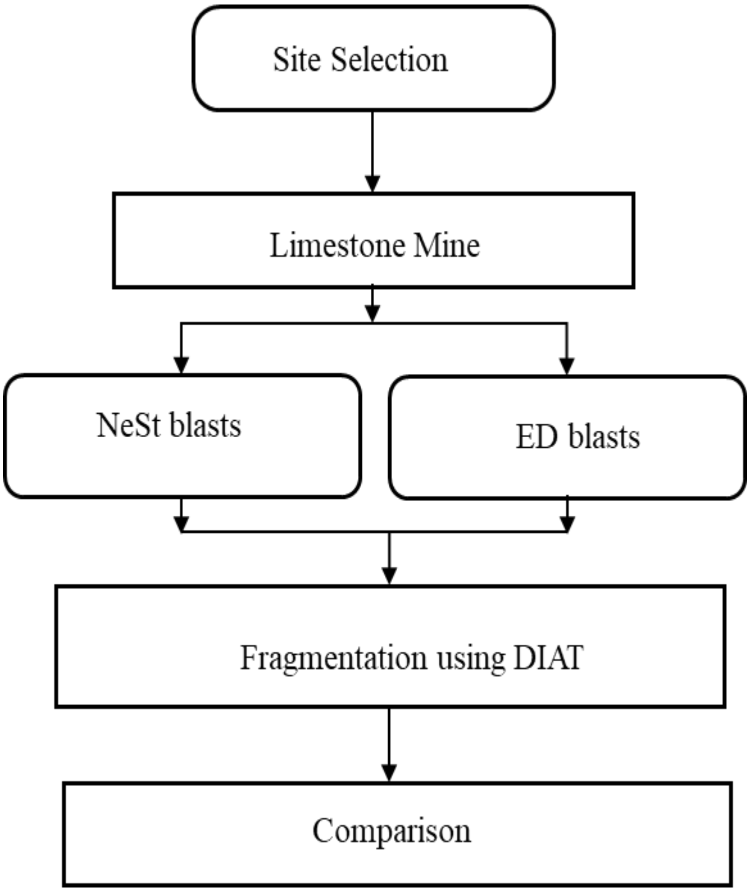


Figure 6: Methodology adopted for determination of blast fragmentation

Fragmentation assessment using image processing technique: After each blast, the muck pile images were captured keeping a calibrator and all these images were processed using Fragalyst software, which gives the output in the form of Rossin-Rammler distribution curve. The process of fragmentation assessment by the Fragalyst software is shown in figure 7. From the fragmentation distribution curve, the average fragment size (k_{50}) was considered for analysis. k_{50} values of *NeSt* initiated blasts varied from 0.39 m to 0.51 m whereas for electronic detonator blasts, the k_{50} values varied from 0.31 m to 0.44 m.

Blast Parameters: In a total, 15 production scale blasts were conducted in limestone mine under controlled conditions. Burden and spacing varied from 2 m × 3 m to 3 m × 4 m. The charge per hole is from 28-52 kg and number of blast holes from 10-40. Total charge per blast varied are from 144-1674 kg. The bench height varied from 7-9 m for all the 15 blasts. The initiation system used for blast is either non-electric based shock-tube (*Nest*) initiation system or electronic detonator. Typical blast layouts with electronic detonator as well as non-electric shock-tube *(NeSt)* initiation are shown in figures 8 and 9. Charging patterns for both electronic and as non-electric shock-tube (*NeSt*) initiation are shown in figure 10 (a) and (b) respectively. Summary of all blasts parameters is shown in table 1.

Results and Discussion

The fragmentation analysis using digital image processing technique is discussed. Also, the fragmentation size distribution from digital image analysis technique is presented here. The values of k_c (Characteristic size), k_{25}, k_{50}, k_{80} & k_{98} for each blast, extracted from the fragmentation distribution curve, are shown in table 2.

Fragmentation analysis using image processing technique: Average fragment size (k_{50}) values of all 15 blasts obtained from images processing technique are depicted in figure 11. The k_{50} values varied from 0.39-0.51 m for *NeSt* initiated blasts, whereas they varied from 0.31-0.44 m for electronic detonator-initiated blasts. On an average, the *NeSt* initiated blasts produced 20% higher k_{50} values than that of electronic initiated blasts. Average k_{50} value of *NeSt* initiated blasts was 0.46 m with a standard deviation of 0.039. Similarly, in case of electronic detonator-initiated blasts, mean of k_{50} value was 0.37 m and standard deviation was 0.046, which is negligible.

In both the initiation systems, the percentages of variations of k_{50} values of different blasts from their respective mean are given in table 3. All the k_{50} values are within 13% variation from the mean, except in one case (Blast 7) where the variation was 18% which may be due to geological variations. The overall analysis indicated that the electronic initiation system resulted in better fragmentation.

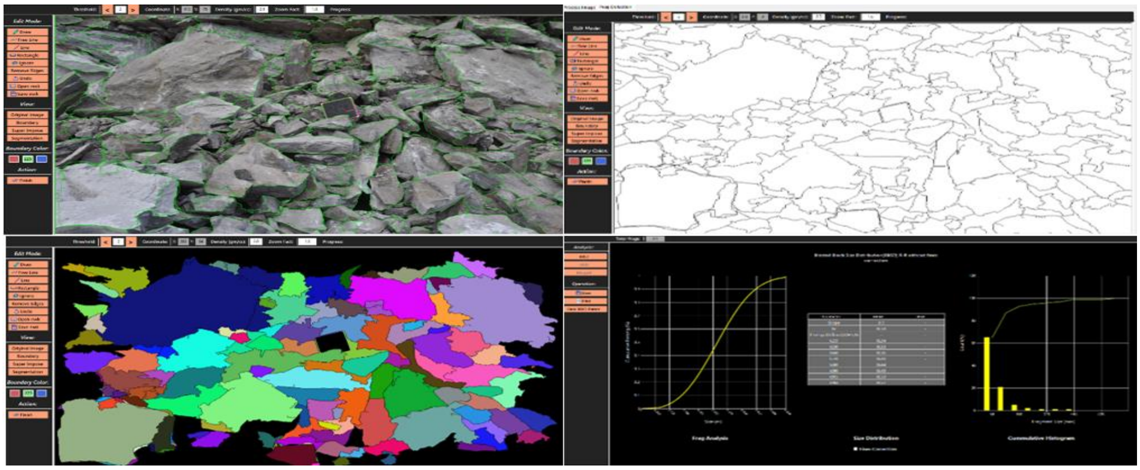


Figure 7: Process of fragmentation assessment by the Fragalyst software

Table 1
Details of the blasts conducted in case study

Blast No	No of Holes	Delay Time (ms)	Bench Height (m)	Burden (m)	Spacing (m)	Stemming Height (m)	Explosive/ Hole, (kg)	Set No	Initiation System
1	17	20	8.5	3	3	3	48.00	1	ED
2	40	17	8.5	3	4	3.5	41.87		*NeSt*
3	10	17	8	3	4	4.4	32.00	2	ED
4	13	17	8	3	4	4.2	52.50		*NeSt*
5	11	25	7.5	2.5	3	3.2	35.60	3	ED
6	11	25	7.5	2	3	3.5	37.16		*NeSt*
7	20	42	8	3	3.5	3.8	28.50	4	ED
8	31	42	8	3	3.5	4	34.00		*NeSt*
9	10	12	8	2	3	4.4	33.60	5	ED
10	10	15	8	3	3	3.6	45.00		ED
11	36	25	9	3	3.5	3.5	48.62		*NeSt*
12	21	42	7	2.8	3	3	33.63		*NeSt*
13	22	42	7.5	2.7	3	3.5	40.45		*NeSt*

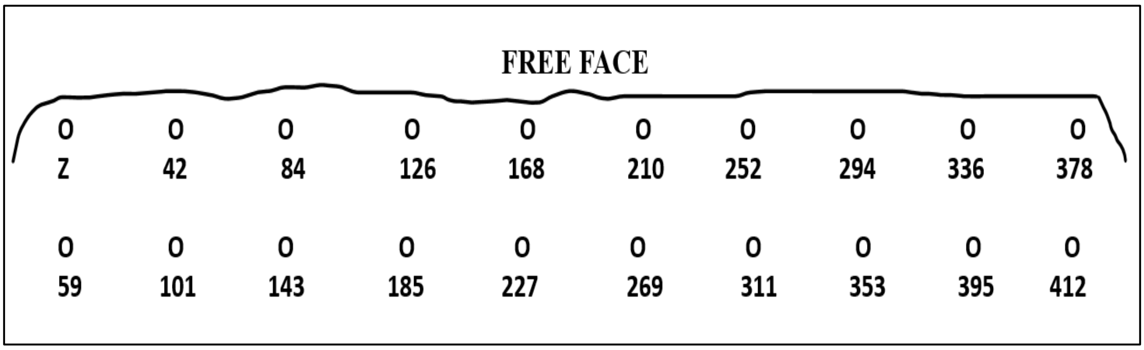


Figure 8: Layout of a blast with electronic initiation system

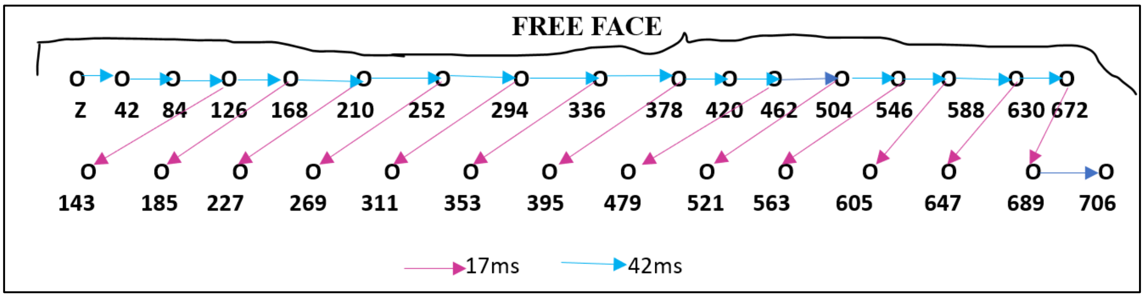


Figure 9: Layout of a blast with non-electric shock-tube *(NeSt)* initiation system

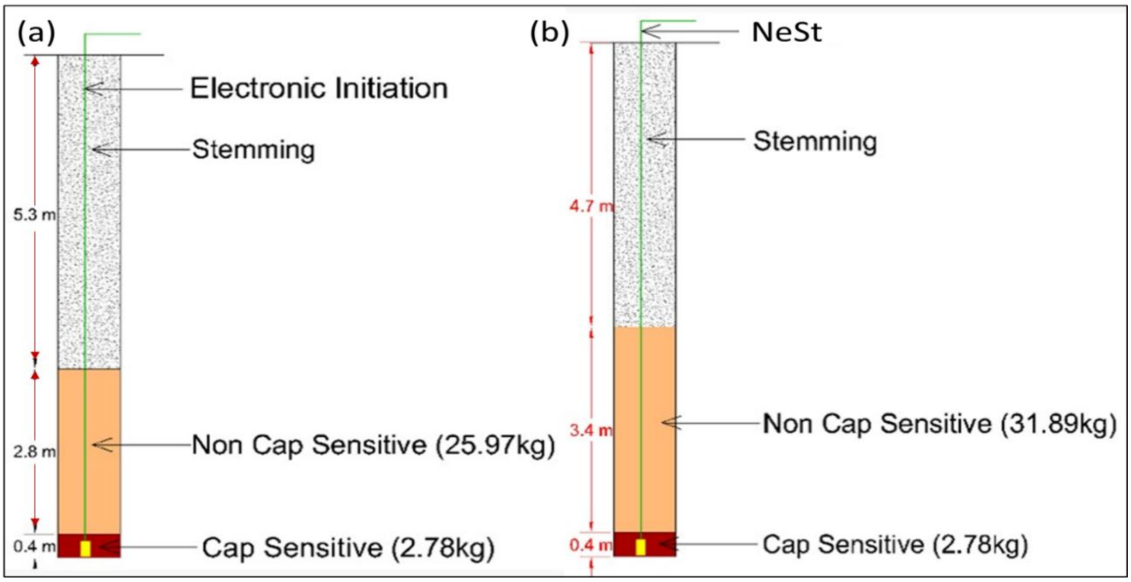


Figure 10 (a) and (b): Charging pattern of blast holes for electronic and non-electric shock-tube *(NeSt)* initiation

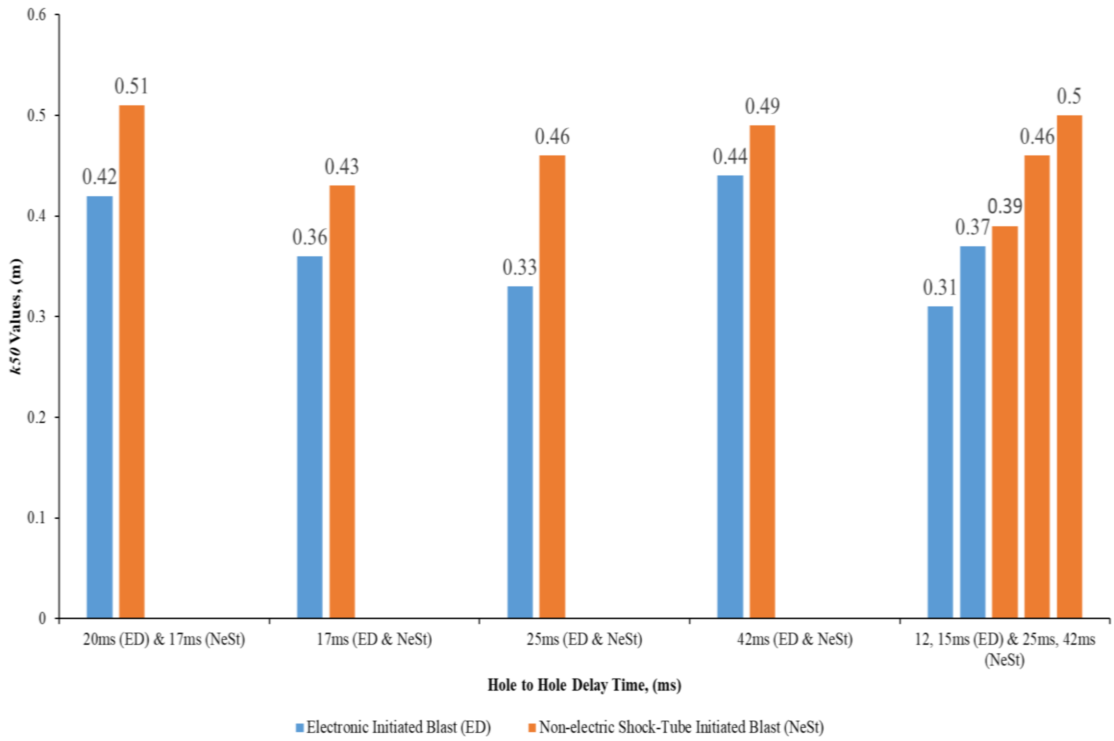
Table 2
Values of k_c, k_{25}, k_{50}, k_{80} & k_{98} for all blasts

Blast No.	k_c	k_{25}	k_{50}	k_{80}	k_{98}	Initiation System
1	0.49	0.3	0.42	0.57	0.77	Electronic
2	0.58	0.37	0.51	0.68	0.9	*NeSt*
3	0.41	0.26	0.36	0.48	0.63	Electronic
4	0.49	0.31	0.43	0.58	0.78	*NeSt*
5	0.38	0.25	0.33	0.44	0.57	Electronic
6	0.53	0.34	0.46	0.62	0.83	*NeSt*
7	0.52	0.31	0.44	0.61	0.84	Electronic
8	0.57	0.35	0.49	0.67	0.9	*NeSt*
9	0.35	0.25	0.31	0.39	0.48	Electronic
10	0.41	0.28	0.37	0.47	0.6	Electronic
11	0.44	0.29	0.39	0.51	0.67	*NeSt*
12	0.5	0.38	0.46	0.55	0.65	*NeSt*
13	0.58	0.37	0.5	0.68	0.9	*NeSt*

Where k_c, k_{25}, k_{50}, k_{80} & k_{98} are passing % of weight

Table 3
Percentage of variation among k_{50} values of different blasts

Blast No.	k_{50} value (m)	Mean (m)	Percentage of variation from mean (%)	Standard Deviation from mean	Initiation System
1	0.42	0.37	13.51	0.046	Electronic detonator
3	0.36		-2.7		
5	0.33		-10.81		
7	0.44		18.91		
9	0.31		-16.21		
10	0.37		0		
2	0.51	0.46	10.86	0.039	*NeSt*
4	0.43		-6.52		
6	0.46		0		
8	0.49		6.52		
11	0.39		-15.21		
12	0.46		0		
13	0.5		8.69		



Note: ED (Electronic Detonator), NeSt (Non-electric Shock-Tube Detonator)

Figure 11: Average fragment size of different blasts

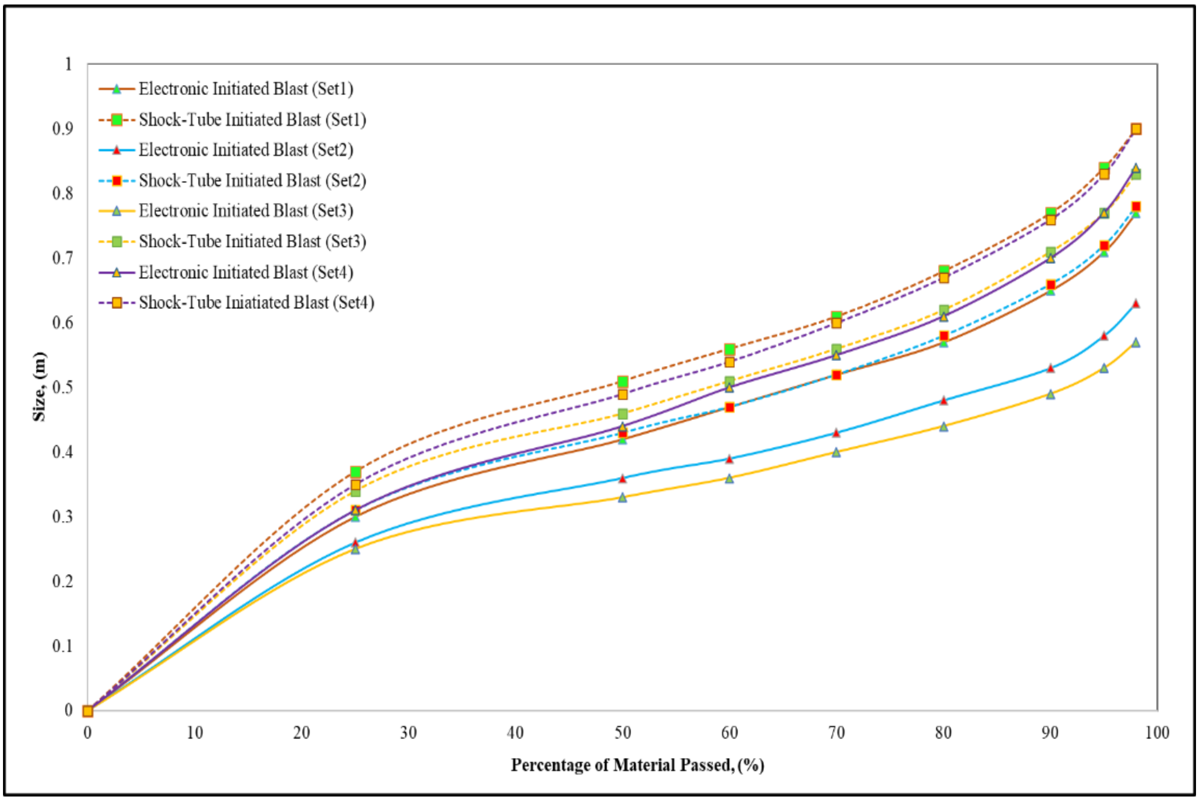


Figure 12: Rossin-Rammler distribution curves for set 1, set 2, set 3 and set 4

Fragmentation size distribution analysis: The image analysis of blasts in five sets (Set 1: Blasts 1 and 2, Set 2: Blasts 3 and 4, Set 3: Blasts 5 and 6, Set 4: Blasts 7 and 8 and Set 5: Blasts 9-13) reveals that the k_{25} to k_{98} values for electronic initiated blasts are lower than those of *NeSt* initiated blasts. Specifically, the k_{50} values for electronic initiated blasts are 17.65%, 16.28%, 28.26%, 10.20% and 19.56% lower in set 1, set 2, set 3, set 4 and set 5, respectively, compared to *NeSt* initiated blasts. The Rossin-Rammler distribution curves for these sets are shown in figures 12 and 13.

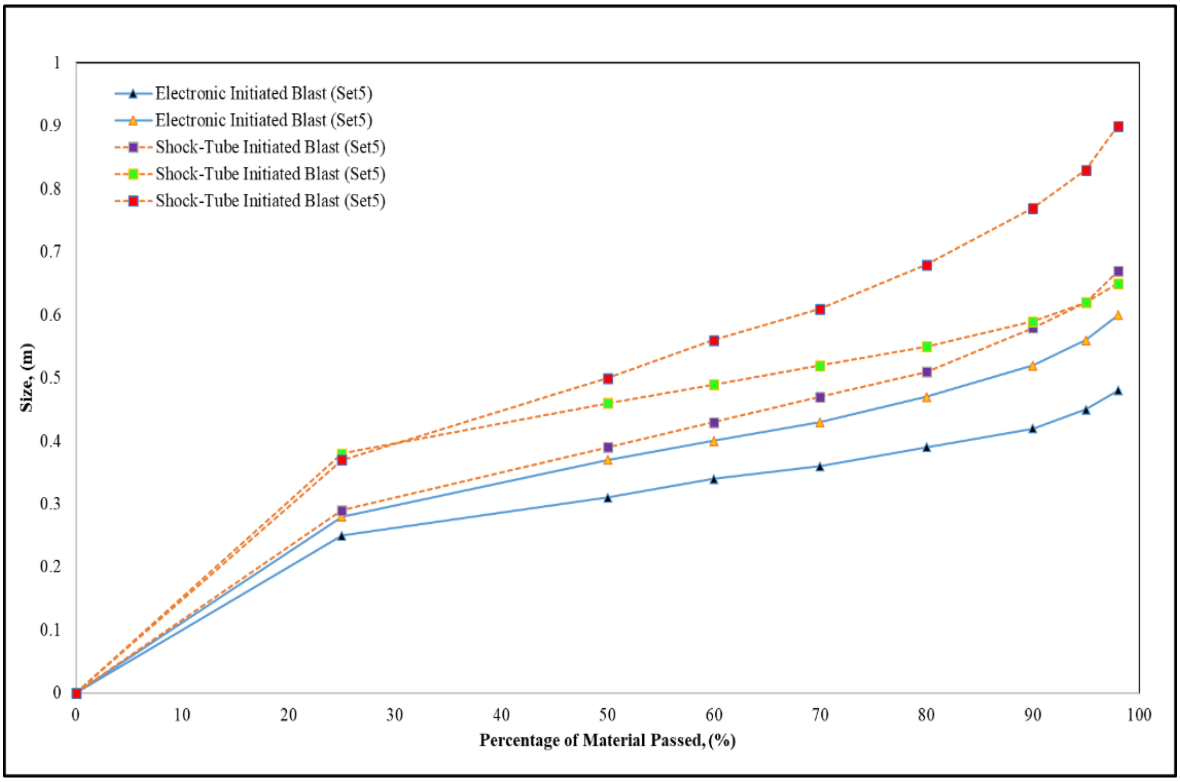


Figure 13: Rossin-Rammler distribution curves for set 5

Conclusion

An analysis of blasts in similar condition in a limestone with determination of fragmentation in case of *NeSt* and EDs revealed that:

- The digital image analysis technique used for fragmentation assessment of blasts revealed that the average fragment size (k_{50}) is 20 % less (on average) for electronic detonator-initiated blasts compared to *NeSt* initiated blasts.
- Electronic detonator-initiated blasts resulted in better and finer fragmentation. This conclusion was based on limited studies only. However, more investigations are being carried out to quantify the same.

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