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Investigation of Some Blast Design and Evaluation Parameters for Fragmentation in Limestone Quarries

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석회석 광산의 파쇄도 관련 발파설계 및 평가 변수들에 대한 고찰

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Abstract The present paper highlights some important fragmentation issues experienced in the limestone quarry blast rounds. In light of these major issues, the paper outlines influence of a few important design parameters, which bear merit to alter the blast performance in order to duly resolve the issues in field scale blast rounds. A comprehensive field based program for evaluation of such blast rounds has also been suggested. The knowledge disseminated in the paper, backed up by sufficient images, is largely based on the experience of the authors, while designing, implementing and evaluating numerous field scale blast rounds in cement grade limestone quarries.

Key words Fragmentation, Effective spacing and burden, Firing pattern, Bench stiffness, High wall

초 록 이 논문은 석회석 광산의 발파 중에 일어나는 파쇄도 관련 문제들에 대하여 고찰한 것이다. 먼저 실규모 발파 시에 발파 결과를 크게 달리 할 수 있는 중요 발파설계변수를 추출하였다. 또 현장에서 간편하게 적용할 수 있는 발파 성과 평가 방법을 제시하였다. 이는 저자들이 시멘트 제조를 위한 석회석 광산에서 다양한 규모로 설계, 시공, 평가 한 경험에 근거한 것이다.

핵심어 파쇄, 유효 공간격과 저항선, 기폭 패턴, 벤치 강성, 높은 벤치

1. Introduction

Limestone, mined from the quarries as crushed aggregate, is an extremely useful non-metallic mineral in the mineral industry being vastly used as raw material by host of manufacturing industries, which essentially includes the cement industry. The limestone quarries, however, are faced with several blasting related issues, which should not be overlooked. Major issues concerning these quarries are enumerated:

1) Occurrence of over sizes within the blasted muck piles in huge proportion.
2) Improper throw and drop of the blasted muck-piles, resulting into tight muck piles lying close to the face.
3) Cumbersome digging of the blasted mucks largely due to improper fragmentation, throw and drop characteristics, which not only escalates the excavator/loader operational and maintenance cost, but also, inordinately increases the dozing hours and its costs. Besides, improper fragmentation entails secondary breakage, which further adds to the overall mining cost.
4) Small sized blasts, with less number of holes accommodated in each row, increase the blast frequency in the quarries, resulting into indirect cost escalations.
5) Generation of irregular wall profile after excavation of the blast.

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6) Frequent occurrence of back breaks that pose difficulties in the execution of the subsequent blast rounds.
7) Generation of over sizes from the collar region, due to improper stemming.
8) Unsystematic documentation, analysis and interpretation of data etc.

Figs. 1-7 reveal some of the fragmentation related problems faced invariably by the limestone quarries. It may be of consequence to mention here that there is a mad rush to adopt the latest technology without properly analyzing results at field scale systematically. Although excellent effort, time and energy have

Fig. 3. Front-end-loader operation vis-à-vispresence of over sizes.

Fig. 1. Occurrence of large over sizes within a blasted limestone muck pile (square scales 0.5 m x 0.5 m)

Fig. 4. Separated over sizes for secondary breakage (linear scale 0.5 m).

Fig. 2. Tight muck piles being pushed by the dozers from top of the bench.

Fig. 5. Severe post-blast back breaking.

Fig. 6. Network of back breaks.

Fig. 7. Improper wall control.

been spent in developing the tools, gadgets, software for warehousing the pertinent blasting data, good effortis needed to systematically synthesize, analyze and interpret this valuable data. We really need to go back to develop a clear cut understanding of some of the pertinent concepts in the field of rock fragmentation by blasting in order to eradicate the fragmentation and its related problems in quarry blasts. In this perspective, the current paper harps upon some important blasting design parameters, which dominantly influence the fragmentation results in cement grade limestone quarries.

2. Important design parameters

2.1 Burden, spacing and mesh area

The crucial role of burden and spacing in any blast round must be clearly understood by the blasting crew prior to finalizing the mesh area (SxB) dimensions for their specific application. Burden distance is defined as the shortest distance to the relief at the time the hole detonates. Relief is normally considered to be either a ledge face or the internal face created by a row of holes that has been previously shot on an earlier delay (Konya, 1996). Burden dimension needs to be carefully decided. Excessive or conservative burden inhibits the flexural rupture due to increased bench stiffness. Hence, an engineering calculation (Konya, 1995; Jimeno et al., 1995) should be done after taking into account the rock parameter, the geological properties of the strata, the explosive factors and hole diameter. It may be consequential to state that the effective burden (instead of drilling burden), which depends on the firing sequence. (Rai, 2002), must be considered for downstream blast design computations.

Spacing controls mutual stress effects between the blast holes and depends upon burden (which already depends on rock, explosive and certain blast design variables) initiation sequence and bench stiffness. Many researchers world wide have reported the spacing to burden ratio of 1 to 2. This ratio remains same as suggested by Vauban, way back in 1704, who explained it by stating that craters make 90^0 angles hence the maximum allowable spacing is twice the burden. On the basis of the scaled tests, Pugliese (1972) published similar relationship. Dick et al. (1973) reported deterioration in fragmentation with increased spacing. Nevertheless, Langerfors, 1965; Lindgren and Travis, 1971; Brown, 1973 and several other researchers have proposed success with enhanced spacing to burden ratio of up to 8. Although satisfactory understanding for spacing to burden ratio does not exist, based on good number of scaled blasts, Bhandari and Vutukuri (1974) concluded that the ratio will depend on the burden selected. This, in turn, implies that engineering of the burden is very crucial. The first front burden, and the subsequent differential burdens need meticulous engineering calculations on aforesaid lines. The past experiences, if any, of burden fixation for normal production blast at the site must be honored. In any case, the spacing provided between two holes in no case should be less than the burden as it causes premature splitting of holes and early loosening of stemming column resulting in sudden drop of blast hole pressure to adversely affect the fragmentation. Furthermore, it favors rapid release of gases to the atmosphere causing air blasts, leading to very poor fragmentation. Besides, in light of effective burden, the concept of effective spacing and the ratio of effective spacing to burden needs consideration, while designing the blasts. In some limestone quarries, effective spacing to burden ratio of almost 2.5 was successfully implemented wherein the advantage of reduced bench stiffness was reaped by increasing the spacing to burden ratio (Rai and Imperial, 2005). Mesh area (SxB), exerts considerable influence on effective utilization of explosive energy. Two components of mesh area, namely, spacing and burden play key role in controlling overall blast results, as explained. Too small mesh area may escalate the drilling and blasting cost enormously (particularly in hard rocks), whereas, too expanded mesh area produces over sizes in the blasted muck pile, which more than offsets the savings made on the part of drilling and blasting the expanded meshes.

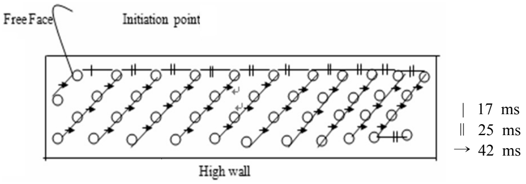

Fig. 8. A representative diagonal firing pattern (not to scale).

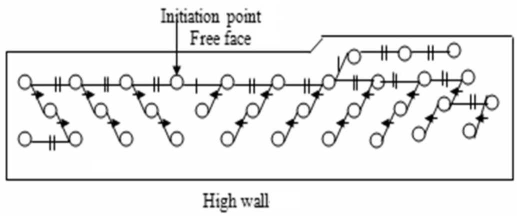

Fig. 9. A representative straight V-type firing pattern (not to scale).

2.2 Firing pattern

Sequential and proper relief to the successive burden rock mass is an essential pre-requisite for the success of any blasting program. To this end, the firing pattern decides the movement and direction of rock by creating free face for subsequent holes/rows. Extensive work has been reported on this by Smith, 1976 and Hagan, 1983.

The researchers suggest that each firing pattern has its own application. Proper use of pattern vis-à-vis the blast requirements can provide optimal blast performance in terms of fragmentation, throw, wall control etc. Firing pattern influences the effective spacing to burden ratio at the time of detonation. By changing the firing pattern, effective burden (which may now be understood as firing burden) changes and the ratio of effective spacing to effective burden during the firing is also subject to change (Hagan, 1983; Oliver, 2003; Rai and Baghel, 2004; Rai, 2008)

In addation each firing pattern has its own characteristic. For instance, although diagonal type patterns (Fig. 8) and straight V-type (Fig. 9) patterns provide same effective spacing to burden ratio, the straight V-type firing pattern increases the opportunity for in-flight collision amongst broken rock fragments during their movement. The row-to-row (in-line) firing pattern provides excellent relief that is capable of extensively heaving the muck pile (a feature important for cast blasting), though at the expense of fragment size. Nevertheless, the inter row and inter hole delay timing selection with any firing pattern is extremely sensitive parameter. Hence, the decision of selection of firing pattern calls for careful understanding of the site-specific needs. This point is explained by visualizing some field-scale post-blast images (Figs 10-14) on a limestone bench in a quarry where Fig. 10 reveals poorly broken and displaced muck pile fired on diagonal pattern, and, Figs. 11 & 12 illustrate the well displaced and fragmented muck pile fired on straight V-type firing pattern on the same limestone bench. Further, Fig. 14 reveals the superio-

Fig. 10. Poorly broken and displaced muck pile in a limestone quarry (diagonal firing linear scale 0.5 m).

Fig. 11. Good throw & drop in the limestone quarry (straight V- type firing).

Fig. 12. Good fragmentation within the well displaced muck pile (linear scale 0.5 m).

rity of diagonal firing over row to row firing (Fig 13) on fragmentation and throw (heave) on limestone

Fig. 13. Poor fragmentation results in a limestone quarry (row- to- row firing square scale 0.5 m x 0.5 m).

Fig. 14. Good throw and uniform fragmentation (diagonal firing).

benches of another quarry.

2.3 Delay timing

Proper delay timing is as important a parameter as the burden, spacing, mesh area, firing pattern etc. The delay timing controls the fragment size and consequently the shape of the blasted muck piles. Longer delay timing leads to greater drop and displacement (Fig. 15a), whereas shorter delay timing may lead to lesser drop and displacement (Fig 15b) of the muck piles. Hence, proper delay time is essential for systematic release of energy and proper burden relief, which, in turn, governs the muck pile shapes. To this end, the recommendations made by Tansey, 1980; Chiapetta and Postupack, 1995; Konya and Walter 1990; Konya, 1995 are useful and need to be clearly

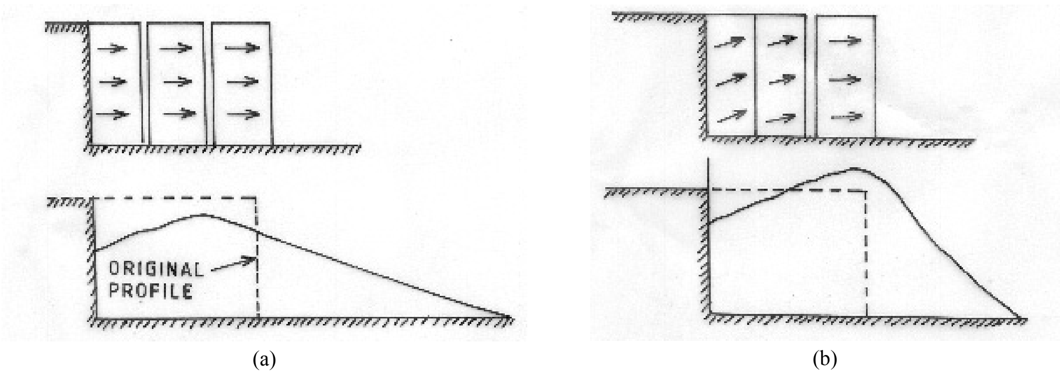

Fig. 15. Muck pile shape as a function of delay timing.

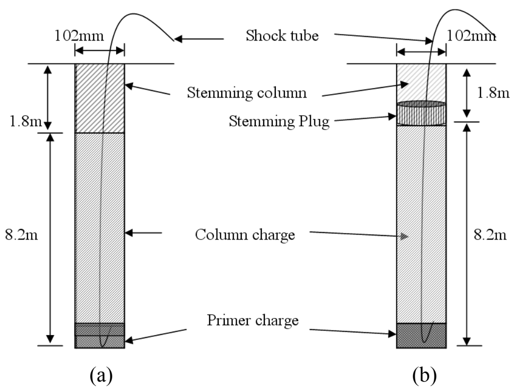

Fig. 16. Longitudinal section of the blast hole (not to scale). (a) without stemming plug (b) with stemming plug

understood vis-à-vis the field specific requirements. In many cases of multi-row blast round designs, the back rows (being congested by the previous rows blasted buffer) may not get adequate relief. A situation that leads to sheer wastage of explosive energy and resulting into numerous problems, such as, emergence of back breaks, over sizes and ground vibrations etc. Increasing the inter row delay timing along the back rows of such multi-row blast rounds proves to be very useful (Rai and Baghel, 2004). Normally, keeping in mind the field specific requirements, the inter row delay time ranging between 8-15 ms/m of effective burden yields good fragmentation in limestone quarries.

2.4 Stemming and confinement

Stemming of the blast holes should provide confinement and retention to promote the rock fracturing by transmitting a major portion of shock as well as gas pressure through the burden rock mass prior to the release of stemming material. Improper confinement results in wastage of this energy leading to poor fragmentation results and creating environmental nuisances. (Bhandari, 1997; Oliver, 2003) Excessive over sizes within the muck piles were reported due to excessive stemming column lengths.(Kanchibotla, 2001) To surmount such problems, the blast hole plugging can be done appropriately without altering the stemming column length. For instance, in a limestone quarry, to overcome the problems of excessive collar over sizes due to the presence of prominent fractures and weak planes in the collar region of the benches, the blast holes were suitably plugged (Rai & Yang, 2009). The blast hole plugging, as depicted in Fig 16b was done by use of a hollow cone shaped device constructed of high impact polystyrene. The plug was serrated along its external surface to firmly grip the blast hole wall. Being made of high impact polystyrene, it was envisaged that the plug would inflate due to the blast hole pressure generated after detonating the explosive inside the blast hole. This phenomenon, in turn, assisted in gas as well as shock pressure retention inside the blast hole for extended duration. The plug was carefully secured at the top of the explosive column without making any changes in the stemming length. (Fig. 16)

Even though host of similar plugging devices are commercially available, if there is any reluctance on part of the management to use these devices, then suitable number of properly sized gunny bags filled with drill cuttings can be inserted in between the stemming column to provide better confinement. This column should then be compacted thoroughly with wooden rods.

2.5 Bench stiffness

The mechanism of rock fragmentation considers the role of flexion in rock breakage, which implies that the pressure applied by the explosion gases in front of the explosive column acts on the burden rock mass that behaves like a beam embedded in the bottom of the blast hole and in the stemming area (Ash, 1963; Ash and Smith, 1976; Smith, 1976; Ouchterlony, 1995). This beam (burden rock mass) is subject to breakage by deformation, fracturing and flexion. The ratio of bench height (H) to burden (B) is understood as stiffness ratio (H/B) of the bench. When the stiffness ratio is high, it is easy to displace and deform this beam, which becomes less stiff and more flexible with the increase in bench height for the given magnitude of B. Consequently, the fragmentation is improved. The stiffness ratio may be engineered in the field scale blasts by planning suitable bench heights, burden and the firing patterns. The authors conducted full scale blasts at stiffness ratio of almost 4 on 9-10 m high limestone benches with favorable results in terms of fragmentation, muck pile spread and high wall profiles (Figs 17 & 18).

Fig. 17. Fine fragmentation & throw at high stiffness ratio (linear scale 0.5 m).

Fig. 18. Almost straight high wall after blast excavation.

2.6 Initiation system

Non-electric initiation system with shock tubes has been experienced to be more effective than the detonating fuse as it largely assists in arresting the disruption of stemming column in addition to its other potential merits. This feature enhances the proper utilization of available explosive energy in the hole. However, in cases of non-homogenous strata, the detonating fuse promises better results.

2.7 High wall profile

The possibility of high wall damages by back break, over break etc. may not be completely ruled out Nonetheless, the practice of line drilling of smaller dia. drill holes, to a restricted depth, at the boundary of the blast round has been used with success in many of the limestone quarries by the authors. For bench heights varying from 6 -12 m, line drilled holes were drilled up to a depth of 3 m. The wall profile after blasting was excellent with almost upright walls (Fig.18) free from back breaks. Furthermore, attempts of reducing the amount of explosive in the peripheral holes by putting suitable decks also controlled the high wall damages. The decks were placed in a sine-wave form to eliminate the chances of slab formation after blasting.

3. Blast performance evaluation parameters

The documentation of pertinent blast design parameters and the blasting results is of paramount importance to clearly analyze and interpret the data, which, in turn, paves the pathway for improvement of the blast performance by identifying the key design parameters which need alterations. Nevertheless, changing too many design parameters at one time needs to be avoided in the same blast as it normally leads to confused interpretations of the results. Further, the changes in blast design parameters should be done in a systematic sequence.

After implementation of designed blasts, the indirect methods of evaluation and characterization of fragmentation can prove very effective, especially for such small scale blasts. These methods do not hamper production and largely rely on correlating the salient field parameters, such as, powder factor, excavator/loader performance, hauler performance, oversize count, dozing hours, fragments size distribution. with the degree of fragmentation in the blasted muck piles. A comprehensive field based evaluation program for such quarry blasts is described briefly.

The program has already been used exhaustively by the authors to quantitatively ascertain the improvements in the blast performance in the field scale on day-to-day basis.

3.1 Powder factor

Powder factor can be precisely estimated by properly observing and recording the total number of trucks loaded during the complete excavation of the muck pile. Total number of truck trips on individual muck pile need to be religiously counted and converted into equivalent tonnage of limestone removed from the muck pile by giving proper consideration to truck factor that can be calibrated by the weighing machine system. The total quantity of explosive actually loaded in the blast round should also be registered meticulously in order to express the powder factor in terms of kg/ton of limestone broken from the blast rounds.

3.2 Boulder count

Total number of separated boulders, which could not be loaded by the loaders/excavators can be counted at the face. Less the number of separated over sizes (boulders), better is the blast performance.

3.3 Cycle time

Several researchers (Williamson, 1983; Jhanwar et al., 1999; Jhanwar et al., 2000; Marton and Crookes, 1999; Kanchibotla, 2001; Singh and Yalcin, 2002) indicated the relationship between diggability of loading machines with respect to degree of fragmentation in the muck pile. The basic premise is that the run-off-mine (ROM) fragmentation is considered good when it is fine enough to ensure efficient digging and loading operations. Hence, the cycle time of loaders/excavators, excavating the muck pile, can be categorically recorded throughout the excavation history of the blasted muck such that cycle time data could be taken as an index to the blast performance.

3.4 Dozer performance

To facilitate the loading operation by the loader, dozers are normally deployed in any blasting program. Nevertheless, excessive deployment of dozer (expressed in terms of total dozing hours) is suggestive of poor blasting performance (Rai & Imperial, 2005; Rai & Yang, 2009). Thus the total number of dozing hours spent by the dozers on a muck pile can also be recorded carefully to be used as a reliable index to diagnose the blast performance.

3.5 Throw and drop measurements

Throw, drop and lateral spreading of the muck pile (Fig. 19) are important parameters which indicate the efficacy of the blast designs (Rai, et al., 2006). Greater throw and drop, spreads the muck pile laterally and facilitates the digging of the muck by

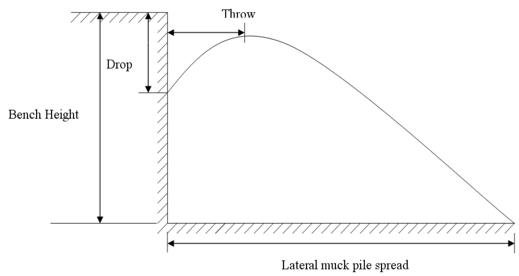

Fig. 19. Throw, drop and muck pile spread.

the loaders/ excavators. The throw& drop values for each blast can be measured immediately after the blast through the tape measurements by taking a number of offset measurements on the blasted muck piles. The average throw and drop values can be estimated thereof.

3.6 Back break/ end break observations

Back breaks/ end breaks present severe problems in view of wall control, wall stability and design of the subsequent blast rounds. For quantifying and analyzing the reason for occurrence, their location (offset measurement from the blast perimeter) and the linear extent should be recorded

3.7 Image analysis

With the advent of sophisticated and advanced computing methods, imaging of the muck pile has gained wide acclaim in the recent decades. The basis of imaging techniques is the visionary sense, which is one of the most advanced and complex of human senses. Adequate vision assists in estimating the size, shape, outline, texture, color etc. of an object. In this technique the photographs/images of the blasted muck pile, captured through ordinary camera, video camera or digital camera, are analyzed through the computer codes after suitable processing. Thus, digital imaging entails image capturing, image processing and image analysis. With use of computers, the cost of the imaging is quite low and aggregate size analysis can be handled quickly and easily (Wang et al., 1996). Speed and precision are of paramount significance in assessment of fragmentation by blasting (Maerz et al., 1987; Maerz, 1990). Images of the muck pile using either a conventional, high speed or digital camera, and then to digitize and scale the depicted fragments to provide a measure of the particle size distributions. This system may be routinely applied to the measurement of blast fragmentation but depends on the manual digitization of the rock fragments (Scott et al., 1996). The use of state-of-art digital imaging to quantify the fragment size and its distribution in the blasted muck piles is endorsed for lime stone quarries.

In addition to above, and very importantly, blast site visits (pre and post-blast) are of great consequence as they provide valuable insights, which need attention. During such visits, the blasting engineers must inspect the designated blast rounds carefully to ensure clean bench top and bench toe surfaces. Initiation point in each blast round must be properly fixed and clearly illustrated in the respective firing patterns. Strict surveillance is required to ascertain that planned blast designs are adhered to religiously in the field settings. Deviation, if any, should be documented appropriately. Immediately after blasting, on obtaining the clearance from safety officers, the blasting crew should re-visit the site to primarily visualize the shape, throw, drop and lateral spreading of the muck pile. Presence of any marked discrepancy, say excessive over sizes, presence of back breaks, poor high wall control etc. must be recorded carefully for proper analysis and interpretation. Wherever necessary, appropriate measurements must be made to quantify the observations.

4. Conclusions

The salient conclusions from the present paper are summarized as:

- Limestone quarry blast rounds present a host of fragmentation related issues. Improper fragmentation is manifested in the form of occurrence of over sizes within the poorly heaved muck piles, occurrence of back breaks, poor performance of loaders excessive use of dozers, poor wall control, etc. In light of these specific issues the role of some important blast design parameters need to be understood clearly. The effective spacing, burden and effective spacing to burden ratio must be designed vis-à-vis firing pattern. By changing the firing pattern this ratio can be increased up to almost 2.5, by enhancing the effective spacing and reducing the effective burden values. The mesh area needs to be designed and implemented in accordance to the firing pattern.
- Delay timing must be carefully planned vis-à-vis the effective burden and the desired shape of the muck piles. Depending on the site specific needs, the inter row delay timing values can range from

6-15 ms/m of effective burden for the desired results.

- The stemming zone problems can be resolved by suitably plugging of the blast holes for adequate retention of gas as well as shock pressure. For this a host of commercial plugging devices are available. Besides, innovative and site specific methods of packing the stemming zone also appear to hold promise.
- Bench stiffness is of vast consequence in fragmentation. Accordingly, this parameter needs to be engineered for improved fragmentation. By suitable planning of firing patterns and effective burden, the stiffness ratio for a given bench height can be engineered. High stiffness ratio of almost 4 can be obtained on just 9-10 m high limestone benches.
- High wall profile needs to be considered as a design parameter (besides considering it as a blast evaluation parameter) to be suitably engineered for upright high walls without appreciable damage. Operationally, the line drilling technique in association with decking of peripheral holes appear practicable in controlling the high wall profiles in quarry blast rounds.
- Evaluation of fragmentation at field scale can be readily done by use of indirect measurement methods that are precise and do not hamper the production. A comprehensive evaluation program, for precise quantification of limestone quarry blasts needs to be properly contemplated and practiced religiously. The evaluation programs are key to identifying the design parameter(s), which need(s) alteration.

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