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ROLE OF ERGONOMICS IN THE SELECTION OF STEMMING PLUGS FOR SURFACE MINING OPERATIONS

Stemming plugs are one of the widely used accessory in surface mining operations. Stemming plugs assist conventional stemming material in gas retention and help in better fragmentation and explosive utilization. Effective use of the stemming plugs results in economic benefits and enhance the efficacy of the project. Economic and productive viability of stemming plugs have been conducted in depth by different researchers. Addition of stemming plugs to a new system requires ergonomic challenges for operators conducting drilling and blasting operation. Induction of a newer product in already established system is subject to overall positive feedback. This work investigates ergonomics of three different stemming plugs introduced to a limestone quarry in Pakistan. The stemming plugs were evaluated based on extra time needed, workers feedback, failures during operation, recovery time after failure and number of extra equipment required to carry out the operation. Points based matrix was established with likeliness of each plug and based on overall scores stemming plug 1 was most acceptable followed by stemming plug 3. Stemming plug 2 was disliked by operation and did not reach the level of acceptability of operators. This work will help stemming plug making industry in adapting to best practices by incorporating ergonomics of plugs in designing. Literature shows no previous work on ergonomics of stemming plugs.

Keywords: Ergonomics, blasting, stemming plugs, drilling, mining, limestone quarry

1. Introduction

Surface mines and quarry operations heavily rely on bench blasting to achieve high volumetric targets and production demands. Use of explosives is the most economic method for rock breakage and movement. Extensive research had been conducted to enhance explosives energy utilization. Innovation in explosives range from studying the drilling pattern, application and addition of air

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decks, stemming plugs, and study of explosive charge per delay. Efficiency of a blasting operation is generally evaluated by the fragmentation size. From post blast conditions at blasting site to efficiency of processing plant, anything can be affected due bad fragmentation resulting from improper blast. Better fragmentation is a necessity for better operation of the system along with consideration of the safety of operation, environmental issues and related costs. Efficient blast design should always attempt to minimize the cost of operation without conceding to acceptable technical and safety necessities (Mohamad et al., 2013).

Economic competition and zeal to excel has pushed every industry towards innovating the design of products. This has resulted in induction of smarter tool and accessories to help in improving productivity of operation. This never-ending quest for excellence has improved blasting operation from quill filled with black powder to remote electronic detonation. Economic or strategic viability of newer product had been the only concern for all industries up to second world war. Second world war was the major industrial consumption event of last century, a lot of questions were raised during that era pertaining to human factors thereby leading to the discussions of ergonomic application of products along with their economic and strategic viability. Since then, work has been carried out related to human factors in safety ranging from safety of oil industry (Wagenaar et al., 1994), observation and correction of postures during work in industry (Karhu et al., 1977, 1981). All previous studies advocate the application of ergonomics in operations for better user experience along with economic benefits of innovations.

Surface mining operation's performance is highly dependent on the effectiveness of the blasting. Good blast always results in improved fragmentation and lack of need for secondary blasting. The blast performance is dependent on different factors associated with the process and researchers have established some of these parameters. These factors have been gauged as blast geometry, explosive specification, and rock mass properties (Zhu et al., 2008). Similarly, in 2013 Mohamad et al. concluded that fragmentation dynamics depends on blast hole diameter, primer, spacing, stemming, burden, and delay timing for blasting operation (Mohamad et al., 2013).

Surface mining industry is adapting to stemming plugs since last three decades and different variety of stemming plugs are commercially available – see table 1. This research work was conducted at D.G. Khan Cement Company Limited, which is located in the Punjab province of Pakistan and relies only on drilling and blasting for effective rock breakage (Ur Rehman, 2017). Drilling and blasting operation is carried out in two major parts. First part is drilling of holes as per the pattern designed by blasting engineer. Once holes are drilled, these holes are charged with explosives. After charging holes, top of holes is filled with stemming material and circuits are completed to initiate the blast. Successful blasts show fragmentation within the crusher's size range along with flyrocks and vibrations under the permissible limits. Majority of the mines in Pakistan still use drill cuttings to fill the drilled holes for blasting (Ur Rehman et al., 2019). The drill cutting (also known as stemming material) help in providing gas confinement which assist in better rock fragmentation along with reduced flyrocks. These drill cuttings are produced during the drilling process and have different size range. The lack of homogenized particle size cause impotence to effective confinement of explosive gases and results of blasts are variable. Variability in blast results multiplies due to blow out of stemming material from stemming section due to extremely fine size. Blown out stemming leads to flyrocks from the collar section of hole, raising the safety concerns, secondary blasting requirement, and bad fragmentation. The phenomenon behind blow out is improper blast energy utilization and gas venting instead of retention. Majority of gases try to move vertically instead of pushing the rock in horizontal direction. The importance of stemming is an established frontier in drilling and blasting industry and have been studied by a great group of researchers (Kopp & J.W., 1987; Singh & Sastry, 1988; Eloranta, 1994; Kojovic, 2005; Rai & Imperial, 2005; Cevizci, 2012, 2013, 2014; Mohamad et al., 2012; Cevizci & Ozkahraman, 2012; Choudhary & Rai, 2013; Trivedi et al., 2014; Sharma & Rai, 2015; Sazid et al., 2016). As this study is focused on ergonomics of stemming plugs, therefore further discussion about importance is beyond the scope of this work.

Although mining industry is considered slower in adaption of modern technology (Tiffany et al. 2019) still ergonomics studies have been conducted in past due to excessive mass maneuvering in affiliated with mining. Researchers have worked on effect of whole body vibrations in mining machinery, designing of seats, skeletal issues related to mining machinery (VILLAGE et al., 1989; McPhee, 2004; Kumar, 2004; Gunaselvam & van Niekerk, 2005; Eger et al., 2008; Howard et al., 2009; Smets et al., 2010; Chen et al., 2012; Wolfgang & Burgess-Limerick, 2014; Rahimdel et al., 2017); usage of smart devices to detect whole body vibrations (Wolfgang et al., 2014), emergency management (Horberry et al., 2013); and vibration exposure of drill operators (Chaudhary et al., 2015a, b). Majority of the work in application of ergonomics majorly cover whole body vibrations and falls in last two decades.

From industry and manufacturer's point of view application of human factors might appear as a cumbersome task with very less or minor gains in the form of profits but it is pertinent to mention here that these minor gains help in longer prospects. From the marketing point of view, ergonomics has also got importance as markets mature after some time, providing a function with good efficiency does not ensure competitive success. Manufacturers must bring in other means of differentiating their products. All manufacturers which have considered ergonomics in their design parameters will be a step ahead. To reach that level in stemming plug design, this paper an the initial step in comparing three different plugs on the ergonomic framework. It is assumed that this research might direct the attention of researchers toward consideration of ergonomics while designing products for mining and explosive industry. As there are a lot of different working steps that must be performed for achieving a certain goal, for example in case of stemming plugs blasting crew has to undergo series of steps to execute their job, which they were not supposed to do with conventional stemming practice.

This work carries out ergonomic analysis of three different stemming plugs and compared them with the conventional system in use. All the stemming plugs selected for this study are tested on full scale blasts and are tested on performance matrix devised for this research. Next section explains about stemming plugs and their operation, methodology section explains about the whole experimental procedure, followed by the result and the discussion sections elaborating the results and drive analysis out of the results. Last section summarizes the work and provide guidance towards future work.

2. Stemming and stemming plugs

Drilling and blasting operation is significant part of mining industry and stemming is a major component of it. The stemming is filled in the topmost part of blast hole to provide confinement for the gases created due to blasting. This gas retention helps in better fragmentation and prevents from the shooting of collar rocks thereby safer and environment friendly operation. Stemming material redirects the energy emerging from explosives back into the rock to assist in breaking the rock more efficiently (Cevizci, 2012). Majority of time drill cuttings are used as conventional stemming material due to their availability in open pit mines and quarries (Cevizci & Ozkahraman, 2012). Stemming plugs are accessories that help in assistance with conventional stemming. Different studies have been conducted on efficacy of stemming plug as compared to the conventional system in past (Kopp & J.W., 1987; Singh & Sastry, 1988; Kojovic, 2005; Rai & Imperial, 2005; Rai et al., 2008; Cevizci, 2012; Mohamad et al., 2012; Choudhary & Rai, 2013; Sharma & Rai, 2015), but no emphasis has yet been given to the aspect of ergonomics while deciding about the use of stemming plugs. Industry utilize different types of stemming plugs ranging from ready-made stemming plugs from providers as shown at Table 1 or on site manufacturable. Air gaps or air decks have also been used in between explosives and with stemming part for enhancing blast performances. Results utilizing air plugs showed significant improvement in explosive utilization and improved fragmentation (Urekar & Pankhurst, 1988; Sazid et al., 2012). Similar to air plugs quick setting cement has also been suggested to aid in providing stemming and (Cevizci, 2012) established the effectiveness of stemming plugs by using plaster of Paris by improving the fragmentation and economic benefits. Results show that use of 0.45 meter of plaster in addition to ordinary drill cuttings provided more strength to blasting activity by resulting in more gas retention as compared to conventional stemming length of 2.5 meter. Based on the literature three different types of stemming plugs are envisaged and were tested.

TABLE 1

Main stemming plugs suppliers worldwide

Sr. No.	Supplier Name	Location
1	Hole Products	United States
2	Vari-Stem	United States
3	Ideal Blasting	United States
4	Blaster Tool	United States
5	Para Plugs	United States
6	LHS Germany	Germany
7	Oresome Products	Australia
8	Super Plugs	South Africa
9	Max Blast	United States
10	BF Carr & Associate	United States

Conventional Stemming

Drilling operation results in production of drill cuttings that are dumped right next to the drilled hole as per the set mechanism of drill machines. These cuttings of rocks are called drill cutting and they vary from being fine powdery sized to small chips of 2-6 mm. The size depends on type of drill machine, size of diameter of drill bit, operator's attributes and type of stratum being drilled in. Loosen or weaken stratum mostly result in finer sizes whereas rocks having higher uniaxial compressive strength tend to have a coarser sized drill cutting. Figure 1 shows the conventional stemming material used in this study.

Stemming-Plugs

Stemming plug A is an off the rack ready to use stemming plug which is shown in Figure 2. This plug is a gear type stemming plug that can be inserted into the hole and filled up with rest

Fig. 1. Conventional stemming material

of the stemming material. Stemming plug B are air plugs envisaged from literature. These plugs are lowered into the hole and then filled with air to inflate and later the hole is topped up with conventional stemming. Figure 3 depicts stemming plug B. Quick setting cement is used as stemming plug C. This mortar was mixed on site and then poured into the hole on same analogy of (Cevizci, 2014).

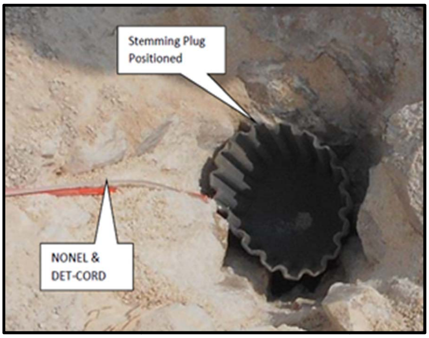

Fig. 2. Stemming Plug A

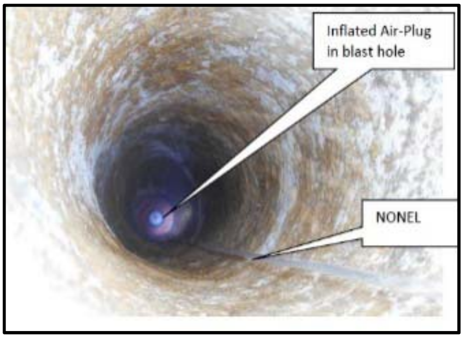

Fig. 3. Stemming Plug B

Fig. 4. Stemming Plug CErgonomic of stemming plugs

A worker executes certain tasks to apply stemming plugs during a blasting operation. From lowering down to pick up the stemming plug (or preparing the setup for stemming plug), aligning it with the hole, lowering it down, and recovery if failed are major components of ergonomics observed to be associated with application of stemming plugs. Rest of the operation is daily routine so is not incorporated in the scope of this work. Research indicate that for designing any industrial workstation (product), it is always necessary to gather data on the similar task that product has to perform and on working environment (Das & Sengupta, 1996) and an ergonomist in product designing must cover attributes of people, their behavior, and cognitive load while execution (Stanton & Young, 1998). For instance, this research work considered attributes of the worker by acquiring their feedback and observing various parameters on ergonomics matrix. The assessment parameters were their behavior and the cognitive load on them which was calculated based on the time of operation. Time of operation was gauged with extra time needed to conventional practice. Other factors such as workers' adaptability required to master the application of new plug, number of failures on site, recovery time for undoing failures, extra accessories to be carried out for the application of plugs, and limitations associated with stemming plugs were also noted.

Methodology

As per the objective of this work, workers were given training about the application of three stemming plugs for better understandings and error free application. A control blast using conventional stemming was also conducted along with each blast incorporating the stemming plugs. Stemming plugs were analyzed based on the extra time required for their operation and its relationship with conventional practice, adaptability required for mastering the application of new plug, number of failures on site, recovery time for undoing failures, workers feedback, extra accessories to be carried out for application of plugs, and the limitations associated with stemming plugs. The detailed application of conventional stemming and the three tested stemming plugs follows.

Application of stemming

As shown in Figure 1, conventional stemming is drill cutting, a worker uses a spade to fill the hole with stemming material and then slightly tamp it with wooden stick to give reasonable compaction until the hole is filled to the top. This process is repeated for all the holes and circuit is built for detonation and blast is initiated after establishing safety parameter.

Figure 2 shows the stemming plug A which has a gear type structure and is ready to use type of stemming plug. A worker must lower down to grab the stemming plug from the box, align it according to hole and then insert it using a wooden stick. Once lowered to the desired depth, conventional stemming is added to the hole like the process discussed in conventional stemming application. Operator makes sure stemming plug A is lowered to the desired depth and avoid halfway blockages due to damaged drill holes. Gear type structure minimizes that risk, but it can not be ignored as it adds time and frustration to the work.

To apply stemming plug B operator picks the stemming plug from the box, attach it to air nozzle and lower it into the hole. The moment it acquires the designated depth it is inflated to make sure it sticks to the walls of the hole, but due to bursting of stemming plug due to contact with some pointed rock or over pressure, whole exercise must be repeated. Due to non-expanding nature during lowering process, the chances of getting stuck during halfway are negligible to none, but bursting of plugs is a big issue related to the tested plugs. Air hoses and detachable nozzles are needed to be carried in spare along the operation of this stemming plug. Once stemming plug B has been setup, remaining process was to load the remaining hole with conventional stemming.

Stemming plug C is a mortar of quick setting cement, measuring containers, chemicals, and water must be carried to the location for preparation on site. Mortar is mixed on site and is poured into the hole and once settled, conventional stemming is added over the settled cement. The cross section is shown in Figure 4. Due to short settling time, mortar must be mixed in small portions making it intensive work for the workers.

Drilling and blasting crew sometime faces other activities such as extra drilling, drill hole correction or any other miscellaneous issues but all of them were kept out of the assessment. A blasting crew comprising of nine members performed all the blasting activity during this work. Three of the members were having more than twenty years of mining experience, five having more than ten years and one worker had less than two years of mine experience. Number of drill holes at which these plugs were tested varied based on production targets and blast designs. For stemming plug A a total of 47 holes were blasted, which means the team had to undergo the process of application of stemming plugs 47 times. Similarly, 57 and 39 holes were blasted for stemming plug B and stemming plug C respectively. The blasting crew worked as a team wherein first they checked the holes for being in requisite condition, orientation, and position. They loaded explosive in the holes and filled the remaining of the hole with stemming. The whole team worked as a unified group so all were participating in all tasks. Final blasting circuits were prepared by blast man and shot-firer. Due to collective operation evaluations were done from the prospective of the team rather an individual. The whole crew was given training on the usage and application of these stemming plugs. The training time was not included in any of the assessment parameters. Their working was evaluated based on parameters such as extra time for operation, skill required for mastering the application of new plug, number of failures during work, recovery time requirement for undoing failures, workers feedback, and extra accessories to be carried out during the plug application, and limitations associated with stemming plugs.

Extra time for operation was calculated as mean difference from loading a single hole with conventional stemming and one with stemming plug with a least count as one minute. In case of any delay due to damaged or wrongly placed drill hole, the time was not calculated. To master the application of stemming plugs, the crew was trained in terms of working mechanism and installation for each plug. The time for mastering the skill was also noted. Failures occurring during the installation of plugs were also observed. In case of failures, the workload for that failure, the remedies, and time consumed to eradicate that failure were also recorded. Extra material carried to the working site for each plug was also recorded. After calculations a table was prepared wherein the best performing plug was given 3 points, followed by 2 for intermediate and 1 for least favored. The plug with the top score is suggested as the best among the three plugs tested.

3. Results and discussions

Stemming plug A consumed on average 1 minute extra from the conventional working mechanism. Using it did not require any extra skill to master, as it was simpler in lowering down the hole like explosive cartridge. Due to flexible structure adjustment to walls was easy, thereby avoiding failures and no failure was observed during operation. Workers feedback was positive about this plug due to no extra accessories to be carried for this operation and easy installation mechanism. Stemming plug B was the cheapest in cost among all the stemming plugs but on average, it took more than 7 minutes in loading. The operator was required to know the exact amount of air to be inflated to avoid overfilling and bursting. In case of failure whole operation was repeated that added more time and ultimately increased extra time up to around 16 minutes for each hole. Bursting of plugs resulted in disliking by the workers hence negative feedback was obtained. Stemming plug C took 5 minutes for preparation and pouring into the hole. This plug required adding of additives for making quick-setting cement. This required a good amount of cognitive load to keep the balance of the additive and measurements of water at required levels. Failure chances in the hole were zero as material was loaded in form of slurry, but the probability of mixing improper proportions of water, additives, and cement still existed. However proper mixing was achieved in all tests as these were performed under careful supervision. Workers feedback was not positive as this involved additional work of adding cement, making mortar by adding in water, adding in additives, and then pouring it into holes that required a lot of measurements. Measuring accessories were also required to the application of this plug. Table 2 provides the summary of results obtained after experimentation.

To compare the three-plug design across all six dimensions, each plug was ranked according to its relative ability to ascribe the best of each of this dimension. For example, plug A has the best time of operation result and was therefore given three score with plug C being coded as number 2 because it received the second-best time. This was repeated for each dimension with tied scores being acceptable. Adaptability requiring the crew to learn new skills, failures, recovery-time after failure, number of accessories, and workers feedback was scored. All of these were scored as 3 being the most desirable and 1 being least desired. Finally, these ranking were tallied for each plug design and a relative score was generated. Table 3 indicates the relative scores for each plug.

TABLE 2

Summary of experimentation

Parameters	Plug A	Plug B	Plug C
Extra time required (minute)	1	7	5
Adaptability	Low	Moderate	High
Failures in application	Nil	30	Nil
Recovery time/failure	0	8	0
No. of accessories	0	1	3
Workers feedback	Positive	Neutral	Negative

TABLE 3

Scale for selection of optimum plug

Parameters	Plug-1	Plug-2	Plug-3
Time of operation	3	1	2
Adaptability required	3	2	1
Failures	3	1	3
Recovery time/failure	3	1	3
No. of accessories	3	2	1
Workers feedback	3	2	1
Total	18	9	7

Based on the cumulative scores it was observed that stemming plug A was most favored followed by plug B and C respectively. It was assumed that all other factors remained constant for all the plugs and had no influence on the selection of the plugs, therefore not discussed in this paper. It has been established that stemming plugs enhance the blast performance, and their economic benefits are not ignorable but ergonomic selection part was not discussed before. The plug that required the least amount of cognitive load to the operators received the best score regardless of its economic viability, thereby strengthening the demand for ready to use stemming plugs. Stemming plug A were appreciated due to their admission to the currently established process, as blasting crew didn't have to do something out of the process, it was just like adding one more cartridge of explosive for them. This suggests that whenever a newer product is designed it must be ensured that it goes in harmony with already established norms of workers and industry. Workers satisfaction and homogeneity with the task they are supposed to perform must be considered in designing products. Quick setting cement might have the best results due to excessive bonding with the walls of the hole and provide maximum gas retention; still it was the most undesirable product due great amount of tasks needed to perform its application. If manufactures or mine management decides to go with the quick setting cement mortar as stemming plug, they must ensure it is optimized according to human factors principles for better acceptability and practicality. As this work followed the methodology practiced in research before, this might have been a reason as well for cumbersomeness to execute this task. Stemming plug with quick setting cement but can be applied the way stemming plug A is applied will be a great addition, but the cost effectiveness of this work will be a challenge. Stemming plug B required to be inflated, but their inflation within permissible limit was beyond the controlling parameters at that time, having proper air quantity calculations, making material burst proof at every condition and providing gauges to measure the pressure inside hole can help in enhancement of acceptability but with addition of extra supports as discussed will keep the plug economically. For better time management self-inflatable mechanism can also be used which will help these come at par with stemming plug A. Bursting and inflation mechanism was not optimized which consumed a lot of time while using stemming plug B. Stemming plug A was most favorable because it did not require any extra tasks from blasting crew to perform. It can be established from this research that workers prefer equipment and accessories easier to operate over those that are complex. Furthermore, it can also be inferred that selection of product merely on basis of the economy may not be a wise decision sometimes, as the cheapest or most economical set of equipment may fail to optimize the working environment, which might result in job stress, lack of attention to other job tasks etc.

4. Summary and conclusion

This paper presents initial stage for induction of ergonomics in selection of accessories and utilities in mining industry. Previously the selection criteria were always focused on technical or economical side of new product regardless of its ergonomic implication. In this work three different types of stemming plugs were tested on ergonomic performance matrix. Stemming plug A performed best followed by B and C. Still there is a discrepancy among the mining community and real world in application of ergonomics. In mining industry seats and cabins of haul trucks, wheel loaders, front shovels, and all heavy equipment are now designed based on the ergonomic principles. Application of that on a smaller scale, such as explosive accessories development and selection is a new era and a lot of work can be done in this area to enhance product design and its practicality along with added marketing benefits. Once the market is mature and the consumer is more aware of these issues, manufacturers with ergonomic scores will lead the market. Apart from that, this analysis can become a prime part of comparative analysis between products.

Recommendations

Based on the findings of the research, stemming plug A performed the best among all three stemming plugs. For stemming plug B ergonomic acceptability can be increased by having better more systematic inflation system. Stemming plug C can improve their performance by having packets that have all the ingredients already measured and ready to activate quick setting cement. These packets can be initiated before inserting into hole, taking away all the hassle of mixing and proportional control.

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Conflict of Interest Statement

This paper might positively influence use of Vari-stem stemming plugs. The other two stemming plugs were locally developed and do not have a trademark name or specific brand that can be negatively influenced. Other than that, on behalf of all the authors, corresponding author states that there is no conflict of interest.

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