The Pennsylvania State University
The Graduate School

AN INVESTIGATION INTO THE COMBINED USE OF ELECTRONIC DETONATORS AND AIR-DECKS TO REDUCE FINES AND OVERSIZE IN QUARRY BLASTS

A Thesis in
Energy and Mineral Engineering

by

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ABSTRACT

Blasting is an essential operation in the conventional production cycle of hard rock mining and serves to free the ore from the host rock and facilitate the handling of the broken ore from the production face to the processing plant. Two unwanted, but all-too-common, consequences of blasting are an excess of material too small for commercial use, a.k.a. “fines,” and fragments that are too large to handle, a.k.a. “oversize.” This pilot study analyzed the effect of combining two blasting practices, air-decking and electronic detonators, on the production of fines and oversize, as well as ground vibration and airblast. Three production blasts were fired in an active limestone mine using both full-column explosive charges and mid-column air-decked charges. During the blast, far-field seismographs recorded ground vibration and airblast data. After the shot was fired, digital image analysis was used to quantify the particle size distribution of the muckpile. Lastly, belt scales in the processing plant were used to determine the effect of air-decking on downstream fines generation. In these trials, it was found that using mid-column air-decks that were 30% of the length of the explosive column had negligible effect on fines generation and oversize particles in the muckpile. However, the measured downstream fines were reduced. Additionally, air-decking resulted in significantly reduced PPV levels in the blasts. The findings from this research identify the advantages of this advanced blasting technique. However, additional research is necessary to validate these findings in a range of geologic settings.
# TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................... vi

LIST OF TABLES ............................................................................................. x

ACKNOWLEDGEMENTS ................................................................................ xi

Chapter 1 Introduction .................................................................................. 1
  Problem Statement ..................................................................................... 3
  Research Question and Specific Aims ....................................................... 4
  Project Scope .............................................................................................. 5
  Thesis Format ............................................................................................. 6

Chapter 2 Literature Review ........................................................................ 7
  Fines Generation by Blasting .................................................................... 7
  Air-Decking .............................................................................................. 11
  Electronic Detonators .............................................................................. 18
  Summary .................................................................................................. 22

Chapter 3 Methodology ............................................................................... 24
  Experiment Layout .................................................................................... 25
    Control Blast .......................................................................................... 26
    Experiment A ......................................................................................... 26
    Experiment B ........................................................................................ 27
  On-Site Data Collection .......................................................................... 34
    Fragmentation ......................................................................................... 34
    Ground Vibration and Airblast .............................................................. 37
  Data Analysis ........................................................................................... 39
    Digital Image Analysis .......................................................................... 39
    Ground Vibration and Airblast .............................................................. 41

Chapter 4 Results and Discussion ............................................................. 43
  Fragmentation ........................................................................................... 43
    Control and Experiment A .................................................................... 50
    Control and Experiment B .................................................................... 52
  Ground Vibration and Airblast .............................................................. 54
    Location 1 ............................................................................................. 54
    Location 2 ............................................................................................. 63

Chapter 5 Conclusions and Recommendations ........................................ 65
  Findings ................................................................................................... 65
  Summary of Key Findings ........................................................................ 67
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommendations for Future Research</td>
<td>68</td>
</tr>
<tr>
<td>Downstream Fines Generation</td>
<td>68</td>
</tr>
<tr>
<td>Inter-Hole Delay Timing</td>
<td>69</td>
</tr>
<tr>
<td>Multi-Row Blasts</td>
<td>69</td>
</tr>
<tr>
<td>References</td>
<td>70</td>
</tr>
<tr>
<td>Appendix A Digital Image Analysis Process</td>
<td>74</td>
</tr>
<tr>
<td>Appendix B WipFrag 3 Example Photos</td>
<td>81</td>
</tr>
<tr>
<td>Control Blast</td>
<td>81</td>
</tr>
<tr>
<td>Experiment A</td>
<td>91</td>
</tr>
<tr>
<td>Experiment B</td>
<td>101</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2-1: The traditional Crushed Zone Model (a), and the modified model (b) (Lu et al., 2016) ..............................................................................................................................................8

Figure 2-2: Comparison of rock mass core and outer layer fragmentation (F Ouchterlony & Moser, 2013) ........................................................................................................................................9

Figure 2-3: Displacement speed versus time in traditional charge as captured on an oscilloscope (Melnikov & Marchenko, 1971) ..................................................................................12

Figure 2-4: Displacement speed versus time in air-decked charge as captured on an oscilloscope (Melnikov & Marchenko, 1971) ..................................................................................13

Figure 2-5: Charge configurations tested by Moxon et al. (Moxon et al., 1991) .......................14

Figure 2-6: Volume of air-deck versus mean fragment size (Moxon et al., 1991) ....................15

Figure 2-7: Effect of air-deck volume on particle size distribution (Moxon et al., 1991) ......15

Figure 2-8: Effect of air-deck length on volume of fragments and specific charge (Liu & Katsabanis, 1996) .................................................................................................................................17

Figure 2-9: An illustration of increased fragmentation as a result of wave collision (Chiappetta, 2001) ............................................................................................................................................20

Figure 2-10: An illustration of increased volume fragmented as a result of wave collision (Chiappetta, 2001) ..........................................................................................................................21

Figure 3-1: The layout and timing map for the control blast .........................................................28

Figure 3-2: The configuration of the explosive column for the control blast .............................29

Figure 3-3: The layout and timing map for experiment A ...............................................................30

Figure 3-4: The configuration of the explosive column for experiment A ..................................31

Figure 3-5: The layout and timing map for experiment B .............................................................32

Figure 3-6: The configuration of the explosive column for experiment B .................................33

Figure 3-7: “Panoramic” photo capturing system used to ensure the entirety of the face was captured ........................................................................................................................................35

Figure 3-8: Schematic illustration of processing plant layout showing location of belt scales ........................................................................................................................................36

Figure 3-9: Locations of fair-field seismographs used in this study .............................................38
Figure 3-10: OSM ground vibration Z-curve plot .................................................................41
Figure 4-1: The particle size distribution curve for the control blast ..................................44
Figure 4-2: The particle size distribution curve for experiment A .....................................45
Figure 4-3: The particle size distribution curve for experiment B .....................................46
Figure 4-4: The particle size distribution curves for all three blasts plotted on the same axes .........................................................................................................................47
Figure 4-5: Comparison of fines generation in muckpile and after loading, hauling, and primary crushing ........................................................................................................48
Figure 4-6: Transverse velocity waveform comparison (top: control; bottom: experiment A) ..................................................................................................................................55
Figure 4-7: Longitudinal velocity waveform comparison (top: control; bottom: experiment A) ..................................................................................................................................55
Figure 4-8: Vertical velocity waveform comparison (top: control; bottom: experiment A) ..................................................................................................................................55
Figure 4-9: Transverse velocity waveform comparison (top: control; bottom: experiment B) ..........................................................................................................................55
Figure 4-10: Longitudinal velocity waveform comparison (top: control; bottom: experiment B) ..................................................................................................................................56
Figure 4-11: Vertical velocity waveform comparison (top: control; bottom: experiment B) ..................................................................................................................................56
Figure 4-12: The Z-curve of the control blast .....................................................................58
Figure 4-13: The Z-curve of experiment A ..........................................................................58
Figure 4-14: The Z-curve of experiment B ..........................................................................59
Figure 4-15: A comparison of transverse FFT for the control blast and experiment (red: control; black: experiment A) .......................................................................................59
Figure 4-16: A comparison of longitudinal FFT for the control blast and experiment A (red: control; black: experiment A) ..............................................................................60
Figure 4-17: A comparison of vertical FFT for the control blast and experiment A (red: control; black: experiment A) .......................................................................................60
Figure 4-18: A comparison of transverse FFT for the control blast and experiment B (red: control; black: experiment B) .......................................................................................61
Figure 4-19: A comparison of longitudinal FFT for the control blast and experiment B (red: control; black: experiment B) .................................................................62

Figure 4-20: A comparison of vertical FFT for the control blast and experiment B (red: control; black: experiment B) .................................................................62

Figure 4-21: The velocity and sound waveforms for the control blast .............................64

Figure 4-22: The Z-curve of the control blast ..................................................................64

Figure A-1: The user interface of WipFrag 3 ..................................................................74

Figure A-2: Example of a scaled photo in WipFrag 3 ........................................................75

Figure A-3: Using the automatic segmentation tool ............................................................76

Figure A-4: A photograph after automatic segmentation is completed ..............................77

Figure A-5: An example of a disintegration error (single particle outlined in red) ............77

Figure A-6: An example of a fusion error (two smaller particles outlined separately in red) ..................................................................................................................78

Figure A-7: An example of a completed net .......................................................................78

Figure A-8: The completed PSD curve for the example analysis .........................................79

Figure A-9: The aggregated curve for the example analysis project .................................80

Figure B-1: Control blast example analysis 1 .....................................................................81

Figure B-2: Control blast example analysis 2 .....................................................................82

Figure B-3: Control blast example analysis 3 .....................................................................83

Figure B-4: Control blast example analysis 4 .....................................................................84

Figure B-5: Control blast example analysis 5 .....................................................................85

Figure B-6: Control blast example analysis 6 .....................................................................86

Figure B-7: Control blast example analysis 7 .....................................................................87

Figure B-8: Control blast example analysis 8 .....................................................................88

Figure B-9: Control blast example analysis 9 .....................................................................89

Figure B-10: Control blast example analysis 10 .................................................................90
Figure B-11: Experiment A example analysis 1 .......................................................... 91
Figure B-12: Experiment A example analysis 2 .......................................................... 92
Figure B-13: Experiment A example analysis 3 .......................................................... 93
Figure B-14: Experiment A example analysis 4 .......................................................... 94
Figure B-15: Experiment A example analysis 5 .......................................................... 95
Figure B-16: Experiment A example analysis 6 .......................................................... 96
Figure B-17: Experiment A example analysis 7 .......................................................... 97
Figure B-18: Experiment A example analysis 8 .......................................................... 98
Figure B-19: Experiment A example analysis 9 .......................................................... 99
Figure B-20: Experiment A example analysis 10 ......................................................... 100
Figure B-21: Experiment B example analysis 1 .......................................................... 101
Figure B-22: Experiment B example analysis 2 .......................................................... 102
Figure B-23: Experiment B example analysis 3 .......................................................... 103
Figure B-24: Experiment B example analysis 4 .......................................................... 104
Figure B-25: Experiment B example analysis 5 .......................................................... 105
Figure B-26: Experiment B example analysis 6 .......................................................... 106
LIST OF TABLES

Table 2-2: Benefits of using air-decks in a coal mine as identified by Jhanwar’s research (Jhanwar, 2013)..................................................................................................................18

Table 3-1: Control and experimental blast pattern characteristics .................................................................................25

Table 3-4: Re:mote™ seismograph specifications ..............................................................................................................38

Table 3-5: The distance of each seismograph from each blast, in feet .................................................................................39

Table 3-3: Number of photos analyzed for each blast .......................................................................................................40

Table 4-1: Cumulative percent passing fragmentation data for control, experiment A, and experiment B ............................................................49

Table 4-2: Downstream fines generation measured by weight of material going to base pile and surge pile ........................................................................49

Table 4-3: A comparison of control and experiment A particle size distributions calculating the difference between them ........................................................................50

Table 4-4: A comparison of control and experiment B particle size distributions calculating the difference between them ........................................................................52

Table 4-5: Ground vibration and airblast data at Location 1 .............................................................................................54

Table 4-6: Ground vibration and airblast data at Location 2 .............................................................................................63
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Chapter 1

Introduction

In aggregate mining, blasting is the first of a series of processes that turns in-situ rock into saleable crushed stone. It may be practical to increase the quantity of saleable material, while reducing secondary breakage and ground vibration, by applying rock fragmentation theory to develop advanced blasting techniques. The combination of air-decking and electronic detonators could provide an unrecognized opportunity to optimize the blasting process.

Air-decking\(^1\) has been established as an acceptable practice in the field for decades (Chiappetta, 2001, 2004, 2010; Davids & Botha, 2001; Katsabanis, 2005; Liu & Katsabanis, 1996; Mead, Moxon, Danell, & Richardson, 1993; Melnikov, 1961; Melnikov & Marchenko, 1971; Moxon, Mead, Richardson, & Diego, 1991). In an air-decked blast, the explosive waves from each explosive deck collide inside the air-deck and expand, reducing initial blasthole pressure on the adjacent rock. Additionally, the air allows this collision to reverberate, delivering several pulses of energy to the rock as the blast dissipates. Due to the reduction in blasthole pressure, the area of rock that is pulverized is reduced by a few blasthole diameters. Furthermore, the energy reverberation allows the growing crack network to expand with every pulse, increasing fragmentation throughout the rock mass. Air-decking has historically been tested with pyrotechnic or electric delays. The actual delay time of these devices can vary

\(^{1}\) An air-deck is a gap in an explosive column that is filled with air.
significantly, making it nearly impossible to control the interaction of the seismic waves during the blast. Today’s high-precision electronic detonators are so accurate that it is practical to design specific wave interactions; and these electronic detonators are widely available, affordable, and have other benefits such as improving security at the blast site. Their use has been shown to improve fragmentation, reduce ground vibration, and increase productivity (Bilodeau et al., 2008; Lewis & Pereira, 2003; Lownds & Louw, 2004; McKinstry, Floyd, & Bartley, 2002; Nojiri, Mendes, Botelho, & Campanha, 2002; Paley, 2010; Preece & Chung, 2005). The precision and accuracy of these electronic devices, which can be programmed to detonate on virtually any delay, allows blasters to design not only optimal patterns, but also to be confident that the blast will detonate as planned. In an air-decked blast, this precision ensures that wave collision will occur in the center of the air-deck, maximizing the effects of the collision.

Air-decking and electronic detonators represent two different advanced blasting techniques that have been shown to have significant benefits separately; however, the combined use of these techniques has received less attention. Since the beginning of the twenty first century, internationally-renowned explosives engineer Frank Chiappetta has pioneered this combination, publishing two papers and conducting trials in over twelve mines in various mining environments (Chiappetta, 2001, 2004). In these trials, he combines air-decks, electronic detonators, and stemming charges to conclude qualitatively that improvements in fragmentation and ground vibration are possible (Chiappetta, 2010).
Problem Statement

The mining and processing of crushed stone creates fines, i.e. particles too small to be sold for a profit. It is well known throughout the industry that overproducing fines has adverse financial consequences. Esen and Onederra write that “increased fines content in run-of-mine feed leads to higher handling and processing costs, low yields, increased product moisture, and in many cases a reduced product value” (Esen, Onederra, & Bilgin, 2003; Onederra, Esen, & Jankovic, 2006). Of course, some level of fines generation is a natural consequence of fragmentation. Mine operators can only hope to minimize their production, not eliminate it. Therefore, fines minimization efforts should be taken at all steps of the mine-to-mill cycle, and that starts with blasting. During a blast, rock comprising the blasthole wall is immediately pulverized due to the very high pressures exerted during detonation. This crushed region is typically a few blasthole diameters wide (Esen et al., 2003; Lu, Leng, Chen, Yan, & Hu, 2016), but if the extent of this zone could be reduced, then fines generation during the blast should be reduced as well.

The likely benefit of combining air-decks and electronic detonators was identified qualitatively by Chiappetta, as described earlier in this chapter. A more quantitative analysis of the benefits is required, and the goal of this research is to explore a more quantitative approach to establish the value of this blasting practice.
Research Question and Specific Aims

This research sets out to answer the following question:

*Does the combined use of air-decked shots with electronic detonators reduce fines and oversize material?*

To answer this question, the following three quantities were determined:

1) Fines generation in blasts with and without air-decks

*Hypothesis: Air-decked shots will generate less fines than those without air-decks due to reduced crushing around the borehole.*

2) Fines generation due to loading, hauling, and primary crushing

*Hypothesis: The microfracture network in air-decked shots will be less extensive than in shots without air-decks, which will make particles more resistant to fines generation during downstream handling and primary crushing.*

3) Oversize material in blasts with and without air-decks

*Hypothesis: Air-decks will increase energy utilization; therefore, more energy will be available to limit oversize.*

Additionally, while not the focus of this pilot study, the combination of air-decking and electronic detonators could have an effect on ground vibration peak particle velocity.
Hypothesis: Due to energy redistribution, less explosive energy will be converted into seismic energy; therefore, peak particle velocity will be reduced as a result of air-decking.

To quantify the generation of fines and oversize as a result of air-deck use, digital image analysis will be used to develop particle size distribution (PSD) curves for muckpiles of blasts that do and do not use air-decked charges.

To determine fines generation due to subsequent handling and processing, belt scales in the plant will be used to determine the quantity of fines after the blasted rock has been loaded, hauled, dumped into the primary crusher, and crushed. The fines at this stage will be compared to the fines present in the muckpile to determine the level of fines generated after blasting.

To determine the ground vibration and airblast, seismographs will be used to capture these parameters during the blast.

Project Scope

There are several combinations of air-decks and electronic detonators that could be applied to a blast design, and indeed, there are a seemingly endless variety of patterns that might be used at a given mine site. However, for the purpose of answering the research questions, two different charge designs and two different blast patterns were

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2Digital image analysis is a technique in which the sizes of particles in a photograph are determined using edge detection algorithms.
selected. Moreover, the decision was made to use full-scale production blasts rather than limiting the pattern to a few holes. This study is focused on surface mining of limestone for the crushed stone market. The geology of surface stone mines is variable, and the specific geology at the mine site will affect the outcome of a specific blast pattern. The experimental study of this research was designed to allow a comparison between blasting practices in one type of geology. The results of such a study will illuminate the comparative advantage of the practice in similar geologic conditions, but will not necessarily be directly transferrable to all mine sites. Ideally, the design of the research study would include multiple mines in both similar and different geologic settings. However, the amount of time required to execute the experiments in one mine, and by extension the cost to acquire data, is very large. Consequently, this study was limited to one active surface limestone mine.

**Thesis Format**

In the next chapter, literature discussing the theory behind air-decking and the findings of past research are reviewed, along with reports of the benefits that operations have seen with the use of electronic detonators. In Chapter 3, the field experiments and the data collection and analysis process will be presented. In Chapter 4, the results from the trial blasts will be presented and discussed. Lastly, the conclusions and recommendations are given in Chapter 5.
Chapter 2

Literature Review

Fines Generation by Blasting

Fines generation is an inescapable part of mining; any process that involves fragmenting rock is going to create dust in large quantities. As a part of the European Union research project “Less fines production in aggregate and industrial minerals industry,” the annual quantity of fines produced across Europe was estimated to be approximately 450 million tonnes, equating to 10 - 15% of all production. In limestone operations, it was possible for fines to account for up to 30% of the mine’s production (Moser, 2005). In a separate European study, it was reported that the UK produced 55 million tonnes of fines in 2005, accounting for about 18% of all material produced. In finer products, the proportion of fines increased until its generation accounted for 40% of all production of 10 millimeter topsize aggregate (Mitchell, Mitchell, & Pascoe, 2008). In Europe, fines generation is wasting a significant percentage of aggregate material, and it is reasonable to assume that American mines produce similar quantities.

There is disagreement throughout the industry regarding how these fines are generated during a blast. One popular theory is the Crushed Zone Model (CZM), in which rock is fragmented in a series of concentric cylinders around the blasthole; the closest cylinder is crushed into fines upon detonation (Bhandari, 2013; Esen et al., 2003; Lu et al., 2016; F Ouchterlony & Moser, 2013). There are several different variations of the CZM, but it is traditionally described as having three regions: the crushed zone, the radial crack zone, and the elastic deformation zone. These models, however, do not account for compressive hoop stresses in the radial crack zone, leading to the development of the modified CZM (Lu et al., 2016). Figure 2-1(a) illustrates the
traditional CZM model, while Figure 2-1(b) shows the modified model. In the modified model, the radial crack zone is divided into an inner cylinder that does experience hoop stress and an outer cylinder that does not.

Figure 2-1: The traditional Crushed Zone Model (a), and the modified model (b) (Lu et al., 2016)

In both the traditional and modified CZM, the crushed zone is subjected to compressive and shear stresses upon detonation, which immediately pulverize the rock in this ring. This modified model
was found to better model actual fragmentation data than the original CZM in laboratory tests and numerical simulations (Lu et al., 2016).

In addition to the CZM, dynamic crack propagation is thought to be a primary source of fines (Bhandari, 2013; F Ouchterlony & Moser, 2013). In small-scale tests, Bhandari found that there was a relationship between burden and fines generation: smaller burdens resulted in more fines, which led him to conclude that the crushed zone cannot be the only source of fines in a blast, and he suggested that crack network extension by stress waves is another source of fines (Bhandari, 2013). At the same time, Ouchterlony and Moser were arriving at the same conclusion. They reviewed several experiments in which the inner and outer regions of a rock mass were identified, blasted, and then analyzed for fragmentation. One such experiment conducted by Svahn used a rock mass comprised of different colored layers. The rock was blasted and the particle size distribution was found for each layer. In Figure 2-2, the results of Svahn’s work in 2003 is presented, showing that the sample’s core has a very similar size distribution to the outer region.

![Figure 2-2: Comparison of rock mass core and outer layer fragmentation (F Ouchterlony & Moser, 2013)](image-url)
The results of the other reviewed experiments also indicated that the inner regions of the blasted rock were not significantly finer than the outer regions, leading Ouchterlony and Moser to theorize that dynamic crack growth is another primary source of fines. Ouchterlony and Moser suggested that when stress waves reach a free face, they reflect back through the rock mass as dynamic tensile stresses. These stresses alter and expand the pre-existing crack network, leading to significant fines generation (F Ouchterlony & Moser, 2013). Fines primarily originate from two different mechanisms during a blast. First, high blasthole pressure and compressive stresses generated during detonation instantly crush the zone immediately around the blasthole. Then, tensile stress waves travel through the rock mass, extending the existing crack network.

Across the industry, it is agreed that fines are a serious problem for mine operators. Perhaps the best statement summarizing their effect on a mine is given by Onederra et al.: “Increased fines content in run-of-mine feed leads to higher handling and processing costs, low yields, increased product moisture, and in many cases a reduced product value” (Esen et al., 2003; Onederra et al., 2006). Besides this, fines represent health, environmental, and logistics problems (Bhandari, 2013). In many ways, it is apparent how fines generation increases costs. In one significant way, however, it is less apparent. During a blast, explosive energy is wasted in fines generation. Ouchterlony calculated that of all the explosive energy released in a blast, only about half of it is useful (F Ouchterlony & Moser, 2013). Losses make up 20-40% of explosive energy, and it is believed that crushing and fines generation near the blasthole could be the primary loss of energy (Finn Ouchterlony, Nyberg, Berqvist, Granlund, & Grind, 2004). This is illustrated by Ouchterlony’s team’s work, in which they developed an estimate of the energy used during a blast. These results are shown in Table 2-1.
Additionally, Sanchidrian et al. reported that only 7 – 25% of explosive energy is converted into useful work, which is much lower than determined by Ouchterlony et al. (Sanchidrián, Segarra, & López, 2007). Despite the differences in results, both researchers agree that explosive energy is inefficiently converted into useful work during a blast.

### Air-Decking

Although a more complete understanding of the mechanisms of fines generation is relatively recent, the fact that explosive energy is not used efficiently has been known for decades. N.V. Melnikov, seeking improved efficiency, led air-decking research in the Soviet Union during the mid 20th century. He found that fragmentation depends on the distribution and utilization of energy within an explosive column. In fragmentation blasts, energy utilization coefficients could be as low as 15 – 25%. Melnikov’s research sought to increase energy utilization and reduce economic losses of explosive energy during a blast, one of which being the crushing of material adjacent to the blasthole wall. His research concluded that an air-deck increases energy utilization by reducing blasthole pressure and extending the time that stresses act on the rock mass (Melnikov, 1961).

<table>
<thead>
<tr>
<th>Site</th>
<th>No. of rounds</th>
<th>$\eta \cdot E_0$</th>
<th>$E_s$</th>
<th>$E_k$</th>
<th>$E_f$</th>
<th>Losses in rock, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klinthagen</td>
<td>5</td>
<td>60-70</td>
<td>3-12</td>
<td>3-12</td>
<td>0.1-0.2</td>
<td>38-53</td>
</tr>
<tr>
<td>La Concha</td>
<td>2</td>
<td>40-50</td>
<td>2-6</td>
<td>16-25</td>
<td>0.1-3.2</td>
<td>16-22</td>
</tr>
<tr>
<td>Eibenstein</td>
<td>2</td>
<td>65</td>
<td>0.4-2.5</td>
<td>6-27</td>
<td>-</td>
<td>35-58</td>
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<tr>
<td>Spathis$^{22}$</td>
<td>1</td>
<td>58</td>
<td>5</td>
<td>27</td>
<td>0.3</td>
<td>26</td>
</tr>
<tr>
<td>Hinzen$^{18}$</td>
<td>5</td>
<td>-</td>
<td>0.1-5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2-1: Explosive energy breakdown estimation determined experimentally in limestone blasts (Finn Ouchterlony et al., 2004)
The mechanism by which air-decks increase energy utilization is widely agreed upon in the literature (Melnikov, 1961; Melnikov & Marchenko, 1971; Moxon et al., 1991). In conventional blasting, detonation releases high-pressure gasses that send a compressive stress wave through the rock mass, which immediately begins to crush and expand the cylinder of rock closest to the blasthole. Once this wave passes, no more energy is transferred from the explosive to the rock. In air-decked blasting, however, the explosive activity within the air-deck generates secondary stress waves. The stress waves from the detonating explosive decks collide and expand in the air-deck, losing velocity but gaining pressure. When they collide, they are reflected into the rock mass, resulting in repeated pulses of energy delivered to the blasthole wall after the initial compressive wave has passed. This mechanism was graphed by Melnikov and Marchenko in 1971 using oscilloscopes. Figures 2-3 and 2-4 show the displacement speeds of rock blasted without and then with an air-deck.

Figure 2-3: Displacement speed versus time in traditional charge as captured on an oscilloscope (Melnikov & Marchenko, 1971).
Because multiple shock waves travel through the rock mass, air-decked charges transfer 1.5 – 1.7 times more energy into the rock than conventional charges. In addition, due to lower initial blasthole pressure, crushing around the blasthole is not as severe, and because of repeated stresses, the crack network expands to affect a larger volume of rock than in conventional blasting (Melnikov & Marchenko, 1971).

Air-decking has been extensively tested in both laboratory and production settings since the 1960’s, and almost all the experiments produced strikingly similar results. In 1961, Melnikov performed full scale tests in a hard rock, a coal, and a limestone mine. He reduced explosive use by 10% and determined that air-decks do increase fragmentation. In addition, he found that air-decking shortened explosive loading time. An important conclusion of this research was that air-decked charges must be fired simultaneously because these charges are susceptible to sympathetic initiation (Melnikov, 1961)\(^3\).

\(^3\) Sympathetic initiation occurs when the detonation of one explosive deck triggers another explosive deck in the same hole prior to its designed delay.
He continued this research in 1971 with Marchenko and found that the use of air-decks decreased the average fragment size up to two times, the amount of oversize by 2 – 10 times, and the explosive consumption by 10 – 30%. They reported that seismicity decreased and productivity increased by 10 – 30% (Melnikov & Marchenko, 1971), and these results are very similar to those found by Melnikov ten years earlier. Finally, they concluded that air-decks do result in significant technical and economic improvements.

Moxon et al. carried out tests in concrete blocks that compared five different charge arrangements, shown in Figure 2-5, to determine the effects of the size and location of an air-deck. They determined that the middle column air-deck produced the finest fragmentation among the air-decked charges, followed by the bottom column. The top column trial could not be analyzed due to stemming ejection. Additionally, the team found that an air-deck could be 40% of the length of the explosive column before significant adverse fragmentation issues arose (Figure 2-6) and that the maximum amount of explosive that could be removed was 50% (Figure 2-7).
However, Moxon’s team felt this was an overestimate, and determined that 30% explosive removal was more reasonable, which agrees with Melnikov’s earlier work. Their research concluded that air-decks using pyrotechnic detonators can be used to increase caprock fragmentation, that middle column air-decks produce the finest fragmentation due to shock wave collisions inside the air-deck, and that air-decks can be used to reduce explosive consumption without adversely affecting fragmentation (Moxon et al., 1991).

Figure 2-6: Volume of air-deck versus mean fragment size (Moxon et al., 1991)

Figure 2-7: Effect of air-deck volume on particle size distribution (Moxon et al., 1991)
Later, the same research team conducted field and lab experiments to determine the effect of size and position on an air-decked shot. From the lab work, they made the same conclusions as their previous project: fragmentation decreases very slightly until a critical air-deck size is reached, and middle column air-decks produce finer fragmentation than top and bottom column air-decks. One new conclusion was that the critical size of the air-deck actually depends on the strength and internal structure of the rock mass. These findings prompted air-decking tests in three different production settings with three different goals. In a copper mine, top column air-decks were used to lower explosive costs by 10%. In these trials, it was found that the charges could contain 20 – 40% less explosive without any significant consequences. This explosive reduction correlated to air-deck sizes of 35 – 45% of the explosive column length. Air-decks were again tested in an iron ore mine in Australia to limit backbreak. The mine had been firing shots with less explosive to protect the highwall, but this reduced fragmentation. They found that they could reduce the charge weight by 20 – 35% and see reduced blast damage while maintaining good fragmentation. Lastly, in a coal mine, middle column air-decks were used to replace explosive in a weak interburden layer. They were found to reduce face bursting and slumping while producing equal fragmentation to fully charged shots (Mead et al., 1993).

Davids and Botha made an important conclusion while performing research in South Africa to deal with weak interburden. In their tests, they compared air to four other decking materials in order to reduce the amount of explosive used in the interburden. They found that air is very susceptible to sympathetic initiation, leading them to conclude that middle column air-decked charges must be fired simultaneously. Because of sympathetic initiation, their tests had two outcomes: either the top or the bottom charge would fire first. They found that the fragmentation results were acceptable as long as the bottom deck fired first (Davids & Botha, 2001).

In 1996, Liu and Katsabanis ran computer simulations that modeled air-decks based on
continuum mechanics and statistical fracture mechanics and performed field tests in a granite
gneiss rock mass. Two important conclusions were drawn from this research. First, they
determined that there was a minimum useful air-deck length. The size of the air-deck is crucial
for storing and releasing energy; if the air-deck is too small, too little energy would be stored in
the air, causing the blast to perform worse than a fully charged blast. In their trials, the minimum
air-deck length was found to be 1.44 meters with a specific charge of 0.658 kg/m$^3$. Their results
are shown in Figure 2-8.

![Figure 2-8: Effect of air-deck length on volume of fragments and specific charge (Liu &
Katsabanis, 1996).](image)

Second, in their simulations, they found that middle column air-decks did not enhance
fragmentation, which is in conflict with prior experiments (Liu & Katsabanis, 1996). In
Katsabanis’ subsequent simulations, he modelled air-decking using the Lagrangian processor of
the Autodyn code. In his top column air-deck simulations, he found that there was an indirect
relationship between collar length and blast damage, which agrees with work from Mead et al. It
was determined that fragmentation only increases when air replaces stemming material instead of explosive material. Lastly, bottom column simulations resulted in decreased toe fragmentation (Katsabanis, 2005).

Finally, in 2013, Jhanwar compared conventional and air-decked charges in open cast manganese and coal mines. At the manganese mine, he found that air-decking worked better in low strength, moderately jointed rock, and he reported several benefits of air-decking at the coal mine, shown in Table 2-2. He concluded that the techno-economic feasibility of air-decks depended on the rock mass structure, air-deck length, and the desired results of the blast. An important point to note in his research is that in the coal mine trials, electric detonators were used; the type of detonator used in the manganese mine was not reported (Jhanwar, 2013).

Table 2-2: Benefits of using air-decks in a coal mine as identified by Jhanwar’s research (Jhanwar, 2013)

<table>
<thead>
<tr>
<th>Fragmentation</th>
<th>Shovel efficiency</th>
<th>Increased by 20–40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Became uniform</td>
<td>Ground vibration</td>
<td>Reduced by 30–94%</td>
</tr>
<tr>
<td>• Fines reduced by up to 70%</td>
<td>Backbreak</td>
<td>Reduced by 50–80%</td>
</tr>
<tr>
<td>Throw of muck pile</td>
<td>Reduced by 65–85%</td>
<td></td>
</tr>
<tr>
<td>Explosive cost</td>
<td>Reduced by 10–35%</td>
<td></td>
</tr>
<tr>
<td>Shovel loading cost</td>
<td>Reduced 36.3%</td>
<td></td>
</tr>
</tbody>
</table>

**Electronic Detonators**

One problem with air-decks that two different research groups found is that the charges are susceptible to sympathetic initiation and therefore must be fired together (Davids & Botha, 2001; Melnikov, 1961). In past research, only conventional pyrotechnic delays or electric initiation systems had been used, but since then, new electronic detonators have been developed,
which allow for precise and accurate timing sequences.

As early as the 1980’s, tests were conducted to determine the effect of high precision initiation systems. At the time, pyrotechnic detonators were accurate to 25 millisecond delays with scatters less than 1%. These tests showed significant ground vibration, fragmentation, and oversize improvements associated with precision initiation systems. The system allowed for larger shots without increasing ground vibration, better energy utilization, and more consistent results (Chiappetta, 2001).

Today, the benefits of using precise electronic detonators with even shorter delays are well known and have been demonstrated in a wide variety of commodities and applications. The first to publish their findings was Barrick in 2001. The company sought to determine the effect of using electronic detonators on fragmentation, digging productivity, and ground vibration. With electronic detonators, Barrick achieved an 18% reduction in mean particle size, an 11% increase in loading productivity, and improved vibration control. Their tests concluded that electronic detonators provide significant downstream benefits, but also that more extensive testing was necessary (McKinstry et al., 2002).

Later, Vulcan Materials published a report testing the ability of electronic detonators to increase tonnage while limiting vibration and airblast levels in aggregate mining operations. As a result of these tests, the company saw reduced drilling and blasting costs, reduced scaled distances, ground vibration variation, and hauling costs, and increased crusher productivity (Lewis & Pereira, 2003). Throughout the industry, there has been extensive research into electronic detonators (Bilodeau et al., 2008; Lownds & Louw, 2004; Nojiri et al., 2002; Paley, 2010; Preece & Chung, 2005), and the industry consensus is that their benefits far outweigh their additional costs when compared to pyrotechnic delays.

Chiappetta’s research discussed the concept of using electronic detonators to control shock and stress waves. Because of their incredible precision, the detonators can be programmed
in such a way as to control and use the waves emanating from them to enhance blasting outcomes, especially fragmentation. In tests axially primed with two electronic detonators, it was found that the colliding waves in the region between the detonators significantly increased fragmentation, and that a larger volume of rock can be broken than with only one detonator. This is illustrated in Figures 2-9 and 2-10. Chiappetta then theorized that the previously reported benefits could be improved further with the use of electronic detonators. This new technology would allow for high-precision wave collision in the center of an air-deck, which would maximize the effects (Chiappetta, 2001).

Figure 2-9: An illustration of increased fragmentation as a result of wave collision (Chiappetta, 2001)
In 2010, Chiappetta tested the combination of air-decking and electronic detonators in thirteen case studies in different mining environments. In addition to these two advanced blasting technologies, he used stem charges to increase caprock fragmentation. In his tests, the use of these techniques resulted in improved fragmentation and reduced or unchanged ground vibrations (Chiappetta, 2010). While the results reported in this lecture show promise for the field experiments conducted in this research, the exact magnitude of the changes in fragmentation and ground vibration are not specifically reported. Additionally, his lecture is focused on reducing oversize in the caprock region; his case studies do not measure changes in fines generation as a
result of these techniques. Finally, Chiappetta uses air-decks that are only a few feet long, while previous researchers tested much larger air-decks.

Summary

The most prevalent model to illustrate rock fragmentation by blasting is the Crushed Zone Model, which states that rock surrounding a blasthole breaks in zones of concentric cylinders centered on the hole itself. The zone closest to the hole is called the crushed zone, and it is defined as the area in which the compressive radial stresses released from the blast are so high that the rock is immediately pulverized. The crushed zone is a major source of fines generation and represents a significant waste of explosive energy that could be used to improve overall fragmentation instead of generating fines.

Energy redistribution can be accomplished by changing the charge configuration to include an air-deck, a gap in the explosive column that is filled with air instead of drill cuttings or other inert material. When a blast detonates, stress waves propagate into the air-deck and expand rapidly. This rapid expansion decreases the blasthole pressure acting on the rock, lowering the initial spike of energy that the hole wall experiences in continuous charge blasting. Additionally, once inside the air-deck, the waves reverberate and act on the rock in several pulses over a longer period of time, causing repeated stresses that extend the fracture network and improve fragmentation. Air-decking reduces borehole pressure and lengthens the acting time of stresses on the rock, reducing fines generation and improving overall fragmentation.

A recent advance in the industry is the development of electronic detonators that allow for precise and accurate timing delays that improve fragmentation, ground vibration, and overall blast performance. The high precision of these detonators has allowed for advances in axial priming, a blasting technique that involves firing an explosive column from both ends, causing
the explosion to collide between the detonators. With electronic detonators, blasters can program the delays so accurately that they can choose exactly where the waves will collide. By combining these advanced detonators with air-decking, significant improvements could be realized. Research has shown that when used alone, air-decking, conventional electronic priming, and axial electronic priming all produce significant benefits both to blasting and to downstream processes. The original air-decking trials were conducted with detonating cord or other pyrotechnic delays. In this research, air-decking will be used in conjunction with recently developed electronic detonators in order to determine their efficacy when used together.

Prior to Chiappetta’s work, air-decking researchers tested large air-decks that could be up to 60% of the length of the explosive column using pyrotechnic detonators. More recently, Chiappetta has combined electronic detonators with air-decks, but in his trials, the air-decks were only a few feet long. Combining large air-decks with new electronic detonators could produce even better results than their use separately. This research attempts to fill this knowledge gap by testing the combination of large air-decks and electronic detonators in an active limestone mine. The air-decked explosive charges used in this study, as well as the data collection and analysis methods, are presented in the next chapter.
Chapter 3

Methodology

A goal of this research is to investigate the effects of the combined use of air-decking and electronic detonators on fragmentation, ground vibration, and airblast in different explosive charge designs.

This investigation was designed for an active mining operation using production-scale blasts as opposed to computer simulations, concrete blocks, or small-scale blasts. Two experiments are planned to study the effects of electronic detonators with and without air-decking. In addition, a control blast will be fired. These blasts are summarized as follows:

- Control blast: host mine’s standard production blast,
- Experiment A: standard production blast using a mid-column air-deck that is 30% of the length of the explosive column in every hole, and
- Experiment B: reduced burden production blast using a mid-column air-deck that is 30% of the length of the explosive column in every hole.

After each blast, blasting fragmentation, downstream fines generation, ground vibration, and airblast will be assessed using digital image analysis, belt scales in the processing plant, and far-field seismographs.

This chapter is divided into three sections. The first section, entitled “Experiment Layout,” will explain the different charges to be tested and the design of each experiment. This will include the blast pattern, charge design, and shot timing. Next, the section entitled “On-Site Data Collection” discusses the methods used to gather data at the mine site. This section will cover how each category of data was obtained, and it will include a brief property description.
Finally, the last section, “Data Analysis,” will cover the processes used to analyze the data gathered at the mine.

**Experiment Layout**

Experiments were designed to measure the effects of a full-column charge and an air-decked charge in two different blasting patterns at an active aggregate quarry in production-scale blasts. One control blast and two different experimental blasts were designed; the salient characteristics of these are presented in Table 3-1.

Table 3-1: Control and experimental blast pattern characteristics

<table>
<thead>
<tr>
<th>Blast</th>
<th>Control</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden (ft)</td>
<td>28</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Spacing (ft)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Stemming (ft)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Hole Depth (ft)</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Face Height (ft)</td>
<td>52</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Subdrilling (ft)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Hole Diameter (in)</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Powder Factor (lb/ton)</td>
<td>0.282</td>
<td>0.199</td>
<td>0.220</td>
</tr>
<tr>
<td>Average Charge/Hole (lb)</td>
<td>609</td>
<td>429</td>
<td>423</td>
</tr>
<tr>
<td>Holes/Delay</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The site selected for this research was in an active limestone mine, utilizing the open pit method, that produces approximately four million tons of construction aggregate annually. The mine property covers approximately 2,000 acres in south central United States. The pit is mined in three levels with a bench height of 55 – 60’. The mine uses a conventional cycle and a typical blast results in approximately 55,000 – 60,000 tons of material on the ground. This muckpile
usually takes between 2.5 – 3 weeks to load out using one loader and a fleet of three haul trucks. The rock is transported to the primary crusher, which is a horizontal shaft impactor (HSI).

**Control Blast**

The control experiment used the mine’s standard blast pattern, timing, and charge. Figure 3-1 illustrates this blast pattern, which consists of a single row of 28 holes having the characteristics previously listed in Table 3-1. Electronic detonators with 40 millisecond (ms) delays between each hole were used to fire this pattern.

Each hole is fully coupled and loaded with ANFO, and two electronic detonators are used in each hole. The first and last holes in the row both use a top-column air-deck. In all other holes, there is only one explosive deck which extends from the bottom of the hole to the stemming. Crushed stone is used to stem the holes. This explosive column is shown in Figure 3-2.

**Experiment A**

Experiment A used one mid-column air-deck in each of the holes. The shot pattern and timing were unchanged from the control blast. Figure 3-3 illustrates this blast’s layout and timing map. In this blast, the last seven holes in the pattern were not fired due to concerns over clay that may have sloughed into the holes. This will not affect the results of the study in any way because enough rock was still blasted to test the air-decked charge and to capture data.

In this experiment, 30% of the explosive column was replaced with air, which is reflected in the decrease in powder factor from 0.282 in the control to 0.199 in experiment A. The shot was end-initiated and fired on 40 ms delays. Both explosive decks in each hole were fired simultaneously.
The charge design used in this blast included a mid-column air-deck in every hole. Each hole consists of 16.5 feet of ANFO, followed by 14 feet of air plugged by a gas bag, an additional 16.5 feet of ANFO, and finally 10 feet of stemming. This size of air-deck represents 30% of the explosive column. This is shown in Figure 3-4. Each hole used three electronic detonators. One was placed on the bottom of the hole, another was placed three feet from the bottom of the air-deck, and the last one was placed three feet from the top of the air-deck. All three detonators in each hole were on zero delay relative to one another.

**Experiment B**

Experiment B used the same charge design as experiment A, but in this experiment the burden was reduced to 24 feet. Additionally, this blast fired the last seven holes from Experiment A. Prior to loading these holes with explosive, the driller inspected and then cleaned these holes. They were then fired as a part of the experiment B blast. This will not affect the results of this study because a sufficient number of experiment B holes were fired. The pattern layout and timing map of this shot are shown in Figure 3-5. The box in Figure 3-5 indicates which holes were originally part of experiment A but were fired in Experiment B.

The last 24 holes of this blast, the true experiment B holes, were drilled with 24’ burden, which is a change from 28’ burden in the previous two blasts. The charge design used in these holes is shown in Figure 3-8. The 40 ms delay time was maintained, and all three detonators in each hole were fired simultaneously.

---

4 The pattern for experiment A was originally 28 holes to match the control experiment. However, concerns related to clay sloughing into the last seven holes of experiment A prevented the last seven holes from being fired in experiment A.
Figure 3-1: The layout and timing map for the control blast
Figure 3-2: The configuration of the explosive column for the control blast
Figure 3-3: The layout and timing map for experiment A
Figure 3-4: The configuration of the explosive column for experiment A
Figure 3-5: The layout and timing map for experiment B
Figure 3-6: The configuration of the explosive column for experiment B
On-Site Data Collection

This research is focused on three areas of blasting outcomes: fragmentation, ground vibration, and airblast. Two far-field Re:mite™ seismographs were used to capture ground vibration and airblast data. After each blast, photos of the muckpiles were captured at various stages of the loading process. Finally, after material was loaded out, belt scales were used to measure the level of downstream fines generation. The methods used to collect this data are described in further detail in this section.

Fragmentation

After each shot, the researchers photographed the muckpile; and the photos were stored for subsequent use in digital image analysis to quantify the fragmentation characteristics of the muckpile. Photos were taken across the entire face of the pile at different stages of loading to ensure that the collection of would be representative of the muckpile.

Belt scales located downstream of the primary crusher were used to estimate the level of downstream fines generation.

Photo Capturing

To take the photos, the researchers used an iPad Pro with WipFrag 3 installed on it. WipFrag 3 is an iOS application manufactured by WipWare that uses digital image analysis to determine the particle size distribution of a blasted muckpile. Once a muckpile was on the ground, photo collection began. A sampling plan was developed to ensure representative photos were taken.

The photographer took photos at the site one to two times per week depending on their...
work schedule that week. If they went a second time in the week, the second day could not be the very next day to ensure that a sufficient quantity of material had been loaded out to expose a new face. During each site visit, photos were taken in the following manner:

- The photographer began at one end of the muckpile and photographed the bottom 25 – 30’ of the pile. This height limit was prescribed to increase the quality of the images. Material higher than this would be too far away to be clearly seen in the photo. It was assumed that material higher than this would fall down after additional loading and be captured in the next set of photos.

- After taking the first image, the photographer moved down the face of the pile and took a second photo so that there was a slight amount of overlap between the images. This was done to ensure that the entire face was captured. Overlap was minimized to ensure that large areas were not repeated in different photos. Using this system, an approximate panoramic view of the pile face could be stitched together among all the photos. Figure 3-7 illustrates this “panoramic” photo capturing system.

![Diagram of muckpile face with scale bar and field of vision](image)

Figure 3-7: “Panoramic” photo capturing system used to ensure the entirety of the face was captured.

Every photo taken contained a scale bar measuring 37”. This length was chosen because the loader operator at this site sorts out 36” and larger particles for secondary breakage before going to the primary crusher. The choice of a 37” rather than a 36” scale bar was one of convenience.
**Belt Scales**

In order to quantify the fines produced as a result of loading, hauling, dumping, and primary crushing, belt scales after the primary crusher were used to determine how much material was sent to the plant for processing and how much was sent to the base pile. The base pile is composed of material too fine to be processed and is treated as waste. In this research, all base material is considered downstream fines. Figure 3-8 illustrates the portion of the processing plant relevant to this research.

![Diagram of processing plant](image)

Figure 3-8: Schematic illustration of processing plant layout showing location of belt scales

The mine uses a screen deck to separate saleable material from base material. The saleable material goes to a surge pile, and the base material is treated as waste unless the mine receives orders for it. This deck is made of ten screens at two different sizes: 1 15/16” (1.94”) and 3/4” (0.75”). The deck configuration for each blast in this study was as follows:

- control: five screens at 1 15/16”; five at 3/4”,
- experiment A: three at 1 15/16”; seven at 3/4”, and
• experiment B: five at 1 15/16”; five at ¾”\textsuperscript{5}.

After the screen deck, each stream is belted to its respective path in the circuit, and these belts are equipped with scales to measure the amount of material on each one. These scales were used to measure the weight of material on each belt and determine if there is less base material after using the experimental charges.

**Ground Vibration and Airblast**

To capture ground vibration and airblast data, two far-field seismographs equipped with microphones were used. These seismographs were the standard ones used by the mine to monitor every shot that takes place on the property.

Both seismographs are Re:motes\textsuperscript{TM} manufactured and operated by GeoSonics/VibraTech out of the company’s office in Austin, TX. These devices are permanently installed in the ground and record ground vibration and airblast data from every shot. They then store each blast’s seismic event record on their memory before automatically uploading the event to VibraTech’s server. This allows the mine operator and VibraTech to see the shot’s seismic report only minutes after the blast occurs. Both seismographs operate under the specifications listed in Table 3-4.

\textsuperscript{5} Maintenance needs in the plant dictated a change in the screen deck in the middle of the experiment. By increasing the amount of ¾” screens, less material should be sent to the base pile. This is a confounding variable in the study, and its effect will be discussed further in Chapter 4.
These Re:motes™ measure peak particle velocity (PPV) in the transverse (T), longitudinal (L), and vertical (V) directions, as well as the airblast level in decibels (dB). The vibration and sound triggers were set at 0.02 in/sec and 132.7 dB, respectively. Using coordinates provided by VibraTech and Google Earth, the locations of the seismographs were plotted and are shown in Figure 3-8. Table 3-5 shows the distances each seismograph was away from the blast as reported in the shot reports for each blast.

<table>
<thead>
<tr>
<th>Seismic Resolution (in/sec)</th>
<th>0.0025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic Range (in/sec)</td>
<td>0 – 5.120</td>
</tr>
<tr>
<td>Frequency Range (Hz)</td>
<td>2 – 250</td>
</tr>
<tr>
<td>Seismic Sampling Rate (samples/sec/channel)</td>
<td>0 – 500</td>
</tr>
<tr>
<td>Seismic Accuracy</td>
<td>2% within 1 year of calibration</td>
</tr>
<tr>
<td>Sound Trigger (dB)</td>
<td>78 – 142</td>
</tr>
<tr>
<td>Sound Accuracy</td>
<td>10% within 1 year of calibration</td>
</tr>
</tbody>
</table>

Table 3-4: Re:mote™ seismograph specifications

![Test Bench](image)

Figure 3-9: Locations of fair-field seismographs used in this study
Data Analysis

Digital Image Analysis

In order to determine the PSD of a pile, the photos captured on-site were imported into WipFrag 3, an iOS application that takes imported photos and uses edge detection algorithms to determine the particle size distribution of the photographed muckpile. They were then segmented automatically by the app and then manually by the researchers, and finally analyzed to produce a PSD curve. After every image in a shot was analyzed, all of them were added to a single project folder to determine the PSD of the entire shot. For additional details of how digital image analysis was used, please see Appendix A.

All of the photos taken for each muckpile were sampled using systematic stratified sampling to eliminate any bias that may have been introduced during the photography of the pile. Additionally, due to the realities of active mining, it was not feasible to station someone in the pit.

---

6 Segmentation: the process by which every rock particle in the image is outlined, shown in WipFrag 3 as a blue outline; the blue outline is called the “net”

Table 3-5: The distance of each seismograph from each blast, in feet

<table>
<thead>
<tr>
<th>Blast</th>
<th>Location 1</th>
<th>Location 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3,414</td>
<td>4,060</td>
</tr>
<tr>
<td>Experiment A</td>
<td>3,519</td>
<td>4,129</td>
</tr>
<tr>
<td>Experiment B</td>
<td>3,064</td>
<td>3,738</td>
</tr>
</tbody>
</table>
for the duration of the loading process for time and safety reasons. Researchers were not able to
be on site collecting data every day during loading, and material could not be loaded out with a
researcher in the pit due to the proximity to moving equipment. Because of this, some portions of
the piles were not photographed. This will not affect the data collected because a sufficient
number of photos were captured to ensure that the PSD curve developed by the app would be
robust and representative.

The pile was divided into three strata: the first third, the second third, and the final third
of material. All the photos captured for a muckpile were divided into these strata depending on
how many tons of material remained on the ground at the time of their capture. Stratified
sampling techniques were then used to determine how many photos from each strata should be
included in the final sample, and then that number of photos were randomly selected from each
strata. Table 3-3 shows how many photos were taken and how many photos were sampled from
each strata for all three blasts.

Table 3-3: Number of photos analyzed for each blast7

<table>
<thead>
<tr>
<th>Sampling Strata</th>
<th>Control</th>
<th>Blast</th>
<th></th>
<th></th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photos Taken</td>
<td>Photos Used</td>
<td>Photos Taken</td>
<td>Photos Used</td>
<td>Photos Taken</td>
</tr>
<tr>
<td><strong>Strata 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginning of Loading</td>
<td>0</td>
<td>0</td>
<td>34</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>First Third of Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Strata 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle of Loading</td>
<td>83</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>Second Third of Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Strata 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of Loading</td>
<td>33</td>
<td>14</td>
<td>89</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Last Third of Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BLAST TOTAL</strong></td>
<td>116</td>
<td>91</td>
<td>123</td>
<td>95</td>
<td>64</td>
</tr>
</tbody>
</table>

---

7 Due to significant production delays, only 64 photos of experiment B were
taken. These were not sampled; every photo taken was used in the analysis.
Examples of individual photos and their corresponding PSD curves for the control, experiment A, and experiment B blasts can be found in Appendix B.

**Ground Vibration and Airblast**

The seismic event reports generated by each seismograph after having been triggered by a blast return the PPV in three (T, L, and V) directions, as well as the airblast level. While the airblast is simply reported as a number in decibels, the ground vibration PPV levels and frequencies are plotted on the OSM standard “z-curve” for measuring vibration levels. This plot is shown in Figure 3-10.

![Figure 3-10: OSM ground vibration Z-curve plot](image-url)
In addition to data provided by the seismographs, a fast-Fourier transform analysis from each seismograph was performed for all three shots. Lastly, using a magnification report, the extent to which humans would respond to the vibration levels was determined. These analyses were used to determine the frequency of the seismic waves resulting from the shots and how humans would react to them.

The following chapter presents the results obtained using these methods and discusses their implications. First, fragmentation results are covered for all three blasts, followed by a discussion comparing each of the blasts. Next, ground vibration and airblast results are shown and discussed.
Chapter 4

Results and Discussion

The results of the data analyses and their significance are presented in this chapter. As described in the first chapter of this thesis, the scope of this research was limited by the time and cost of acquiring data, and consequently, the results obtained in the geology of the study’s mine site do not necessarily transfer directly to mines in other geologic settings. Further, the inability to execute a statistically significant number of blasts precludes the use of statistical metrics.

Fragmentation

Figures 4-1 through 4-3 show the particle size distribution (PSD) curve for the control, experiment A, and experiment B, respectively. In Figure 4-4, all thee curves have been plotted on the same axes to facilitate comparison between the experiments. Figure 4-5 shows only the bottom 40% of material to shed additional detail on fines generation. Data points have been added that show the percent of material passing the screen deck, i.e. percent fines after loading, hauling, and primary crushing. All material sent to the base pile is considered downstream fines as previously explained in chapter 3. Table 4-1 tabulates the percent passing data for each of the three experiments. Finally, Table 4-2 shows the percentage of material by weight going to the production plant and to the base material pile.
Figure 4-1: The particle size distribution curve for the control blast
Figure 4-2: The particle size distribution curve for experiment A
Figure 4-3: The particle size distribution curve for experiment B

Experiment B
Experimental Pattern, Experimental Charge

D01 = 0.13 in
D20 = 1.34 in
D50 = 3.72 in
D80 = 12.17 in
D99 = 33.79 in

<table>
<thead>
<tr>
<th>Size (in)</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.00</td>
<td>99.29%</td>
</tr>
<tr>
<td>34.00</td>
<td>99.06%</td>
</tr>
<tr>
<td>32.00</td>
<td>98.47%</td>
</tr>
<tr>
<td>30.00</td>
<td>97.95%</td>
</tr>
<tr>
<td>28.00</td>
<td>97.64%</td>
</tr>
<tr>
<td>26.00</td>
<td>95.65%</td>
</tr>
<tr>
<td>24.00</td>
<td>94.87%</td>
</tr>
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<td>22.00</td>
<td>94.01%</td>
</tr>
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<td>20.00</td>
<td>92.35%</td>
</tr>
<tr>
<td>18.00</td>
<td>90.46%</td>
</tr>
<tr>
<td>16.00</td>
<td>86.99%</td>
</tr>
<tr>
<td>14.00</td>
<td>83.37%</td>
</tr>
<tr>
<td>12.00</td>
<td>79.68%</td>
</tr>
<tr>
<td>10.00</td>
<td>75.55%</td>
</tr>
<tr>
<td>8.00</td>
<td>70.29%</td>
</tr>
<tr>
<td>6.00</td>
<td>63.18%</td>
</tr>
<tr>
<td>4.00</td>
<td>52.77%</td>
</tr>
<tr>
<td>2.00</td>
<td>32.98%</td>
</tr>
<tr>
<td>1.94</td>
<td>32.04%</td>
</tr>
<tr>
<td>0.75</td>
<td>8.13%</td>
</tr>
</tbody>
</table>
Figure 4-4: The particle size distribution curves for all three blasts plotted on the same axes.
Figure 4-5: Comparison of fines generation in muckpile and after loading, hauling, and primary crushing
Research personnel were unavailable to collect downstream fines data during experiment B.

**Table 4-1:** Cumulative percent passing fragmentation data for control, experiment A, and experiment B

<table>
<thead>
<tr>
<th>Size (in)</th>
<th>Control</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>97.79%</td>
<td>99.14%</td>
<td>99.29%</td>
</tr>
<tr>
<td>34</td>
<td>97.60%</td>
<td>98.82%</td>
<td>99.06%</td>
</tr>
<tr>
<td>32</td>
<td>96.65%</td>
<td>98.53%</td>
<td>98.46%</td>
</tr>
<tr>
<td>30</td>
<td>95.83%</td>
<td>97.83%</td>
<td>97.94%</td>
</tr>
<tr>
<td>28</td>
<td>94.56%</td>
<td>97.39%</td>
<td>97.64%</td>
</tr>
<tr>
<td>26</td>
<td>93.82%</td>
<td>96.62%</td>
<td>95.65%</td>
</tr>
<tr>
<td>24</td>
<td>92.43%</td>
<td>95.50%</td>
<td>94.87%</td>
</tr>
<tr>
<td>22</td>
<td>91.05%</td>
<td>94.47%</td>
<td>94.01%</td>
</tr>
<tr>
<td>20</td>
<td>89.37%</td>
<td>92.62%</td>
<td>92.35%</td>
</tr>
<tr>
<td>18</td>
<td>87.46%</td>
<td>91.06%</td>
<td>90.46%</td>
</tr>
<tr>
<td>16</td>
<td>84.62%</td>
<td>89.04%</td>
<td>86.99%</td>
</tr>
<tr>
<td>14</td>
<td>81.34%</td>
<td>86.24%</td>
<td>83.37%</td>
</tr>
<tr>
<td>12</td>
<td>77.50%</td>
<td>82.14%</td>
<td>79.68%</td>
</tr>
<tr>
<td>10</td>
<td>73.22%</td>
<td>77.41%</td>
<td>75.55%</td>
</tr>
<tr>
<td>8</td>
<td>67.64%</td>
<td>71.46%</td>
<td>70.29%</td>
</tr>
<tr>
<td>6</td>
<td>59.80%</td>
<td>63.05%</td>
<td>63.18%</td>
</tr>
<tr>
<td>4</td>
<td>48.47%</td>
<td>51.84%</td>
<td>52.77%</td>
</tr>
<tr>
<td>2</td>
<td>26.85%</td>
<td>31.17%</td>
<td>32.98%</td>
</tr>
<tr>
<td>1.94</td>
<td>25.95%</td>
<td>30.09%</td>
<td>32.04%</td>
</tr>
<tr>
<td>0.75</td>
<td>5.80%</td>
<td>5.74%</td>
<td>8.13%</td>
</tr>
</tbody>
</table>

**Table 4-2:** Downstream fines generation measured by weight of material going to base pile and surge pile

<table>
<thead>
<tr>
<th>BLAST</th>
<th>Control</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>37.84%</td>
<td>37.60%</td>
<td>N/A</td>
</tr>
<tr>
<td>SURGE</td>
<td>62.16%</td>
<td>62.40%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

---

8 Research personnel were unavailable to collect downstream fines data during experiment B.
Control and Experiment A

In Figure 4-4, it is seen that experiment A resulted in slightly more material passing at every size except ¾”. Table 4-3 compares the control and experiment A particle size distributions and calculates the difference between the blasts at all sizes. A positive difference indicates that more material passed, i.e. the experiment A muckpile was finer, at that size. Conversely, a negative difference indicates that less material passed, i.e. the experiment A muckpile was coarser, at that size.

Table 4-3: A comparison of control and experiment A particle size distributions calculating the difference between them

<table>
<thead>
<tr>
<th>Size (in)</th>
<th>Control</th>
<th>Experiment A</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>97.79%</td>
<td>99.14%</td>
<td>1.35%</td>
</tr>
<tr>
<td>34</td>
<td>97.60%</td>
<td>98.82%</td>
<td>1.22%</td>
</tr>
<tr>
<td>32</td>
<td>96.65%</td>
<td>98.53%</td>
<td>1.88%</td>
</tr>
<tr>
<td>30</td>
<td>95.83%</td>
<td>97.83%</td>
<td>2.00%</td>
</tr>
<tr>
<td>28</td>
<td>94.56%</td>
<td>97.39%</td>
<td>2.83%</td>
</tr>
<tr>
<td>26</td>
<td>93.82%</td>
<td>96.62%</td>
<td>2.80%</td>
</tr>
<tr>
<td>24</td>
<td>92.43%</td>
<td>95.50%</td>
<td>3.07%</td>
</tr>
<tr>
<td>22</td>
<td>91.05%</td>
<td>94.47%</td>
<td>3.42%</td>
</tr>
<tr>
<td>20</td>
<td>89.37%</td>
<td>92.62%</td>
<td>3.25%</td>
</tr>
<tr>
<td>18</td>
<td>87.46%</td>
<td>91.06%</td>
<td>3.60%</td>
</tr>
<tr>
<td>16</td>
<td>84.62%</td>
<td>89.04%</td>
<td>4.42%</td>
</tr>
<tr>
<td>14</td>
<td>81.34%</td>
<td>86.24%</td>
<td>4.90%</td>
</tr>
<tr>
<td>12</td>
<td>77.50%</td>
<td>82.14%</td>
<td>4.64%</td>
</tr>
<tr>
<td>10</td>
<td>73.22%</td>
<td>77.41%</td>
<td>4.19%</td>
</tr>
<tr>
<td>8</td>
<td>67.64%</td>
<td>71.46%</td>
<td>3.82%</td>
</tr>
<tr>
<td>6</td>
<td>59.80%</td>
<td>63.05%</td>
<td>3.25%</td>
</tr>
<tr>
<td>4</td>
<td>48.47%</td>
<td>51.84%</td>
<td>3.37%</td>
</tr>
<tr>
<td>2</td>
<td>26.85%</td>
<td>31.17%</td>
<td>4.32%</td>
</tr>
<tr>
<td>1.94</td>
<td>25.95%</td>
<td>30.09%</td>
<td>4.14%</td>
</tr>
<tr>
<td>0.75</td>
<td>5.80%</td>
<td>5.74%</td>
<td>-0.06%</td>
</tr>
</tbody>
</table>
From Table 4-3, it appears that the air-decked charge had the biggest impact on -24+10” particles. Air-decking had the least effect on particles coarser than 24”. At ¼”, experiment A resulted in less material passing by 0.06%. This indicates that the air-decked blast produced 0.06% fewer fines than the control; however, this change is so small it could be considered negligible. At 36”, experiment A increased the percent of material passing by 1.35%, which means the amount of material requiring secondary breakage decreased by 1.35% as well. Additional research would be required to determine if these reductions in fines and oversize are statistically significant, and time studies and financial analyses would be necessary to determine the full benefits of the explosive column design used in experiment A.

The literature is inconsistent regarding whether air-decks would produce finer or coarser fragmentation in a muckpile compared to a full-column charge. Work by Melnikov and Marchenko reports that using air-decks increases fragmentation, while Moxon et al. concludes the opposite (Melnikov & Marchenko, 1971; Moxon et al., 1991). The results of these two blasts compare favorably with the results reported by Melnikov and Marchenko, but more trials should be conducted to definitively determine the answer.

Through belt scale measurements, it was determined that 37.84% of material passed the screen deck in the control muckpile, while only 37.60% passed the screen deck in the experiment A muckpile. These values are remarkably similar; however, the changes to the screen deck arrangement make these values difficult to compare directly. The screen deck has a maximum aperture size of 1.94” as previously explained in chapter 3. In Figure 4-5 and Table 4-3, it can be seen that more material passed 1.94” in experiment A than in the control. Despite the experiment A muckpile containing more particles passing 1.94” than the control muckpile, experiment A resulted in less material passing 1.94” at the screen deck. This indicates that using a mid-column air-deck did reduce downstream fines generation in loading, hauling, and primary crushing operations.
Changes in the PSD between the control blast and experiment A were small; however, experiment A used 30% less explosive than the control. It should be noted that this represents a considerable cost savings despite a lack of significant PSD changes.

**Control and Experiment B**

Table 4-4 compares the control particle size distribution with that of experiment B. A positive difference indicates that more material passed at that size in experiment B than in the control, while a negative difference indicates that less material passed at that size.

**Table 4-4**: A comparison of control and experiment B particle size distributions calculating the difference between them

<table>
<thead>
<tr>
<th>Size (in)</th>
<th>Control</th>
<th>Experiment B</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>97.79%</td>
<td>99.29%</td>
<td>1.50%</td>
</tr>
<tr>
<td>34</td>
<td>97.60%</td>
<td>99.06%</td>
<td>1.46%</td>
</tr>
<tr>
<td>32</td>
<td>96.65%</td>
<td>98.46%</td>
<td>1.81%</td>
</tr>
<tr>
<td>30</td>
<td>95.83%</td>
<td>97.94%</td>
<td>2.11%</td>
</tr>
<tr>
<td>28</td>
<td>94.56%</td>
<td>97.64%</td>
<td>3.08%</td>
</tr>
<tr>
<td>26</td>
<td>93.82%</td>
<td>95.65%</td>
<td>1.83%</td>
</tr>
<tr>
<td>24</td>
<td>92.43%</td>
<td>94.87%</td>
<td>2.44%</td>
</tr>
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<td>91.05%</td>
<td>94.01%</td>
<td>2.96%</td>
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<td>89.37%</td>
<td>92.35%</td>
<td>2.98%</td>
</tr>
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<td>18</td>
<td>87.46%</td>
<td>90.46%</td>
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</tr>
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<td>16</td>
<td>84.62%</td>
<td>86.99%</td>
<td>2.37%</td>
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<td>14</td>
<td>81.34%</td>
<td>83.37%</td>
<td>2.03%</td>
</tr>
<tr>
<td>12</td>
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<td>79.68%</td>
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<td>73.22%</td>
<td>75.55%</td>
<td>2.33%</td>
</tr>
<tr>
<td>8</td>
<td>67.64%</td>
<td>70.29%</td>
<td>2.65%</td>
</tr>
<tr>
<td>6</td>
<td>59.80%</td>
<td>63.18%</td>
<td>3.38%</td>
</tr>
<tr>
<td>4</td>
<td>48.47%</td>
<td>52.77%</td>
<td>4.30%</td>
</tr>
<tr>
<td>2</td>
<td>26.85%</td>
<td>32.98%</td>
<td>6.13%</td>
</tr>
<tr>
<td>1.94</td>
<td>25.95%</td>
<td>32.04%</td>
<td>6.09%</td>
</tr>
<tr>
<td>0.75</td>
<td>5.80%</td>
<td>8.13%</td>
<td>2.33%</td>
</tr>
</tbody>
</table>
Percent oversize (+36”) in experiment B was reduced by 1.50%, while percent fines (-3/4”) was increased by 2.33%. More material passed at every size in experiment B than in the control blast. Experiment B resulted in the largest increase in percent passing at any size in all three blasts. At 2”, experiment B increased the percent of material passing by 6.13%.

The PSD curve of experiment B indicates that percent oversize was reduced in this blast, while percent fines was increased. This is different than experiment A, which resulted in a reduction in both +36” and -3/4” material. Experiments A and B used the same charge design but with two different blast patterns. Experiment A was fired with the mine’s standard 28’ burden, while experiment B used a 24’ burden. These results indicate that reducing the burden when using mid-column air-decks does not reduce fines generation during a blast.

The literature is inconsistent regarding the effect of burden on fines generation. Multiple authors report a direct relationship between fines generation and burden (Adhikari, Barman, & Singh, 1990; Bhandari, Bhandari, & Arya, 2004; Hagan, 1979). As burden increases, energy and gases released during detonation become more confined, resulting in more breakage in the rock mass. It makes sense then that the opposite would be true as well; as burden decreases, there is less confinement, which would reduce fines. Nine years after Bhandari’s original paper in which he described a direct relationship between burden and fines generation, he describes the opposite in a new paper. In this more recent, he cites personal correspondence with Ouchterlony, who conducted an F-test to determine that burden has a statistically significant inverse relationship with fines generation. (Bhandari, 2013). The data in this research more closely aligns with Ouchterlony’s results than those of the authors previously mentioned in this paragraph. Blasting with reduced burden could yield several benefits, including but not limited to improve throw and muckpile profile and reduced ground vibration. Additional research would be required to determine if any benefits of reduced burden were realized in this mine site, and if they warranted increased fines generation.
Ground Vibration and Airblast

Ground vibration and airblast data were recorded at two different locations by far-field Re:mote™ seismographs as explained in Chapter 3. The results for all three experiments at each of these two locations are presented in the remainder of this chapter.

Location 1

Table 4-5 summarizes the ground vibration and airblast data for the control, experiment A, and experiment B at Location 1. Following this, Figures 4-6 through 4-8 compare the velocity waveforms between the control blast and experiment A, and Figures 4-9 through 4-11 compare those waveforms for the control with experiment B.

Table 4-5: Ground vibration and airblast data at Location 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Experiment A</th>
<th>Experiment B</th>
<th>Trendline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle Velocity (m/s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>0.0275</td>
<td>0.033</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.0875</td>
<td>0.053</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.0150</td>
<td>0.02</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>22.7</td>
<td>27.8</td>
<td>27.8</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>22.7</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>15.6</td>
<td>17.9</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td><strong>Airblast (dB)</strong></td>
<td>101.7</td>
<td>104</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4-6: Transverse velocity waveform comparison (top: control; bottom: experiment A)

Figure 4-7: Longitudinal velocity waveform comparison (top: control; bottom: experiment A)

Figure 4-8: Vertical velocity waveform comparison (top: control; bottom: experiment A)

Figure 4-9: Transverse velocity waveform comparison (top: control; bottom: experiment B)
The longitudinal vibration at this location was the highest of the three directions, which is to be expected. The seismographs are oriented so that the longitudinal direction of the geophone is oriented towards the blast, and in all three shots, the hole firing sequence progressed directly along this axis. The downward trend in PPV level in this direction is as expected as well. The control blast used the mine’s standard charge weight per delay. Experiment A used 30% less charge per delay and resulted in 39.4% reduction in longitudinal PPV. Experiment B used the same charge per delay as experiment A, but with lighter burden, energy was allowed to travel more easily through the free face as opposed to into the in-situ rock. Vibration in the transverse direction increased from the control to experiment A, but then decreased to a level lower than the control blast in experiment B. Vertical ground vibration increased from the control to experiment A, and then increased again from experiment A to experiment B. Despite ground vibration increases in the vertical direction, the peak particle velocity remained the same in the control,
experiment A, and experiment B blasts. The mid-column air-deck charge reduced the PPV by 39.4% compared to the control, and using the same air-deck with less burden reduced PPV by 60% compared to the control.

Humans are able to feel ground vibration levels as low as 0.02 in/s (Stiehr, 2011). To illustrate the effect of small changes in PPV, a magnification report was developed to measure the difference in human response levels between the control and experiments A and B. At Location 1, humans inside a structure would have felt a 0.523 in/sec seismic wave during the control blast. During experiment A, humans inside a structure at Location 1 would have felt a 0.265 in/sec seismic wave. This is a 49.3% reduction from the control blast to experiment A. In experiment B, humans inside a structure would have felt a 0.175 in/sec seismic wave, which is 66.5% less than the control blast.

In Figures 4-12 through 4-14, the standard Z-curve plots are shown. It can be seen immediately that all three blasts fall below the compliance threshold. These plots confirm the data presented in Figures 4-6 through 4-11; in each of the blasts, the highest ground vibration levels were in the longitudinal direction, followed by the transverse and then vertical directions.
Figure 4-12: The Z-curve of the control blast

Figure 4-13: The Z-curve of experiment A
In Figures 4-14 through 4-17, FFT analyses comparing the control blast to experiment A are presented. In each of the graphs, red indicates the control and black indicates the experiment.

**Figure 4-14**: The Z-curve of experiment B

**Figure 4-15**: A comparison of transverse FFT for the control blast and experiment A (red: control; black: experiment A)
Figure 4-16: A comparison of longitudinal FFT for the control blast and experiment A (red: control; black: experiment A)

Figure 4-17: A comparison of vertical FFT for the control blast and experiment A (red: control; black: experiment A)
In the transverse and longitudinal directions, experiment A resulted in a slightly higher frequency than the control. The frequencies in both of these directions was over 20 Hz, and this is much higher than the racking response resonant frequency of residential structures, 3 -12 Hz, but falls within the resonant frequency range of midwall response, 12 - 25 Hz (Siskind, Stagg, Kopp, & Dowding, 1989). In the vertical direction of experiment A; however, the result of the FFT showed that the frequency was reduced to 7 Hz. This is not similar to the vertical frequency measured by the seismograph (17.9 Hz). Additionally, this is the only data point in which the FFT resulted in the experimental blast having a lower frequency than the control blast.

The FFT analyses for the waveforms recorded in experiment B are shown in Figures 4-18 through 4-20. The comparison between the control and experiment B is similar to that which was observed in the comparison between the control and experiment A.

Figure 4-18: A comparison of transverse FFT for the control blast and experiment B (red: control; black: experiment B)
Figure 4-19: A comparison of longitudinal FFT for the control blast and experiment B (red: control; black: experiment B)

Figure 4-20: A comparison of vertical FFT for the control blast and experiment B (red: control; black: experiment B)
In all three directions, experiment B resulted in slightly higher frequencies than the control blast, all of which fall above the resonant frequency range of residential structures. These results indicate that the significant frequency reduction shown in Figure 4-16 may be an anomaly, which would require further investigation.

The airblast level from each blast increased from the previous one. From the control blast to experiment A, airblast increased from 101.7 dB to 104 dB. In experiment B, the airblast was 105 dB. It takes a change of approximately 3 dB for humans to begin to notice elevated levels, making the increases seen in these trials inconsequential.

**Location 2**

Table 4-6 shows the ground vibration and airblast data for the three blasts at Location 2. However, at this location, the vibration levels from experiment A and B shots were too low to trigger the seismograph, and accordingly, there are no Z-curves or FFT plots for these shots. The velocity waveform and Z-curve for the control blast is shown in Figures 4-21 and 4-22.

Table 4-6: Ground vibration and airblast data at Location 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
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<td>Particle Velocity (in/s)</td>
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<td></td>
<td></td>
</tr>
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<td>T</td>
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<td>NO TRIGGER</td>
</tr>
<tr>
<td>L</td>
<td>0.0200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.0175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
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<td></td>
<td></td>
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<tr>
<td>L</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>19.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airblast (dB)</td>
<td>96.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

9 The correct operation of the seismograph was verified based on blasts in other locations of the quarry. This indicates that vibration levels were not high enough to trigger the seismograph during experiments A and B.
In this chapter, the data collected during research was analyzed and the hypotheses proposed in chapter 1 were evaluated. In the next chapter, key findings will be drawn from these results that can be used as guidance in future research.

Figure 4-21: The velocity and sound waveforms for the control blast

Figure 4-22: The Z-curve of the control blast
Chapter 5
Conclusions and Recommendations

Due to the limitations on the scope of this research, definitive and generalizable conclusions regarding the combination of electronic detonators and air-decking cannot be drawn. However, this project does provide positive insight regarding the hypotheses and further, the experiences of this research can guide future studies. Conclusions regarding the methods used to quantify fragmentation and ground vibration data can be made.

Findings

This research yielded positive insights regarding each of the four hypotheses introduced in Chapter 1. Despite the lack of sufficient tests to draw statistically significant conclusions, these findings provide insight on the practice of combining air-decks and electronic detonators and these insights can be used in the future to design a more comprehensive experimental program. The findings of this research are summarized here for each hypothesis.

- Hypothesis: Air-decked shots will generate less fines than those without air-decks due to reduced crushing around the borehole.

The results of the experiments did not support this hypothesis. The particle size distributions for both experiment A and B were finer than the control in almost all sizes measured; the exception is the ¾” size class in experiment A, which was actually 0.06% coarser than the control. The differences between the control and experimental blast PSD curves were too small to definitively say that mid-column air-decks and electronic detonators will reduce fines generation during blasting. What this does show, however, is that 30% reductions in explosive use without significant changes in PSD can be realized,
which represents a substantial explosive costs savings for the operation. Given the potential of significant savings, future testing with mid-column air-decks and electronic detonators should look to optimize an air-deck length that would produce a coarser muckpile and further reduce explosive costs.

- **Hypothesis:** The microfracture network in air-decked shots will be less intense than in shots without air-decks, which will make particles more resistant to fines generation during downstream handling and primary crushing.

  The results of this research show that reducing downstream fines generation can be achieved through the use air-decks and electronic detonators. From the control blast to experiment A, the weight of fines after primary crushing of the material from experiment A were reduced by over 4% as compared to the material from the control. If similar fines reductions were realized throughout subsequent processing stages, operations could significantly reduce fines and their associated costs while increasing the quantity of saleable material. Downstream fines generation was only measured after loading, hauling, and primary crushing in this research. Given that additional fines are generated throughout the entire processing circuit, it would be necessary to measure the fines at each stage of the downstream processing to quantify completely the amount of fines reduction attributable to the blasting practice.

- **Hypothesis:** Air-decks will allow for increased energy utilization; therefore, more energy will be available to fracture boulders.

  The percent passing 36” in both experiments A and B was very similar, and both showed a slight decrease in oversize material as compared to the control. Secondary breakage is known to be dangerous and costly, and any reductions would be beneficial to the operation. In experiment B, the entire PSD curve was finer than the control, but in experiment A, percent passing 36” was increased while percent passing ¾” was
decreased. Experiment A was also the most uniform of the three blasts fired. This suggests that it may be possible to optimize the size and position of the air-deck, as well as shot timing, to increase uniformity even further.

- **Hypothesis:** Due to energy redistribution, less explosive energy will be converted into seismic energy; therefore, peak particle velocity will be reduced as a result of air-decking.

Both air-decked blasts resulted in dramatically lowered PPV levels, albeit with slight increases in airblast levels. This indicates that electronic detonators and air-decking could have a much bigger impact on ground vibration that fragmentation. At Location 1, humans inside a structure would have felt 49.3% lower vibrations in experiment A compared to the control blast, and in experiment B, humans would have felt a 66.5% lower vibration compared to the control blast. This technique could be regularly applied in mines with geology or other conditions sensitive to vibration or those prone to ground vibration violations. In addition, this research did not test the effect of using short delay times or of using multi-row blasts. In optimally timed blasts fired with electronic detonators, seismic wave interaction could occur, which would further reduce PPV levels.

**Summary of Key Findings**

The results of this research cannot be generalized across the industry as explained previously. Even the results from this mine must be interpreted cautiously due to the limited number of trials. Nonetheless, there are noteworthy findings that may be used to guide current practices and future research.

1. Overall, the muckpile PSD was finer when using mid-column air-decks as compared to full-column explosive charges.
2. The percent fines and oversize in the muckpile were practically unchanged by the air-decked charge.

3. The generation of downstream fines were reduced by using an air-decked charge.

4. The peak particle velocity, i.e. ground vibration, was significantly reduced by the combined use of air-decks and electronic detonators.

5. The frequency of the ground vibration increased slightly with the use of air-decks.

6. Similar particle size distributions can be achieved with only 70% of the original explosive weight.

7. The use of mid-column air-decks has a greater effect on ground vibration than fragmentation.

**Recommendations for Future Research**

The foregoing list of key findings also details topics that merit additional research to determine the extent to which they can be generalized. It is suggested that special consideration should be given to the following topical areas.

**Downstream Fines Generation**

The material split data from the control blast and experiment A indicate that reducing fines associated with material handling and crushing could be feasible. This represents an opportunity for future research to definitively determine if this holds true over a large number of samples and sites. Downstream fines generation was only measured after loading, hauling, and primary crushing in this research, but as described earlier, a more complete understanding would require measurement after each processing stage.
Inter-Hole Delay Timing

Each of the blasts fired in this pilot study used 40 ms delays between all of the holes, but the true power of electronic delays is unlocked at delay intervals on the order of 2 – 3 ms. At such short intervals, stress waves from adjacent holes would be allowed to interact, which could result in destructive interference and reduce PPV levels even more than what was seen in these trials.

To study the effect of short delay intervals in air-decked shots, the shear wave velocity of the rock at the test site would need to be determined. Then, the optimal inter-hole delay time that would allow for maximum wave interaction within the air-decks and between the holes could be calculated.

Multi-Row Blasts

The blasts fired in this study were based on the single-row production pattern at the host mine site. Single-row patterns do not allow for wave interaction between adjacent rows of blastholes. The use of an optimal inter-row delay time in a multi-row pattern could result in destructive interference that would minimize PPV even more than at standard delay intervals. Signature row analysis should be used to calculate this inter-row delay time, and then trials should be conducted at this delay to determine the effect on ground vibration levels.

This research identified comparative advantages of combining electronic detonators with air-decking in this geologic setting. It is recognized that the findings presented are specific to the geologic conditions of the mine site in this study. The findings of this study should facilitate future research to further quantify the general benefits of this blasting practice.
References

https://doi.org/10.1016/0167-9031(90)90333-N


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https://doi.org/10.1016/S1365-1609(03)00018-2


Have 10Mm Aggregate With No Fines? *14th Extractive Industry Geology Conference*, 37–44.


Appendix A

Digital Image Analysis Process

First, a new photo is imported into the app and an “analysis card” is created. The app’s user interface and an example of an imported analysis card is shown in Figure A-1. The “3” in the top right corner of the analysis card indicates how many steps remain in the analysis. The steps are:

1) Indicate the image scale.
2) Generate the net.
3) Create the PSD curve.

![Analysis Card]

Figure A-1: The user interface of WipFrag 3

1) Indicate the image scale

The analysis card is then opened to analyze the image associated with that card. The scale of the image is then assigned using the scale tool in the app. Figure A-2 illustrates an open analysis card with both the scale tool and the scale labelled. In this image, the scale is 37” long.
2) Generate the net

After the scale is defined, the image is automatically segmented by the app. This done by adjusting a slider that controls the level of automatic delineation. The farther to the right the slider is positioned, the more intense the automatic segmentation will be. In this research, the level of automatic segmentation was set so that the small- to mid-size particles would be outlined well, while the larger particles would be subjected to disintegration errors\textsuperscript{10}. This was done because disintegration errors are much easier to manually correct than fusion errors\textsuperscript{11}. Figure A-3 shows the automatic segmentation controls with the slider labeled, and Figure A-4 illustrates an image after automatic segmentation is complete.

\textsuperscript{10} Disintegration error: an automatic segmentation error that occurs when one large particle is treated as several smaller particles; corrected by drawing an outline around the large particle and erasing the interior boundaries; see Figure A-5

\textsuperscript{11} Fusion error: an automatic segmentation error that occurs when several smaller particles are treated as one large particle; corrected by individually outlining each separate particle in the error; see Figure A-6
Once automatic segmentation is complete, the researchers manually edited the net for five minutes. During this time, errors to the automatic net were corrected, mine floor, sky, and highwall areas were hidden if necessary, and fines were manually identified. After five minutes, the researchers received an alert from the app, allowing them to stop editing once the alert was given. An example of a net that has been manually edited is shown in Figure A-7.

Figure A-3: Using the automatic segmentation tool
Figure A-4: A photograph after automatic segmentation is completed

Figure A-5: An example of a disintegration error (single particle outlined in red)
Figure A-6: An example of a fusion error (two smaller particles outlined separately in red)

Figure A-7: An example of a completed net
3) Create the PSD curve

After the net is edited, the image is ready for PSD analysis. The software reads the net to determine the sizes of each individual particle delineated, and then returns a PSD curve for that image. This curve is shown in Figure A-8. The figure shows a plot in which the vertical axis measures the cumulative percent passing a corresponding size on the x-axis. To the right of the graph, the data table from which the curve was generated can be seen. Once this graph has been calculated for each image, the PSD of the entire pile can be determined.

Figure A-8: The completed PSD curve for the example analysis

Finally, all analysis cards from the same pile were added to one single project folder. In doing so, the data from each individual image was combined into a single PSD data set used to
estimate the size distribution of the blasted muckpile as a whole. This is known as the “aggregated curve.” One aggregated curve is displayed in Figure A-9, where it can be seen that 50 individual analysis cards have been merged into one folder to create this particular curve.

Figure A-9: The aggregated curve for the example analysis project
Appendix B

WipFrag 3 Example Photos

Control Blast

Figure B-1: Control blast example analysis 1
Figure B-2: Control blast example analysis 2
Figure B-3: Control blast example analysis 3.
Figure B-4: Control blast example analysis 4
Figure B-5: Control blast example analysis 5
Control Blast
Example Photo 6

March 26, 2019 15:42:02

3.3.16.0 - Penn State - EME Department (WipFrag OS)

D01 = 0.16 in
D20 = 1.37 in
D50 = 5.47 in
D80 = 16.62 in
D99 = 23.79 in

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Figure B-6: Control blast example analysis 6
Figure B-7: Control blast example analysis 7
Figure B-8: Control blast example analysis 8
Figure B-9: Control blast example analysis 9
Figure B-10: Control blast example analysis 10
Figure B-11: Experiment A example analysis 1
Figure B-12: Experiment A example analysis 2
Figure B-13: Experiment A example analysis 3.
Figure B-14: Experiment A example analysis 4
Figure B-15: Experiment A example analysis 5
Figure B-16: Experiment A example analysis 6
Figure B-17: Experiment A example analysis 7
Figure B-18: Experiment A example analysis 8
Figure B-19: Experiment A example analysis 9
Figure B-20: Experiment A example analysis 10
Figure B-21: Experiment B example analysis 1
Figure B-22: Experiment B example analysis 2
Figure B-23: Experiment B example analysis 3
Figure B-24: Experiment B example analysis 4
Figure B-25: Experiment B example analysis 5
Figure B-26: Experiment B example analysis 6