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Abstract
Over time, limestone quarries have developed means and methods to plan mining operations in order to meet material quality requirements and at the same time maximize quarry life. These methods employ the use of analytical information obtained from sampled materials from both pre-quarry investigatory drill surveys and production drilling. This paper reviews a new technique for obtaining elemental analysis results from production drill cuttings.

Introduction

Problem Statement
Many limestone quarries are heterogeneous, requiring the quarry manager to decide which material goes to the plant and which material goes to waste or other uses. Sometimes the quarry has to blend material from several faces to meet stockpile quality requirements. Frequently, blasted material must be moved quickly to permit the reconfiguring of haul roads and the opening of new areas for exploitation. All of these decisions require that the quarry manager has reliable knowledge of rock quality of every open face in the quarry.

Sending off-specification material to the plant can damage the kiln and produce bad clinker. Sending good quality materials to the waste dump cuts the quarry life and wastes the money spent in blasting, loading, and hauling of on-specification material that is not used for making cement.

Drill surveys performed to map a reserve prior to opening a quarry are not adequate for day-to-day operation of a limestone quarry because the drill-hole patterns are too widely spaced for sufficient resolution to meet the quarry manager’s operational needs. Currently, quarry managers rely on blast-hole cuttings sampled in the quarry and sent to the plant laboratory for analysis. The analysis is sent back to the quarry office to be used in decisions for reclamation activity. This process is usually slow and relatively inaccurate for optimal quarry management. The result is that important decisions are made either without data or with unreliable data. Incorrect quarry decisions based on inaccurate or inadequate data can lead to off-specification clinker, in the worst case, or high fuel cost and various kiln problems in the best case.

The inaccuracy of blast-hole analysis is primarily the result of sampling variance due to the procedures employed for sample collection. In addition, laboratory costs can be high for sites that sample most or all of the blast-holes.

Solution
Real time blast-hole analysis would provide the quarry manager with the data he needs at the earliest possible time. Additionally, analysis of all of the drill cuttings would significantly reduce sampling variance which accounts for the majority of the inaccuracy of blast-hole analyses by existing methods.

A new product has been developed for the online analysis of drill cuttings from quarry blast holes. This new instrument mounts on a drill rig and measures the elemental composition of the entire stream of drill cuttings in real time. Important features of the instrument include the following:

• mounts on existing blast hole drilling machines
• operates automatically with no additional manpower required
• requires minimal drill operator interaction
• does not impede drilling production
• transmits elemental analysis directly to the quarry office
• correlates real-time analysis with drill depth

Benefits
Real time blast-hole analysis produces many cost savings, efficiencies, and quality benefits:
• Reduced hauling costs (eliminates unnecessary trips to the dump)
• Increased quarry efficiency (Decisions related to material transport can confidently be made prior to blasting. This provides increased flexibility to blend materials into the crusher.)
• Extended quarry life (enables better decisions relative to the use of quarried material)
• Eliminated instances of material re-handling
• Increased homogeneity of the stockpile, resulting in more consistent kiln operation and reduced fuel costs.
• Significantly reduced laboratory labor costs

Yearly savings could range from $25k to $300k per year depending on the complexity of the quarry and current demand on the laboratory for the analysis of quarry samples.

Technology

Laser Induced Breakdown Spectroscopy (LIBS) Principles
The LIBS analysis technology uses a low-energy laser pulse to produce small plasma in a stream of air, dust, and rock chips. The plasma, which looks much like a spark-plug spark, reaches temperatures in excess of 20,000 degrees, and consists of free electrons and ions of the elements in the air and rock.

On initial formation, the plasma emits a blue-white glow from the free electrons, but as it begins to cool, the electrons recombine with the ions, and the atoms emit characteristic spectral emissions. Most of these emissions are in the ultraviolet-to-near infrared range (200-900nm), with many in the range of visible light (420-780nm). The specific wavelengths in the emitted light qualitatively indicate which elements are present in the plasma, while the intensity of the spectral emissions quantitatively indicates the concentration of each element.

Current State-of-the-Art
The first use of breakdown spectroscopy was recorded by J. Norman Lockyer of the London Mint in 1873. Lockyer used Spark Induced Breakdown Spectroscopy, SIBS, which is commonly used today for analysis of conductive materials.

XIV. On the Quantitative Analysis of certain Alloys by means of the Spectroscope.

Received November 20,—Read November 27, 1873.

Figure 1: Citation for the first use of breakdown spectroscopy

Lockyer’s instrument consisted of a carbon arc, lenses, prisms, and photographic plates. The development of laser technology led to LIBS. In recent years, lasers and spectrometers, two of the key components of any LIBS instrument, have developed rapidly. They have been employed in diverse rugged environments, including the battlefield and space exploration. Their reliability and robustness have enabled the development of commercial LIBS instruments for use outside of the laboratory. These rugged instruments do not have the same capabilities as the modern laboratory versions, but have adequate capabilities to become the basis of a LIBS field instrument.
**Instrument Description**

**Overall Description**

The product employs several diverse technologies which have been developed into a modular system that comprise the instrument as a whole. Refer to Figure 2: Instrument Block Diagram for an overview of the modular nature of the system.

The instrument functions by first collecting cuttings from the drilling process and then passing those cuttings in front of a laser where a plasma is induced. Electro-optical components then collect photons from the plasma and process them to generate an energy spectrum. Software algorithms analyze the spectrum and generate a measurement of the material composition. The modular components of the system include:

- Chip and Dust Collection Mechanism
- Optical Module
- Control Module
- Data Input Module
- Analysis Module

The Chip & Dust Collector, C&DC, is a mechanical and hydraulic subsystem that collects the material exiting the blast-hole and conducts it through the analytical portion of the analyzer and into a cyclone which deposits the cuttings on the ground. The hydraulic component of the C&DC raises and lowers the Extraction Hood for tramming and drilling.

The analytical subsystem consists of the Optical Module, OM, and the Control Module, CM. The OM houses the optics block, laser, and spectrometers. The CM provides power to all subsystems and contains the processor that controls the instrument, including radio transmission of data. These components are mounted very compactly using rigid construction to prevent temperature and vibration from affecting the optical path. Because of issues related to material transport, the OM must be located between the Extraction hood and the cyclone. The CM can be located at any convenient location on the drill.

The Data Input Module is a rugged industrial tablet computer located in the drill rig cab that provides the opportunity for the operator to assign identifiers to the blast-holes. It also alerts the operator if the system is not functioning properly. Blast-hole information, tagged to the oxide analysis is then transmitted via radio modem to the quarry office.
The Analysis Module is located in the quarry office and is the graphical user interface that enables the quarry manager to interpret and manipulate blast-hole data. The analysis module also contains the spectral analysis algorithms that interpret the data generated by the Optical Module.

**LIBS Implementation**
In order to make the instrument rugged and compact, the laser and optical components are mounted on the analysis tube, parallel to the material stream. The optics assembly focuses the laser beam into the material stream to create plasma from the passing material. The optics assembly captures light from the decaying plasma which is sent to spectrometers via fiber optics. One important development of this instrument is a unique shutter and purging technique which keeps the optics clean under all operating conditions. This allows for long-term reliable and accurate measurements.

**Homogenizer**
Since plasma is formed from only a small portion of the material, it is important that on average this material be representative of the entire stream. This is accomplished in two ways. First, plasma is created many times a second and the spectra from each plasma event are analyzed. Second, a homogenizer is placed in the analysis tube to counter segregation that occurs during material transport. The homogenizer is intended to present material to the plasma zone in the same particle size distribution that exists in the material as a whole.

**Data Communications**
Telemetry of data from the drill rig to the quarry office is accomplished using a wireless communications network. A specialized wireless communications package developed for online analyzer instruments is employed by the blast-hole analyzer. This wireless product consists of a modular array of hardware and software components able to be configured to create a secure local area network. The choices of hardware components from a list of compatible equipment include omnidirectional and highly directional antennae, solar powered and AC powered repeaters, Ethernet or WiFi connections to computers in the network, and more. The wireless network software components enable network users to select data from standard databases and configure it for graphical display on small devices such as PDAs and notebook computers that may be used in mobile equipment such as loaders and trucks. The blast hole analyzer employs the wireless network as a stand-alone LAN requiring no software component.

**Software**
Software used in conjunction with the instrument resides in three separate computers:
- Control Module
- Data Input Module
- Analysis Module

**Control Module**
An embedded computer within the Control Module collects data from several sensors, packages this information into blast-hole files, and then transfers these blast-hole files, using FTP (File Transfer Protocol), to the Analysis Module computer in the quarry office. The embedded computer uses Web
Services both to provide diagnostic information and to also allow remote computers to configure and control the embedded computer. This is a significant benefit that enables service engineers to perform remote maintenance and repair on the equipment.

**Data Input Module**
A tablet computer, utilizing a touch screen, is used by the drill operator. This computer allows the drill operator to create, collect, and close blast holes. Before a blast hole is drilled the operator will first “create” a new blast hole and then set the software into its blast-hole collection mode. Using auto incrementing of blast-hole numbers, this operation may only require two taps on the touch screen. After the blast hole is fully drilled, the operator then “closes” the blast-hole. During each of these collection modes the overall status of the instrument is presented to the drill operator.

**Analysis Module**
The Analysis Module computer will usually reside in the quarry manager’s office. This computer will be linked to the Control Module computer using a wireless network. All completed blast-hole files will be transferred automatically to the Analysis Module computer. This computer will then generate blast-hole analyses from the blast-hole files and store these analyses to an SQL database. The Analysis Module provides a graphical interface that enables the quarry manager to view and manipulate blast-hole data. A web server on the computer is used to present the data stored in the SQL database, allowing any computer on the same network access to the blast-hole analysis.

![Figure 3: Instrument installed on an exploratory drill rig (Trident, MT)](image)

**Product Performance**

**Test Results**
Field testing was carried out at Holcim’s Poverty Point quarry outside of Salt Lake City, UT. The quarry is generally mined for high-grade limestone and contains relatively little alkali or magnesium inclusion. Drilling was conducted in an area being prepared for production mining, using one or two 3.7m (12’) steels to reach the desired blast-hole depth. In total, 44 steels were analyzed.
To generate comparison data, cuttings from each steel were collected separately. A particulate chain separator was used to collect the coarse chips from the air stream and the rig dust collector was used to collect the fines. The dust collector was back-blown after each steel to minimize cross contamination between steels. Each physical sample was then reduced, divided and prepared for XRF analysis.

Spectra were accumulated every 3 seconds and composited into a single data set for each steel. Data from the 44 steels was then used to generate a field calibration for the instrument. The results are summarized in Table 1. The coefficients of determination \( (r^2) \) for the dry basis weight percents range from 0.69 (MgO) to 0.96 (K\textsubscript{2}O). The t-statistic for the regression coefficients for the various oxide rations ranges from 4 (Na\textsubscript{2}O) to 14 (K\textsubscript{2}O) with a \( t_{\text{critical}} \) of 2.31 for 95% confidence. The statistical conclusion is that the applied calibrations are significant to within the 95% confidence limit.

<table>
<thead>
<tr>
<th>Oxide/QC</th>
<th>Range (Dry Basis wt%)</th>
<th>Accuracy (RMSD)</th>
<th>( R^2 )</th>
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</thead>
<tbody>
<tr>
<td>SiO\textsubscript{2}</td>
<td>17.1 - 27.1</td>
<td>0.80</td>
<td>0.93</td>
</tr>
<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>0.4 - 1.3</td>
<td>0.12</td>
<td>0.85</td>
</tr>
<tr>
<td>Fe\textsubscript{2}O\textsubscript{3}</td>
<td>0.5 – 0.9</td>
<td>0.03</td>
<td>0.93</td>
</tr>
<tr>
<td>CaO</td>
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<td>0.56</td>
<td>0.94</td>
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<tr>
<td>MgO</td>
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<td>0.26</td>
<td>0.79</td>
</tr>
<tr>
<td>Na\textsubscript{2}O</td>
<td>0.0 – 0.10</td>
<td>0.02</td>
<td>0.69</td>
</tr>
<tr>
<td>K\textsubscript{2}O</td>
<td>0.0 – 0.3</td>
<td>0.02</td>
<td>0.96</td>
</tr>
<tr>
<td>LSF</td>
<td>48.4 – 92.1</td>
<td>3.28</td>
<td>0.95</td>
</tr>
</tbody>
</table>

**Table 1: Field Accuracy**

**Product Requirements**
The instrument requires a 24V power connection to the drill rig battery (there is no power draw when the system is off), and a supply of air from the compressor. Also required are ignition and drilling signals, and physical space to mount the various instrument modules.

**Conclusion**
The implementation of the LIBS analysis technique into an instrument for the online measurement of blast hole drill cuttings has proven to be viable and a commercially available product will soon be introduced. Information provided by such an instrument should provide a multitude of cost savings, efficiencies and quality benefits for the enhanced management of limestone quarries.