5-22-2006

# Performance and Total PM Emission Factor Evaluation of Expendable Abrasives

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## Recommended Citation

Kambham, Kalpalatha, "Performance and Total PM Emission Factor Evaluation of Expendable Abrasives" (2006). *University of New Orleans Theses and Dissertations*. 385.
https://scholarworks.uno.edu/td/385

# PERFORMANCE AND TOTAL PM EMISSION FACTOR EVALUATION OF EXPENDABLE ABRASIVES

A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Engineering and Applied Science

by

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B.S., S.V.University College of Engineering, 1999
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May 2006

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, Dr. Bhaskar Kura from the Department of Civil and Environmental Engineering, whose advice, support, and encouragement have provided me with an invaluable source of motivation over the last five years.

I am grateful to Dr. Donald E. Barbé, Dr. Gianna M. Cothren, Dr. William H. Busch, and Dr. Matthew Tarr for serving on my Ph.D. Examining Committee and providing me with further assistance. I am also grateful to Dr. Tumulesh Solanky from the Department of Mathematics for his advice on statistical analysis.

I would like to thank my friends Sivaramakrishnan Sangameswaran, Xavier Silvadasan and Babruvahan Hottangada, without whose help my research work would not have been successful.

I would especially like to thank my parents, whose love and great support was indispensable, and who have provided me with lifetime motivation and inspiration. I would also like to thank my sister and brother for their boundless love and encouragement. I would like to dedicate this work to my family.

My greatest appreciation goes to my beloved husband Sunil Battepati, for his encouragement and support over the last years.

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# Abstract

Dry abrasive blasting is one of the most widely used methods of surface preparation. Air emissions from this process include particulate matter (PM) and metals. Spent abrasive generated from this process may be hazardous in nature. With increasing concern on health effects due to silica emissions from sand, use of alternative materials is suggested by health and regulatory agencies.

The objective of this research was to evaluate performance of expendable abrasives and determine PM emission factors. Dry abrasive blasting was performed in an enclosed chamber and total PM samples were collected. Three commonly used expendable abrasives, coal slag, copper slag and specialty sand, were used to evaluate cleaner alternatives. Blast pressure and abrasive feed rate, two important process conditions were varied to study their effect on performance of an abrasive. Productivity, consumption and emission factors (performance parameters) were calculated and their variation with pressure and feed rate was evaluated. Two dimensional and three dimensional predicted models were developed to estimate the performance at intermediate blast pressure and feed rate conditions. Performance of the three abrasives was compared with respect to emission potential, productivity and consumption.

Emission factors developed in this research will help in accurate estimation of total PM emissions and to select cleaner abrasives and optimum process conditions that will results in minimum emissions and reduced health risk.

The productivity and consumption models will help is estimating life cycle costs including material cost, equipment cost, energy cost, labor costs, waste disposal cost, and compliance costs. Consumption models will also help in determining the quantity of spent abrasive generated, identify abrasives with lower material consumption, and identify process conditions that generate minimum spent abrasives. In addition, these models will help industries in making environmentally preferable purchasing (EPP), which results in pollution prevention and cost reduction.

# 1. Introduction

Dry abrasive blasting is one of the widely used methods of surface preparation for steel or metal surfaces. This process is used to create a rough profile and to remove contaminants such as rust or old coating before applying a new coating to ensure proper bonding between the surface and coating. Several industries such as aerospace, automobile, bridge construction, metal finishing, shipbuilding and ship repair use dry abrasive blasting for preparation and maintenance of steel or other metal surfaces (U.S. ACE 1995, U.S. EPA 1997a). In this process, abrasive materials are propelled at high velocities with the aid of compressed air. The energy transfer between the abrasive grains and base plate results in removal of contaminants and creation of rough profile (U.S. ACE 1995).

Some of the commonly used abrasives are coal slag, copper slag, garnet, silica sand, specular hematite (barshot), steel grit, steel shot, aluminum oxide, silicon carbide etc. (U.S. EPA, 1997a). Dry abrasive blasting process results in air emissions (particulate matter and metals) and spent blast media which may be harmful to human health and environment (U.S. EPA 1997b). Silica sand has been widely used as an abrasive material due to its low cost and abundant occurrence in nature. However, silica dust emissions from abrasive blasting with silica sand have been of great concern due to adverse health effects on workers upon exposure to these emissions. Thus, use of alternative materials to silica sand is suggested by several health organizations and environmental agencies (NIOSH 1998, Abrasive Blasting, 1995) to protect worker health as well as the environment.

In addition, owing to the environmental impacts of the process and waste management challenges faced for safe disposal of the wastes, United States Environmental Protection Agency (US EPA) encourages industries, businesses, and institutions to make environmentally preferable purchasing (EPP), which means considering the environmental impacts (air and water pollution, toxic wastes), energy-efficient technologies and material performance prior to purchasing materials. This will result in resource conservation, waste minimization, minimization of energy consumption, and extension of landfill capacity. In addition, costs incurred due to material purchase, energy consumption, waste management and disposal can be reduced by EPP (U.S. EPA 1994, U.S. EPA 2001).

In order to address and achieve the above mentioned objectives, namely, protect worker health, environment and make EPP, it is important to evaluate waste generation potential (air emissions and spent abrasive) and performance of alternate abrasive materials as well as understand the effect of various parameters that affect performance and waste generation potential. Performance of abrasive in dry abrasive blasting depends on properties of abrasive material (size, shape, hardness, and chemical composition), blast pressure, abrasive feed rate, nozzle size, base plate (substrate), surface contamination, quality of desired finish and others (U.S. ACE 1995). While some abrasives can be reused in abrasive blasting, others can not be reused due to their properties such as hardness and dust generation rate. These materials are called expendable or non-reusable abrasives. The goal of this research was to evaluate performance of expendable abrasives to identify cleaner alternatives and process conditions that will result in pollution prevention and cost reduction.

# 2. Scope and Objectives

Existing literature provides limited data on performance, process conditions and test procedures adopted for evaluating the performance of alternative materials for dry abrasive blasting. This research was focused on evaluating performance of three of the most commonly used expendable (single use) abrasive materials, namely coal slag, copper slag and specialty sand, on painted mild steel surfaces.

The primary objectives of this research were:

**Objective 1:** The first objective of this research was to determine emission factors for total particulate matter (TPM). Emission factors help in quantifying the emissions released from a process and these are important input parameters in developing emission inventories.

**Objective 2:** The second objective of this research was to determine productivity. Productivity (or cleaning rate) determines how fast the surface can be cleaned (area cleaned per unit time). The higher the productivity, the faster the cleaning rate and less consumption of energy. Higher productivity also results in reduced labor and energy costs.

**Objective 3:** The third objective of this research was to determine consumption. Consumption is the amount of material used to clean a unit area. Lower consumption results in better conservation of resources, reduced amounts of wastes generated and efficient use of landfills for waste disposal. In addition, lower consumption results in reduced material costs, waste management and disposal costs.

**Objective 4:** The fourth objective of this research was to identify optimum process conditions (blast pressure and abrasive feed rate) to minimize total PM emissions and abrasive consumption, and maximize productivity. Since the performance of an abrasive depends of process conditions, it is important to study the variation of performance with process conditions to achieve maximum efficiency through process optimization.

**Objective 5:** The fifth objective of this study was to develop predictive mathematical models to estimate total PM emission factors, productivity and consumption at intermediate operating conditions for a specific abrasive material. These models will help industries and regulatory agencies in determining accurate TPM emissions and assist in life cycle cost and assessment methodologies with more accurate data on productivity and consumption.

**Objective 6:** The sixth objective of this research was to compare the three abrasives based on emission factors, productivity and consumption.

# 3. Literature Review

## *3.1. Dry Abrasive Blasting*

Surface preparation methods are used to remove impurities such as rust, corrosion, and old coatings from a substrate and create a rough profile (or anchor pattern) that will help better adhesion of new coating as well as improve the performance of new coating. Some of the most commonly used methods are dry abrasive blasting, wet abrasive blasting, hydro blasting (water blasting), chemical stripping, and vacuum blasting. Dry abrasive blasting is one of most effective and widely used methods of surface preparation. In this method, an abrasive material is mixed with compressed air and this mixture is projected onto the surface. The pressurized air (compressed air) imparts high velocities to the abrasive particles. The mass of abrasive particles and high velocity imparted by the compressed air create kinetic energy, which is given by $\frac{1}{2} mV^2$, where m is the mass and V is the velocity of the abrasive material. The energy transfer between the abrasive material and the surface is responsible for removing the contaminants and creating the required profile (U.S. ACE 1995, U.S. EPA 1997a). The equipment used in this process is discussed in the Methodology Section.

## *3.2. Pollutant Outputs and Their Effects on Health and Environment*

### *3.2.1. Air Emissions*

The abrasive particles, when bombarding the surface at high velocities, remove the contaminants and breakdown into smaller particles. This process releases particulate matter (PM) that includes blast material as well as contaminants removed (U.S. ACE 1995, U.S. EPA 1997a, NIOSH 1998). These particles vary in size and may contain metals such as arsenic, cadmium, chromium (trivalent and hexavalent), lead, manganese, nickel, and titanium (NIOSH 1998, NSRP 1999, Vallyathan *et al* 1999, Conroy *et al* 1996, MacKay *et al* 1980). Particulate emissions are of great concern due to the health effects, visibility impairment, ecosystem imbalance and aesthetic damage. Fine particulates can be carried over long distances and settle on ground or water. This may make lakes and streams acidic, change nutrient balance is coastal waters, and deplete nutrients in soil. Inhalation of particulate matter causes respiratory problems, asthma, chronic bronchitis, and decreased lung function (U.S. EPA, Dockery *et al* 1993, Oberdorster 1995, Pope *et al* 1995). Recent studies (Wilson *et al* 1985, Daigle *et al* 2003, U.S. EPA, 2004a, U.S. EPA, 2004b, Voutilainen *et al* 2004) on health effects of PM show that fine (PM less than 2.5 μm in diameter) and ultrafine particles (PM less than 0.1 μm in diameter) have significantly greater effects on respiratory systems and lung functions because finer particles are absorbed into the respiratory system and lungs as compared with coarser particles. Moreover, ultrafine particles deposited in lungs release toxic compounds (associated with PM) faster than fine and coarse particles. The emissions may be toxic due to heavy metals present in airborne particulates and exposure to these emissions may cause adverse health effects (specific) (Hubbs *et al* 2001, Vallyathan *et al* 1999, Conroy *et al* 1996, MacKay *et al* 1980, NIOSH 2001). Most importantly, exposure to silica dust emitted from sandblasting, abrasive blasting with silica sand, causes silicosis (NIOSH 1974, Lipton and Herring 1996, Rappaport *et al* 2003).

### 3.2.2. Solid/ Hazardous Waste

While lighter particles get airborne, heavier particles fall off and this waste (spent abrasive) contains both abrasive materials and contaminants removed such as rust or paint chips. The waste may be toxic if the abrasive material or surface contamination contains heavy metals such as arsenic, lead, chromium, and others (NFESC 1996, Townsend 1997, NAVFAC 1998, Angie and Wayne 1999). In case of removal of coatings that contain lead or antifouling agents, the waste generated may be hazardous (U.S. EPA 1997b). The spent abrasive media may be recycled or reused for blasting operations or other purposes if the material is clean enough and meets the regulatory requirements for recycling and reusing options. If the spent abrasive cannot be recycled or reused, it must be disposed of as a solid or hazardous waste in landfills depending on the toxic characteristics of the waste, which are determined by Toxicity Characteristic Leaching Procedure (TCLP) tests (Townsend 1997, NFESC 1996, Angie and Wayne 1999).

## *3.3. Important Parameters in Dry Abrasive Blasting*

### *3.3.1. Abrasive Material*

Proper selection of abrasive material is essential to achieve maximum efficiency in dry abrasive blasting. Some of the important parameters are: abrasive cost, abrasive type, characteristics of the material, surface to be cleaned, contaminants to removed, level of contamination, surface finish desired (cleanliness and profile), waste generation potential, consumption rate, reusability, and others. Significance of some of these parameters is discussed in this section.

#### *3.3.1.1. Abrasive type*

Abrasive materials are generally categorized into slag abrasives, metallic abrasives, natural abrasives, and synthetic abrasives. The slag abrasives are by-products from smelting and combustion processes. Coal slag, copper slag, and nickel slag are some of the most widely used slag abrasives. These abrasives have high breakdown rates and thus, slag abrasives are generally not reused. Due to their dark color, these materials may leave dark residue on the blasted surface. Metallic abrasives such as steel grit, steel shot, and cast iron are manufactured abrasives. These abrasives are hard and can be reused many times. Natural abrasives include silicates (sand, garnet, olivine), hematite and others. The abrasive properties of these naturally occurring materials are enhanced by washing and grading the material. Synthetic abrasives include aluminum oxides, aluminum silicates, calcium silicate, crushed glass, glass beads, and others. The performance of these abrasives depends on the surface type and contamination to be removed (U.S. EPA 1997a, Paddison 2000, Hansink 2000)

#### *3.3.1.2. Abrasive particle size*

Particle size of abrasive material is an important factor in selection of abrasives. The size of abrasive particles varies widely between 0.06 to 2 mm. Too fine or coarse particles may not be effective in removing contamination and creating the desired profile. While larger particles cut deep into the surface and create deep surface profile, smaller particles create shallow profiles. In addition, if the particle size is too high, a smaller number of particles impact the surface which increases material consumption and decreases productivity as compared to smaller particles that result in greater number of impacts per unit surface area. Since abrasive particles breakdown into smaller particles upon striking the surface, too fine abrasive materials may release very fine PM, which is of great concern due to associated health effects. While a mixed size of particles may result in better performance, particle size is important when selecting reusable or expendable (single use) abrasives. In case of reusable abrasives, it is important to select an abrasive particle size which results in efficient size of reusable abrasive material after breaking down into smaller particles (U.S. ACE 1995, Paddison 2000, Hansink 2000).

#### *3.3.1.3. Abrasive particle shape*

The shape of abrasive particles is important in determining the surface profile required. While angular particles cut the surface, round particles peen the surface. Thus, round particles such as steel shot and glass beads are effective for removing mill scale and angular particles such as steel grit, slags, and other metallic grits are effective for creating a rough profile (U.S. ACE 1995, Hansink 2000).

#### *3.3.1.4. Hardness*

Hardness of an abrasive material indicates its resistance to abrasion by other materials. Hardness of abrasives is measured on Mohs scale of hardness. Metallic and slag abrasives have higher hardness (6 – 8 Mohs) and cut deeper and faster than soft or brittle abrasives such as organic or plastic abrasive media (2 – 4 Mohs) reducing their cleaning efficiency (U.S. ACE 1995, Paddison 2000, Hansink 2000).

#### *3.3.1.5. Specific gravity*

As mentioned earlier in Section 3.1, the kinetic energy of the abrasive particles is given by ½ $mV^2$. Mass of abrasive material, m, is proportional to specific gravity (SG) of the abrasive particles. Abrasives with higher SG are more efficient and clean faster, which increase productivity (Paddison 2000, Hansink 2000).

#### *3.3.1.6. Density*

Density of abrasive material is important in selecting the size of blast pot and storing the abrasive material. Since lower density abrasives occupy more volume for the same mass, bigger blast pot and greater storage area are needed as compared to abrasives with higher density, which occupy less volume and need smaller blast pots and storage areas (Hansink 2000).

### *3.3.2. Process Parameters and Equipment*

#### *3.3.2.1. Blast pressure*

Blast pressure determines the velocity of abrasive particles and hence kinetic energy acquired by the particles. Thus, increase in pressure increases the kinetic energy of particles and hence the impact on a surface. This results in higher productivity. However, at very high pressures, the particles may suffer more damage due to collision of these particles with rebounding particles before striking the surface and reduce productivity, increase consumption, and results in higher emissions. In addition, blasters may not be able to handle these high pressures and must be provided with additional protection. At very low pressures, the velocity of particles is less and the particles may not strike the surface with sufficient impact to remove contaminants and create required profile. This will result in decreased productivity and increased consumption since more material is required to clean a unit surface area. Very low pressures may also result in fewer emissions due to less breakdown rate at lower velocities (Clemco Industries 1989, Hansink 1995, Holt and Austin 2001, Paddison 2000, Seavey 1985). Thus, it is important to select an optimum pressure that results in high productivity, low consumption, and low emissions while providing a safe working environment for workers.

#### *3.3.2.2. Abrasive feed rate*

Feed rate determines the mass flow rate of abrasive. Very low feed rates may result in uneven distribution of particles and decrease productivity while consuming more material. As the feed rate is increased, more abrasive is released which increases productivity and more number of abrasive particles breakdown, causing increase in emissions. However, at very high feed rates, the same effect may not be observed because abrasive particles collide with rebounding particles and decrease productivity while consuming more material. An increase in emissions may occur at very high feed rates due to more number of particles participating in the abrading action (Clemco Industries 1989, Hansink 1995, Paddison 2000). Thus, it is important to regulate the flow of material to achieve maximum efficiency from a given mass of abrasive while reducing emissions.

#### ***3.3.2.3. Nozzle size***

Nozzle sizes used in abrasive blasting typically range from 1/8 inch to 1/2 inch orifice diameter. While larger nozzles may increase productivity by increasing the number of impacts per unit time by allowing more abrasive to flow through the nozzle, smaller nozzles may also increase productivity due to increase in blast pressure. However, for the same volume of air, larger nozzles require high capacity compressors to provide required blast pressure to achieve higher productivity (U.S. ACE 1995, Gorripati 2000). Thus, selecting the proper size of nozzle is important in maintaining required blast pressure and determining the capacity of air compressor.

#### ***3.3.2.4. Nozzle type***

Venturi and straight-bore nozzles are two types of nozzles used in abrasive blasting process. Venturi nozzles converge to specified orifice diameter at the center of the nozzle and then diverge. This enables an increase of exit velocity of abrasive particles and thus increases the productivity. Straight-bore nozzles have uniform diameter throughout the length of the nozzle. Thus, venturi nozzles provide higher cleaning rate as compared to straight-bore nozzles. Blast nozzles are available in various lengths, diameters and lining materials. The life of a nozzle depends on the lining materials. Nozzles lined with tungsten or boron carbides have longer life than the nozzles lined with ceramic or cast iron (U.S. ACE 1995, Gorripati 2000).

#### ***3.3.2.5. Angle of deflection***

Angle of deflection or angle of attack is the angle of the nozzle with respect to the work piece or surface being blasted. This parameter depends on the surface contamination being removed and varies between 45 to 90 degrees. While for removing rust and mill scale, angle of deflection may vary from 80 to 90 degrees whereas for removing old coatings, it may vary from

45 to 60 degrees (U.S. ACE 1995). In some cases, nozzles held at an angle of greater or lesser than 90 degrees may scour the surface (Gorripati 2000).

#### *3.3.2.6. Stand-off distance*

Stand-off distance is the distance between the nozzle and the work piece or surface. This may vary from 6 to 24 inches (15 to 60 cm). The closer the distance, the smaller the blast pattern. In case of removing mill scale or heavy levels of contamination, a lesser stand-off distance creates greater impact and increases cleaning power. However, this may reduce productivity due to decreased blast pattern. For removing smaller levels of contamination, this distance may be increased to increase the blast pattern and thus achieve higher productivity. Hence, optimum stand-off distance is important since it affects the blast pattern, productivity and impact of the abrasive material (U.S. ACE 1995, Gorripati 2000).

#### *3.3.2.7. Dwell time*

Dwell time is the amount of time spent cleaning a particular area on the surface to achieve required cleanliness and profile. For removing lightly adhered contaminants or smaller levels of contamination, shorter periods will achieve the desired finish. When removing tightly adhered contaminants or greater levels of contamination, it may take longer time to clean the surface. In addition, if the nozzle is held close to the surface, lesser dwell time is required as compared to when nozzle is held far from the surface. Thus, angle of deflection and stand-off distance also affect dwell time (Gorripati 2000, Technology Publishing Company 1999).

### *3.3.3. Initial Surface Contamination*

Performance of an abrasive also depends on the type of contamination to be removed. For heavy levels of contamination, it may take longer time and consume more material to clean a unit surface area. This will decrease productivity, increase consumption and waste quantities generated. The type of contamination being removed such as rust, mill scale or paint determines the toxic characteristics of the emissions and spent abrasive generated. In the case of removing lead-based paints, resulting wastes may be toxic due to the presence of lead.

In addition, depending on the properties of abrasive such as particle size, shape and hardness, a particular abrasive may be more effective in removing rust while another abrasive may be more effective in removing paint. Thus, it is important to determine level and composition of the contaminants being removed to achieve maximum efficiency from an abrasive material and the dry abrasive blasting process.

### *3.3.4. Desired Surface Finish*

Proper adhesion of new coating is important to its life and effectiveness. Thus, the surface must be free of underlying dust and contamination. In addition, surface roughness or profile is important for the new coating to adhere to the surface since it provides more surface area for adhesion. For commercial steel structures, the Society of Protective Coatings provides surface preparation standards in terms of quality of the finish. For example, SP-5 refers to a white metal blasting, which involves removal of all visible rust, mill scale, paint and contaminants, leaving the metal uniformly white or gray in appearance. SP-6 refers to a commercial blast cleaning. According to this standard, all oil, grease, dirt, rust scale, old paint and foreign matter must be completely removed from the surface except for slight shadows, streaks or discolorations caused by rust stain, mill scale oxides, or slight, tight resides of paint or coating that remain. SP-10 refers to brush-off blast finish. This standard requires removal of all oil, grease, dirt, mill scale, rust, corrosion products, paint, or other foreign matter, except for very light shadows, very slight streaks or slight discolorations caused by rust stain, mill scale oxides, or slight residues of paint or coating. At least 95% of each square inch of surface area shall be free of all visible residues (SSPC). The higher the quality of surface finish, the higher abrasive consumption will be, air emissions, quantity of spent abrasive, and the lower productivity will be since more material and time are consumed to clean a unit surface area. Thus, desired surface finish or degree of cleaning is an important factor that must be considered while selecting an abrasive material, process conditions and evaluating performance of abrasive materials.

### *3.3.5. Waste Generation Potential*

Waste generation potential of an abrasive is important to evaluate health, safety and environmental impact of the material as well as environmental compliance and waste disposal costs in dry abrasive blasting. This depends on a number of factors including breakdown rate, dust generation rate, and chemical composition. Abrasives with smaller particle size and brittle properties generate more dust since they breakdown easily into very fine particles. In addition, composition of the abrasive material such as metals, free silica content and other toxic chemicals is important to assess the toxicity of both air emissions and spent abrasives. With increasing concern on health effects due to silica emissions, abrasives with less free silica content (<1%) must be used to protect worker health. Abrasive materials with less potential for waste generation and decreased health risk due to exposure to toxic emissions, reduce the quantities and concentrations of hazardous waste generated. Industries can reduce the costs incurred due to environmental compliance and waste disposal (U.S. ACE 1995, NIOSH 1998, Appleman *et al.* 1998).

### *3.3.6. Reusability*

Based on the reusability of abrasives, they can be categorized into reusable and non-reusable or expendable abrasives. Abrasive properties such as particle size, hardness and breakdown rate determine reusability of an abrasive. If the particle size of abrasive material is too low or if the breakdown rate abrasive is too high, the spent abrasive generated may be too fine to create the desired surface finish. And abrasives with high breakdown rates generate significant amounts of dust, decrease productivity and increase abrasive consumption. Slag abrasives such as coal slag and copper slag generate high dust and breakdown easily. Thus, the materials are not reused. Harder abrasives such as steel grit and garnet may be reused for a number of times based on their particle size and breakdown rate (U.S. ACE 1995, Paddison 2000, Hansink 2000). While non-reusable abrasives are cheaper than reusable abrasives, overall costs incurred due to reuse of abrasives and cost of recycling the spent abrasive for reuse must be considered while selecting an abrasive.

## *3.4. Regulations*

### *3.4.1. Federal Regulations*

#### *3.4.1.1. Clean Air Act (CAA)*

The Clean Air Act and the Clean Air Act Amendments (CAAA) of 1990 are intended to protect and enhance the nation's air resources, promote public health, and protect the environment. Ambient air quality is regulated by the National Ambient Air Quality Standards (NAAQS), established for six criteria pollutants: carbon monoxide, lead, nitrogen dioxide, ozone, PM, and sulfur dioxide (U.S. EPA 2004). Of the six criteria pollutants, particulates and lead (in case of lead-based paints) can be generated during dry abrasive blasting. Particulate matter (PM) is a mixture of solid and liquid particles suspended in air. PM may be directly emitted from industrial processes and motor vehicles. PM may also be formed in atmosphere due to chemical reaction of pollutants from these sources.

The size and composition of PM varies widely and particulates less than 10 micrometers in diameter ($PM_{10}$) cause serious health effects. Larger particles cause irritation to eyes, nose, and throat (U.S. EPA, 2003). Exposure to PM has been associated with various health effects including asthma, chronic bronchitis, premature death, decreased lung function, and severe respiratory problems (U.S. EPA 2003, Pope *et al.* 1995, Atkinson *et al.* 2001, Schwartz 2004, Dockery *et al.* 1993). Thus, in order to regulate these PM concentrations, NAAQS established new standards for $PM_{10}$, $PM_{2.5}$. Two types of standards, primary standards and secondary standards are developed to protect public health, and to prevent environmental damage respectively. Current NAAQS for $PM_{10}$, $PM_{2.5}$, and lead are shown in Table 1.

Table 1: NAAQS for PM10 and PM2.5

| Pollutant | Primary Standard | Secondary Standard | Averaging Time |
|---|---|---|---|
| $PM_{10}$ | 50 $\mu g/m^3$ | Same as Primary | Annual |
| | 150 $\mu g/m^3$ | | 24-hour |
| $PM_{2.5}$ | 15.0 $\mu g/m^3$ | Same as Primary | Annual |
| | 65 $\mu g/m^3$ | | 24-hour |
| Lead (Pb) | 1.5 $\mu g/m^3$ | Same as Primary | Quarterly |

In addition, EPA initiated “Particulate Matter Research Program” to understand the relationships between sources, exposure mechanisms and health effects of PM (U.S. EPA 2004). EPA and state environmental regulatory agencies are required to maintain and implement these standards. If ambient air concentrations exceed the NAAQS, regulatory agencies may impose stringent emission limits for industrial sources. Emission factors developed in this research will greatly help in determining the PM emission quantities and the effect of an abrasive blasting source on ambient air can be studied by atmospheric dispersion modeling. By carefully selecting an abrasive and process conditions, PM emissions can be reduced thereby attaining the emission limits and NAAQS.

#### *3.4.1.2. Resource Conservation and Recovery Act (RCRA)*

Resource Conservation and Recovery Act regulates the waste generated from industrial processes. Based on the characteristics of the waste, it is categorized as solid waste or hazardous waste. Removal of coating may result in hazardous waste based on composition of the coating. In case of hazardous waste, waste must be properly contained and disposed of to comply with the generator, transporter, treatment, storage, and disposal (TSD) regulations. Facilities that generate at least 100 kilograms of hazardous waste per month must comply with the hazardous waste generator requirements according to 40 CFR Part 262 (PCRC, U.S. EPA, 1997b). Some of sources of hazardous waste in dry abrasive blasting are toxic metals and blast media contaminated with paint chips. Based on the consumption of abrasive materials, industries will be able to estimate the quantities of spent abrasives and hazard wastes generated. With proper selection of materials and process conditions, waste generation and costs incurred due to waste management can be minimized.

#### *3.4.1.3. Clean Water Act (CWA)*

Clean Water Act regulates discharges of wastewater streams containing heavy metals, toxic organics, and conventional pollutants. If the wastewater is discharged into rivers, lakes or oceans, the facilities must comply with effluent limits according to National Pollutant Discharge Elimination System (NPDES). Facilities that discharge wastewater streams into Publicly Owned Treatment Works (POTW) must meet the effluent limits in their POTW agreements. Blast media and residue from coating removal may contaminate waster streams or during clean up operations. Some of the regulated pollutants such as lead, cadmium, zinc, total suspended particles may be present in the wastewater generated from dry abrasive blasting. Facilities must periodically monitor the wastewater to demonstrate compliance with the regulations. In case of exceeding the effluent limits, facilities must treat the wastewater prior to final discharge (PCRC, Shipbuilding Sector Notebook). Material substitution and process optimization will help in minimizing both quantities and characteristics of wastewater generated and storm water contamination during abrasive blasting.

#### *3.4.1.3. Occupational Safety and Health Administration (OSHA)*

In order to protect worker health from exposure to PM, silica dust, lead and other toxic emissions, the Occupational Safety and Health Administration regulates health hazards due to abrasive blasting. Abrasives with higher free silica content generate silica dust, which is associated with acute silicosis, bronchitis, and lung cancer. OSHA enforces permissible exposure limits (PEL) to reduce exposure of workers to respirable silica emissions. OSHA also suggests using abrasives with less free silica contents. Other health hazards regulated by OSHA include metal emissions, noise, and mechanical hazards during abrasive blasting. Abrasive blasting at very high pressures may cause severe damage to workers limbs. Proper personal protective equipment, engineering controls, worker training, and periodic medical examinations must be employed to comply with the OSHA regulations (PCRS, NIOSH 1998). Emission potential of an abrasive material can be determined by emission factors. Selecting a material with less emission potential will reduce the emissions as well as exposure of workers to hazardous emissions. In addition, selecting process condition to achieve maximum productivity will reduce the exposure time and health risk associated with longer exposure time.

### *3.4.2. State Regulations and Guidelines*

Due to significant hazards from silica-based abrasives and enormous amounts of dust generated during abrasive blasting, many state agencies restrict the use of silica sand for outdoor blasting and suggest using alternative materials to reduce silica emissions and their health effects on workers and public. Regulations and guidelines by some of the state environmental agencies are discussed in this section.

#### ***3.4.2.1. Bay Area Air Quality Management District (BAAQMD)***

BAAQMD protects public health environment in San Francisco Bay region. BAAQMD provides permit requirements, and performance standards for facilities that carry out abrasive blasting operations (BAAQMD 1990, BAAQMD 1998). Abrasive materials used for unconfined blasting operations must comply with particle size standards. According to these standards, before blasting "*Before blasting, the abrasive shall not contain more than 1% by weight material passing a #70 U.S. Standard sieve when tested in accordance with "Method of Test for Abrasive Media Evaluation," Test Method No. California 371-A. Certified abrasives re-used for dry unconfined blasting must conform with Section 12-4-305.1*". In order to control size of PM emissions after blasting, "*the abrasive shall not contain more than 1.8% by weight material five micron or smaller when tested in accordance with "Method of Test for Abrasive Media Evaluation", Test Method No. California 371-A. Certified abrasives re-used for dry unconfined blasting are exempt from Section 12-4-305.2*". All abrasive materials used for unconfined blasting must be certified by California Air Resources Board (CARB). Confined blasting shall be used for all abrasive blasting operations except when (a) using steel grit, steel shot, iron grit or iron shot, (b) When the structure or item being blasting exceeds 8 feet in height, 8 feet in width, or 10 feet in length, and (c) When the structure is at its permanent location.

#### *3.4.2.2. Louisiana Department of Environmental Quality (LDEQ)*

LDEQ regulates environmental quality of Louisiana State to protect the environment, public health, and safety. Steel fabrication, shipbuilding, metal cleaning and any activity that uses abrasives blasting must comply with regulations specified in LAC 33:III.1305.3 (LDEQ 1998). Some of the applicable regulations are discussed in this section. In case of outdoor blasting, shrouds must be used at all the times during blasting to confine air emissions from escaping into atmosphere. These shrouds (a) must be placed close to blast area to prevent dispersion of emissions in larger areas, (b) must have overlapping seams to prevent leakage of PM emissions, and (c) must repair tears greater than one foot in length before blasting is carried out. Industries must use abrasives that contain less than 1% (by mass) of fines that would pass through a No.80 sieve. Abrasive with less dust generation rates must be used. Materials derived from hazardous, toxic, medical or municipal wastes are prohibited from use as abrasive materials. In case of indoor blasting, the blast cabinets must be equipped with exhaust systems and emission control equipment.

Industries must maintain a daily record of actual operating times and monthly records of abrasive material usage with percentage mass of fines as specified by the manufacturer. During blasting, precautions must be taken to prevent PM from becoming airborne. To minimize hazardous waste generation, personnel must maintain optimum blast pressure levels, minimize contamination of abrasive materials with hazardous wastes or lead paints, and remove spent abrasives prior to working with surface that contain lead-based coatings.

#### *3.4.2.3. Texas Natural Resource Conservation Commission (TNRCC)*

TNRCC’s Air Permits Division provides permit application information and applicable regulations for facilities that perform dry abrasive blasting (TNRCC 2001). Facilities must submit information on type abrasive blasting, abrasive materials and quantities used, size of blast cabinet (in case of enclosed blasting), control equipment data, exhaust system data and methods of disposal of wastes generated in order to obtain an operating permit (TNRCC 1993).

Facilities must estimate hourly and annual TSP and $PM_{10}$ emissions using emission factors specified by TNRCC. In addition, off-property concentrations of all chemicals must be estimated. The off-property concentrations of PM cannot exceed 400 $\mu g/m^3$ for any one-hour period and cannot exceed 200 $\mu g/m^3$ for any three-hour period. In addition, the facilities must comply with NAAQS for $PM_{10}$, $PM_{2.5}$, and lead emissions.

## *3.5. Available Data for Emission Factors*

Emission inventories are important tools for air quality management. These are used to determine applicability of permitting programs, identify major sources of pollutants, and develop emission control technologies. Emission factors (EF) are key input parameters for developing emission inventories. Since 1972, U.S. EPA has been compiling and publishing emission factors for various pollutants from a variety of stationary point and area sources in AP-42 documents (U.S. EPA 1997c). An emission factor is defined as the quantity of pollutant released to the atmosphere from a source in relation to an activity. Generally, emission factors are expressed in terms of weight of pollutant emitted per unit weight, duration, volume or distance of the activity that emits the pollutant. Usually, emission quantities are estimated using Equation 1 given below:

$$E = A * EF * \left[1 - \left(\frac{ER}{100}\right)\right] \tag{1}$$

where: *E* = emissions, *A* = activity rate, *EF* = uncontrolled emission factor, and *ER* = overall emission reduction efficiency, %.

Emission factors can be developed using mass-balance approach, emissions monitoring, engineering calculations, or a combination of these methods. AP-42 documents provide emission factor ratings to indicate the robustness, or appropriateness of emission factors based on source operation, sampling procedures, sampling and process data, analysis and calculations. These ratings are given from A through E.

A = Excellent.

B = Above average.

C = Average.

D = Below average.

E = Poor.

Since emission factors represent average emission rate for an entire process or source category, actual emissions may vary widely from one source to another.

### *3.5.1. U.S. EPA Emission Factors*

Section 13.2.6, Emission Factor Documentation for AP-42, provides emission factor data applicable for abrasive blasting processes (U.S. EPA 1997a). Emissions factors for TPM, $PM_{10}$ $PM_{2.5}$, derived from various studies conducted on sand and garnet are compiled in this document. The test conditions and data quality ratings of these studies are shown in Table 2. The average emission factors provided U.S. EPA, from these studies are shown in Table 3. These EFs are given a rating of E, which means a poor quality. Since these EFs are based on wind velocity, emissions from enclosed blasting operations may vary significantly from these values. In addition, emission potential depends on abrasive material used, surface contamination being removed, method of abrasive blasting, and other factors discussed in Section 3.3. Hence, estimating emissions from this data may not represent actual emissions.

Table 2: Summary of Test Data for Abrasive Blasting Operations

| Reference document | Type of operation tested | Type of abrasive | Sampler location | Particle size fraction, µmA$^b$ | Time weighted average concentration, mg/m$^3$ | Data quality rating | Emission factor, mass/source extent | Comments |
|---|---|---|---|---|---|---|---|---|
| Samini, 1973; Samini et al., 1975 | Outdoor sandblasting at two steel fabrication yards | Silica sand | Within 5 yd (4.6 m) of sandblaster | TP | 1.46-76.8 | NR | N/A | 31 samples; no process data |
| | | | | < 11 | 11.8 | NR | N/A | 16 sample average; no process data |
| | | | | RP | 0.109-8.93 | NR | N/A | 29 samples; no process data |
| Samini et al., 1974 | Abrasive cleaning of ship hull | Stan-Blast | < 5 yd (4.6 m) from source | TP | 10.2 | NR | N/A | Sampling time = 185 min |
| | | | | RP | 4.58 | NR | N/A | Blasting time = 180 min; no process data |
| | | | Sandblaster's chest | RP | 88.8 | NR | N/A | Sampling time = 181 min; blasting time = 150 min; no process data |
| | | | < 10 yd (9.1 m) from source | RP | 2.26-9.88 | NR | N/A | No process data available |
| | | | | < 11 | 6.98 | NR | N/A | |
| Landrigan et al., 1980 | Abrasive bridge cleaning of lead-based paint | Grit (Black Beauty) | 27 m downwind of bridge | TSP (Pb) | 0.0129 | NR | N/A | Data for a 6.1-h sampling period during which canvas shroud was not in place for a 2-h period; Pb contributions from paint chips, vehicle exhaust, and grit; no process data available |
| Bareford and Record, 1982 | Abrasive bridge cleaning of lead-based paint | Sand | Center of plume exiting sandblasting bay | TP | — | D | 57-455 lb/h/ sandblaster | 2.5% Pb for particles < 2.4 µm; sand usage—700 lb/h per blaster (no exact throughput available) |
| | | | | TP (Pb) | - | D | 1.5-4.8 lb/h/ sandblaster | < 1% Pb for particles > 75 µm; sand usage—700 lb/h per blaster (no exact throughput available) |
| | | | | < 10 | — | D | 24 lb/h/ sandblaster | Sand usage—700 lb/h per blaster (no exact throughput available) |
| | | | | < 10 (Pb) | — | D | 0.46 lb/h/ sandblaster | Sand usage—700 lb/h per blaster (no exact throughput available) |
| Beddows, 1983 | General abrasive blasting of lead-based paint | Grit | Breathing zone samples | TP | 3-30+ | NR | N/A | 8-h time-weighted averages; grit from coal slag typically contains from 20-40 µg of Pb/g of material; grit from copper smelting can contain up to 6,000 µg Pb/g of material; no process data reported |
| Lehner et al., 1985 | Abrasive bridge cleaning of lead-based paint | Sand | 300-400 ft (91-122 m) downwind of bridge | TSP | 0.339-0.482 | NR | N/A | 24-h time-weighted averages; no process data or controls specified; assumed to be essentially uncontrolled |
| | | | | TSP (Pb) | 0.00122-0.00215 | NR | N/A | |

Source: U.S. EPA, AP-42

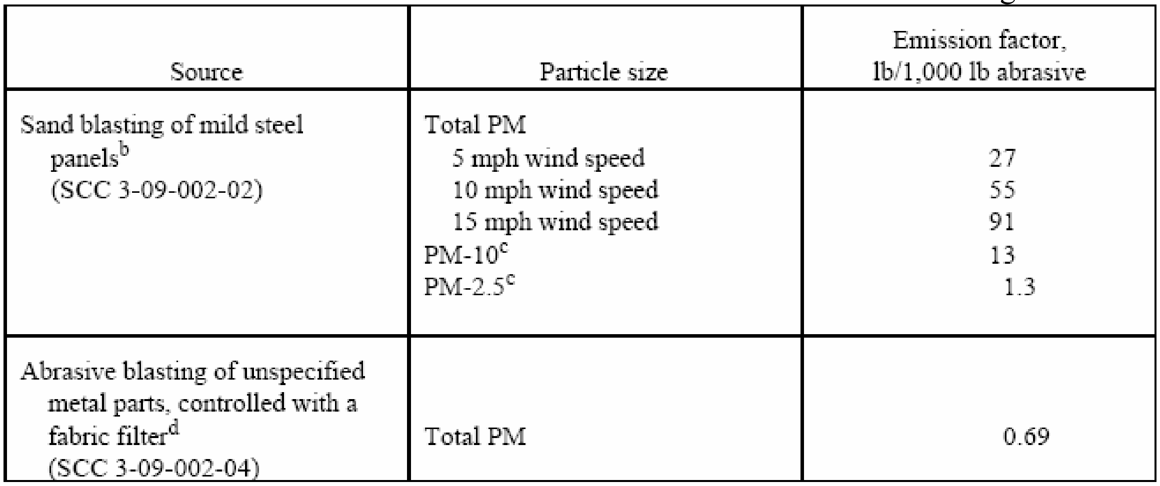
(Table 2 continued..)

| Reference document | Type of operation tested | Type of abrasive | Sampler location | Particle size fraction, µmA$^b$ | Time weighted average concentration, mg/m$^3$ | Data quality rating | Emission factor, mass/source extent | Comments |
|---|---|---|---|---|---|---|---|---|
| WhiteMetal Inc., 1987 | Outdoor blasting of steel panels coated with lead-based paint | 30-60 mesh (0.59-0.25 mm) silica sand | 5 ft (1.5 m) downwind | TSP | 257.61 | NR | N/A | Hi-vols installed downwind of dry blasting operation to demonstrate control effectiveness of "Jet Stripper"; no sampling time or process data reported |
| | | | 50 ft (15 m) downwind | TSP | 45.99 | NR | N/A | |
| | | | 100 ft (30 m) downwind | TSP | 6.18 | NR | N/A | |
| | | | 200 ft (61 m) downwind | TSP | 2.71 | NR | N/A | |
| | | | 500 ft (152 m) downwind | TSP | 0.90 | NR | N/A | |
| South Coast Air Quality Management District, 1988 | Outdoor abrasive blasting | Sand | In ventilation system duct | TP | N/A | D | 0.041 lb/lb sand | Emission factors determined by source test of an uncontrolled indoor blasting operation using a quasi-stack technique; original test report not available |
| | | Grit | | TP | N/A | D | 0.010 lb/lb grit | |
| | | Shot | | TP | N/A | D | 0.004 lb/lb shot | |
| | | Other | | TP | N/A | D | 0.010 lb/lb abrasive | |
| Kinsey et al., 1995 | Blasting of molded steel panels, painted, cleaned, or rusted | 30-50 mesh silica sand | 40 ft (12 m) downwind | TP, < 10, < 2.5 | See Reference 1 | A | See Table 4-4 | Emission factors determined by source tests in low speed wind tunnel using standard test methods for total particulate, particle size distribution, and iron and 10 HAP metals |
| NEESA 2-161, 1990 | Enclosed blasting of aircraft parts | Plastic | Fabric filter stack | TP | 3.61 | NR | N/A | Fabric filter-controlled plastic media blast room. No process data. Chromium conc. of 0.00187 mg/m$^3$ and Cr$^{+6}$ conc. of 0.00095 mg/m$^3$ |
| Hunter Schlesser Sandblasting, 1993 | Enclosed blasting of motor shields and handrails | Glass beads | Fabric filter stack | TP | 2.3 | NR | N/A | Fabric filter-controlled glass bead blast room. No process data. |
| Poly Engineering, 1990 | Enclosed blasting of unspecified parts | Garnet | Fabric filter stack | TP | 126 | C | 0.00069 lb/lb garnet | 1,740 lb/hr of abrasive used to blast 700 lb/hr of parts |

TP = total particulate matter. RP = respirable particulate matter (# 3.5 µmA) as determined using a 10-mm nylon cyclone followed by a 37-mm filter cassette.

Source: U.S. EPA, AP-42

Table 3: Particulate Emissions Factors for Abrasive Blasting



| Source | Particle size | Emission factor, lb/1,000 lb abrasive |
|---|---|---|
| Sand blasting of mild steel panels[b] (SCC 3-09-002-02) | Total PM | |
| | 5 mph wind speed | 27 |
| | 10 mph wind speed | 55 |
| | 15 mph wind speed | 91 |
| | PM-10[c] | 13 |
| | PM-2.5[c] | 1.3 |
| Abrasive blasting of unspecified metal parts, controlled with a fabric filter[d] (SCC 3-09-002-04) | Total PM | 0.69 |

Source: U.S. EPA, AP-42

### *3.5.2. Emission Factors from State/ Environmental Agencies*

Available emission factors from environmental agencies from various states (TNRCC, BAAQMD, SCAQMD, SDAPCD) are shown in Table 4. National Shipbuilding Research Program developed emission factors for coal slag, copper slag, garnet, hematite, and sand at blast pressures of 80 and 122 PSI for $PM_1$, $PM_{2.5}$, $PM_4$, and $PM_{10}$. The disadvantages of available data on emission factors are some of the data are very general and do not provide process condition information. While NSRP provided more information on process conditions, the data is not continuous. Thus emissions cannot be estimated at intermediate operating conditions. Moreover, these were based on mass-balance methods and may not represent true quantities of emissions.

Table 4: Available Emission Factors for PM

| Agency | Abrasive Material | PM Size | EF (lbs/lb of abrasive) |
|---|---|---|---|
| TNRCC (2001) | Sand | TPM | 0.0059 |
| | | $PM_{10}$ | 0.0014 |
| | Coal Slag | TPM | 0.00286 |
| | | $PM_{10}$ | 0.00034 |
| | | | |
| BAAQMD (1998) & SCAQMD (1989) | Sand | $PM_{10}$ | 0.041 |
| | Grit | $PM_{10}$ | 0.01 |
| | Shot | $PM_{10}$ | 0.004 |
| | Glass bead | $PM_{10}$ | 0.01 |
| | Other | $PM_{10}$ | 0.01 |
| | | | |
| SDAPCD | Aluminum Oxide | $PM_{10}$ | 0.0075 |
| | Copper Slag | $PM_{10}$ | 0.005 |
| | Garnet | $PM_{10}$ | 0.004 |
| | Glass Bead | $PM_{10}$ | 0.0075 |
| | Silica Sand | $PM_{10}$ | 0.0125 |
| | Steel Grit | $PM_{10}$ | 0.0038 |
| | Steel Shot | $PM_{10}$ | 0.005 |
| | Walnut Shells | $PM_{10}$ | 0.0075 |
| | Miscellaneous Media | $PM_{10}$ | 0.005 |

## ***3.6. Available Data for Productivity and Consumption***

Material suppliers often provide average or wide-ranging values for productivity and consumption of abrasives. Some of the research studies performed on evaluating various abrasives also provide productivity and consumption data for various abrasives. In order to protect worker health from exposure to silica emissions, NIOSH evaluated the performance of substitute materials in abrasive blasting (NIOSH, 1998). This study involved testing various commonly used abrasives, both expendable and reusable, for industrial hygiene concentration levels of various pollutants. This study also provides productivity, abrasive flow rate, and cleanup costs. For example, productivity of coal slag varied from 29.5 to 42.0 square feet/hour with a 1/4 inch nozzle. With increase in nozzle size to 3/8 inch, the productivity of coal slag increased to 94.8 square feet/hour. In case of silica sand, productivity varied from 26.6 to 39.0 square feet/hr with a 1/4 inch nozzle. For copper slag, the productivity varied from 32.7 to 91.6 square feet/hour. These tests were conducted at a blast pressure of 100 PSI with a feed valve of 1/2 inch, except for some tests. Since these were conducted at a single blast pressure condition, it is not feasible to determine productivity and clean up costs at other blast pressure or feed rate conditions, which may be more economic and faster.

NSRP studied emission factors of PM for abrasive materials commonly used in shipbuilding sector (NSRP 1999). This study also provides information on productivity and consumption of coal slag, copper slag, hematite, garnet, and sand. The blasting operations were performed at 80 and 100 PSI with varying feed rates from 3 to 8 turns of opening of feed valve. However, only a single test run was performed for each operating condition. Thus, these results may not provide truly representative data for productivity and consumption. In addition, this study does not help in determining productivity and consumption at intermediate blast pressures.

Productivity and consumption rates of typical abrasives are given by U.S. ACE (1995). For example, coal slag has a productivity of 0.36 $m^2$/min and consumption rate of 15.62 kg/$m^2$. Copper slag has a productivity of 0.40 $m^2$/min and consumption rate of 15.13 kg/$m^2$, while silica sand has a productivity of 0.44 $m^2$/min and consumption rate of 12.69 kg/$m^2$. This data is provided only as an example of effect of abrasive materials on productivity and consumption. Often material and equipment suppliers provide an average value or a range of productivity and consumption data (Virginia Materials Inc). Some of the data in these studies provide insufficient information on process conditions and there is limited information on effect of varying pressure, feed rate on productivity and consumption.

### *3.7. Previous Studies at UNO*

Previous research performed at the University of New Orleans focused on evaluating productivity, consumption and total PM emission factors for coal slag, garnet (Datar 2003), specialty sand and steel grit (Silvadasan 2004) for removal of flash rust. These studies did not distinguish between expendable and reusable abrasives. Since some industries may not have equipment to clean the abrasives for reuse, or it may not be a cost-effective option to reuse, it is important to study the performance of expendable abrasives for a better assessment. Other limitations of these studies were:

- Effect of pressure and feed rate for removing paints was not studied
- Physical effect of blast pressure and feed rate on performance was not explained
- Simultaneous effect of blast pressure and feed rate were not studied or modeled.

# 4. Methodology

## *4.1. Abrasive Materials*

Shipyard survey results showed that coal slag comprise 68%, copper slag comprise 20%, steel grit/shot comprise 6%, sand comprise 4% and miscellaneous abrasives comprise 2% of the industrial consumption of abrasives (National Steel and Shipbuilding Company 1999). The objective of this research was to evaluate the performance of non-reusable, or expendable abrasives. Thus, from the literature review, three most commonly used expendable abrasive materials were selected for this research: coal slag, copper slag, and specialty sand. The characteristics of these materials are discussed in this section.

### *4.1.1. Coal Slag*

Coal slag is a by-product of the combustion of coal in coal-fired utility boilers. The molten slag from the combustion of coal is quenched in water and the rapid cooling breaks the slag into rough angular particles. The quality of this material is often improved by crushing and screening followed by magnetic separation. Some of the other characteristics of coal slag such as noncrystalline hardness, uniform density, low friability, and low free silica content are very effective in removing heavy rust and providing a high profile finished surface. Coal slag, commercially known as Black Beauty $^{TM}$ or Black Diamond $^{TM}$, is thus used by many industries for dry abrasive blasting. Average productivity of coal slag is 100 sq.ft/hr and density is 90 lbs/ft$^3$. These values may vary from one supplier to another. Coal slag may contain high levels of heavy metals such as arsenic, beryllium, chromium, nickel, lead as well as iron, and aluminum (NIOSH 1998, Paddison 2000, NFESC 1996, Virginia Materials Inc., Chesapeake Specialty Products, Inc., Reed Minerals).

The MSDS sheet in Appendix C provides detail information. Coal slag has been replacing sand because of the health effects associated with silica dust from sandblasting. A survey of U.S. shipyards showed that coal slag is a predominantly used abrasive on the East Coast and the Gulf of Mexico (JPCL 2000). A medium grade coal slag was used in this research.

### *4.1.2. Copper Slag*

Copper slag is a by-product of copper smelting industry. The molten slag from the smelter is quenched in water and quick cooling of this slag results in an amorphous, noncrystalline particulates. Some of the characteristics of copper slag such as hardness, high density, and low free silica content are useful in removing heavy rust and providing a high profile surface finish. Kleen Blast ™ and Tru-Grit ™ are two of the commercially available copper slag abrasives. Average density of copper slag is 100 lbs/ft$^3$.The composition of copper slag may vary from one manufacturer to other, but can contain arsenic, beryllium, chromium, nickel, lead, and copper (Paddison 2000, Appleman 1998, Hansink 2000, Obery and Wayne1999). The MSDS sheet in Appendix C provides detail information. Copper slag is a predominantly used abrasive in shipyards on the West Coast (JPCL 2000). A medium grade copper slag was used in this research.

### *4.1.3. Specialty Sand*

Due to its low cost, natural occurrence and abrasive properties such as high hardness, sand is still being used by many industries. However, the quality of sand can be improved to increase productivity, decrease consumption and breakdown rate sand. Specialty sand supplied by Pontchartrain Materials Corporation was used in this study. Raw sand was hydraulically dredged, washed twice, and passed through a rotary kiln. This process removes most of the volatile impurities from sand. This was then passed through a single-deck screen filter system with a flat 0.25" screen. Special properties of this sand include purity, inertness, hardness, resistance to high temperatures, grain size, and color make it useful to a variety of industrial applications. Medium grade specialty sand was used in this research and average density is 100 lbs/ft$^3$. The MSDS sheet in Appendix C provides detail information.

## 4.2. Equipment

In order to carry out enclosed abrasive blasting operations and collect PM emissions from these operations, an emissions test facility was constructed at north side of the engineering building on the main campus of the University of New Orleans (UNO). This facility was equipped with test chamber, blasting equipment, test plates, exhaust duct, stack sampling system, and particulate collection system. Figure 1 shows a sketch of the emissions test facility. The details of this equipment are discussed in this section.

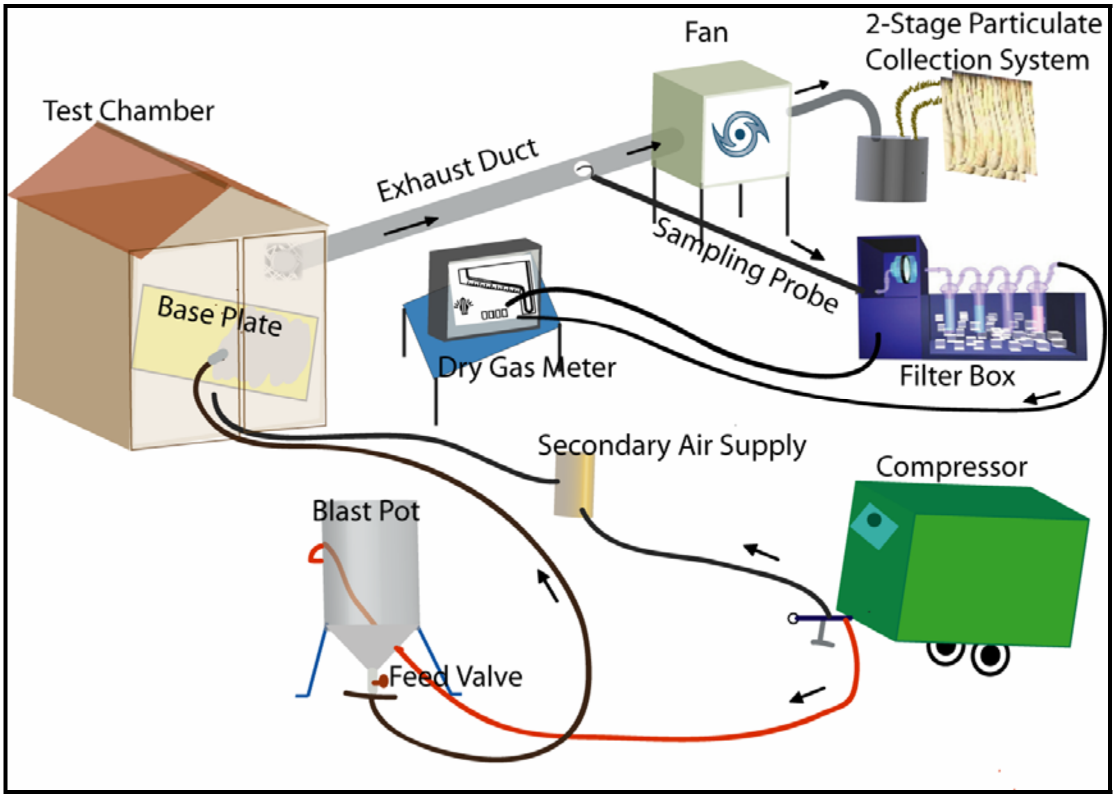


Figure 1: Emissions Test Facility

### *4.2.1. Test Chamber*

An enclosed test chamber of 3.7 m length, 3 m width and 2.5 m height (12 x 10 x 8 feet) was constructed using plastic sheets to contain the particulate emissions and protect the environment and prevent excessive duct discharge into atmosphere during strong winds. These plastic sheets were firmly riveted to the wooden floor, made of seasoned wood and treated with waterproofing material. In order to prevent seepage of water into the test chamber, the gaps in the floor were sealed with silicon. A wooden ramp was constructed to smoothly move the test plates cart in and out of the chamber before and after blasting. An exhaust window was located at one end of the test chamber to provide for make-up air and vent PM emissions through an exhaust dust for sampling. The test chamber was also provided with internal lighting for visibility.

### *4.2.2. Blasting Equipment*

Blasting equipment consists of a blast pot, blast nozzle, air hose, blast hose, secondary-air supply unit, moisture separator, and personal protective equipment.

#### *4.2.2.1. Blast pot*

Compressed air pressure systems are widely used in shipyards, refineries and other large-scale blasting operations. This system typically consists of a blast pot, an abrasive hopper, air inlet and outlet valves, an air filter, an easily opened hand hole, and a metering valve. The abrasive is contained in the blast pot and compressed air hose is connected to both the top (inlet) and bottom (outlet) of the blast pot. This enables maintaining equal pressures at the top and bottom of the blast pot. Abrasive material flows by gravity. Blast pots are available in various sizes based on abrasive capacity and as portable or mounted on wheels. A smaller blast pot needs more frequent filling of abrasive materials than a larger blast pot (U.S. ACE 1995, U.S. EPA, 1997a).

The hopper located at the top of the blast pot serves as an opening for easy feeding the blast material. An automatic filling valve at the center of the hopper seals (pops up) when compressed air supplied and opens when the compressor is turned off. The hand hole on the side of the blast pot allows easy access for cleaning and removal of any foreign objects fallen into the blast pot. Conical bottom of the blast pot enables a smooth flow of material. A metering valve, or feed valve, fixed at the bottom of the blast pot allows control of material flow for abrasive blasting. These valves vary in size and material flow is controlled by turning the valve. While some blast pots readily come with a feed valve, others may need a separate feed valve (U.S. ACE 1995, U.S. EPA, 1997a). In this research, a 273 kg (600 lbs) capacity Abec© blast pot, mounted on wheels was used. A Schmidt feed valve was used to control the abrasive material flow. Figure 2 shows the blast pot and its important components.

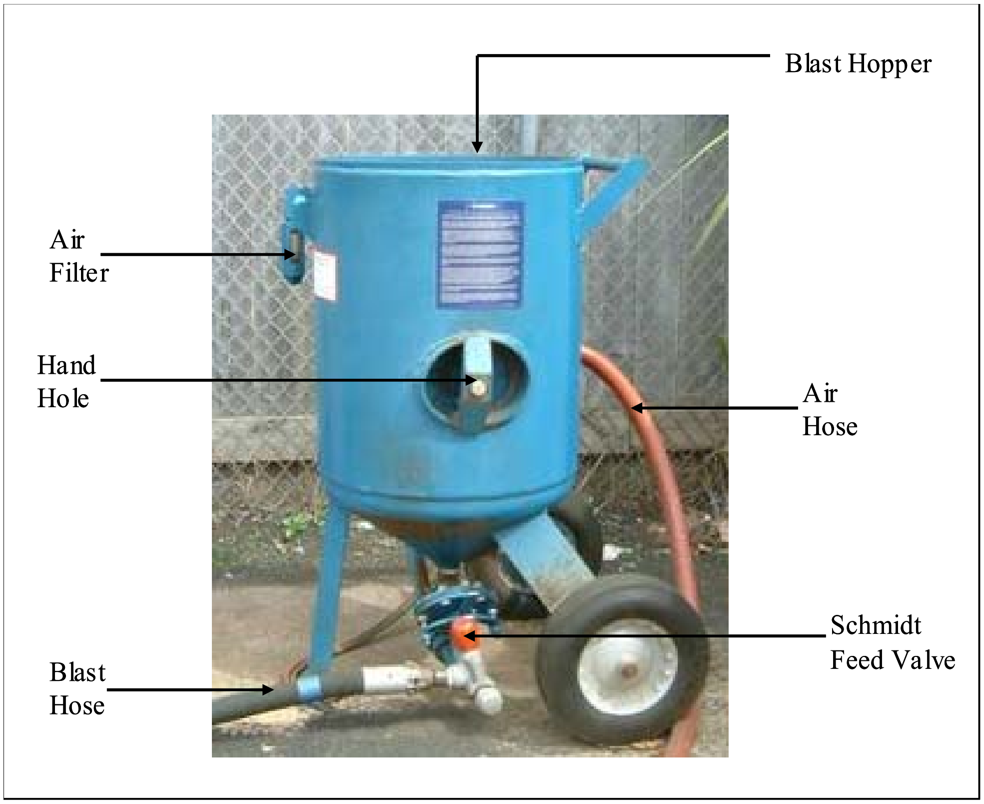


Figure 2: Blast Pot

#### *4.2.2.2. Blast nozzle*

Blast nozzle are identified by the inside diameter on the orifice and measured in sixteenths of an inch (3/16-inch, 5/10-inch). These nozzles are assigned a number based on the diameter. Selection on nozzle diameter depends on the capacity of air compressor and blast pressure required. If the nozzle is too large, more volume of air must be supplied to achieve required blast pressure. A Bazooka No.6 venturi type blast nozzle (3/8-inch or 9.5 mm diameter) was used in this research.

#### *4.2.2.3. Air hose and blast hose*

The air hose is used to connect the compressor to the blast plot. The diameter of the hose must be sufficient in preventing frictional losses and pressure drops, which decrease the process efficiency. The blast hose is used to connect the blast pot to the blast nozzle and it carries both abrasive material and compressed to the nozzle. This hose must be strong enough to carry the material at high pressures.

#### *4.2.2.4. Other blasting equipment*

A secondary air supply unit was used to provide air to the blaster and moisture separators were used to remove moisture from compressed air and secondary air supply. Personal protective equipment included a respirator, helmet and heavy duty shoes.

### *4.2.3. Test Plates*

Mild steel test plates of 2.5 x 1.5 m (8 x 5 feet) were used as base plates. The steel plates were coated with a 1:1 volume mixture of commercially available Rust Oleum© Safety Yellow paint and a thinner. Average thickness of the coating was calculated to be 0.73 mills assuming average transfer efficiency of 50%. To support these plates during the experiment a panel cart was used. The mount was also used to move the panels in and out of the test chamber.

### *4.2.4. Air Compressor*

The air compressor provides the blast pressure required in dry abrasive blasting. The compressor must be able to provide required blast pressures to achiever maximum productivity. Sullair Model 375H© and Ingersoll Rand (power rating: 125-130 hp) compressors were used as compressed air sources, which were able to provide a maximum blast pressure 150 PSI.

### *4.2.5. Exhaust Duct System*

The exhaust duct system consisted of an exhaust duct and a fan. This system was used to vent the emissions from the blasting operations in the test chamber to a particulate collection system. Another important use of this systems was to collect sample PM emission factors. The entrance of the duct system was fitted with a mesh to prevent too coarse particles from entering the duct. The duct was 0.30 m (1 foot) in diameter with smooth inner surface to avoid disturbances in the flow and designed according to EPA Method 1 (U.S. EPA 1997d). An exhaust fan with maximum capacity of providing a volumetric flow of 5000 cfm was used to vent the emissions by suction. An average of 3000 cfm was used in this research to vent emissions from the test chamber. A sampling port was located on the exhaust duct to draw sample exhaust gas for determining PM emission factors (Figure 3).

Figure 3: Exhaust Duct System (top left: From inside the test chamber, top right: from outside the test chamber, bottom: duct connected to exhaust fan)

### *4.2.6. Stack Sampling System*

U.S. EPA approved stack sampling system was used in this research. Components of this system are mentioned in this section. The purpose of these components is discussed with the sampling procedure.

#### *4.2.6.1. Sampling train*

The sampling train consisted of a tapered nozzle, sampling probe, filter holder, and a series of four impingers, all of which are connected by connectors. The nozzle is used to draw exhaust gas for PM sampling. For the sample to be representative, it must be drawn at isokinetic conditions, i.e., the velocity of the gas in the stack and the velocity of the gas in the nozzle of the sampling probe should be equal. Following the guidelines specified by U.S. EPA for stack sampling, various nozzles were tested for isokinetic conditions and a nozzle with diameter of

4.57 mm (0.18 inch) was selected in this research. The sampling probe has nozzle on one end and the other end is connected to filter holder at the top. An S-type pitot tube and a thermocouple are attached to the sampling probe. The exhaust gas from nozzle flows through the filter holder which holds a filter paper. The bottom of the filter holder is connected to a series of four impingers, kept in a cold box. The first two impingers are filled with 100 ml water. The third impinger is left dry and empty. Fourth impinger contains a measured quantity of silica gel.

#### 4.2.6.2. Dry gas meter system

Dry gas meter (DGM) system consists of various components: pyrometer, vacuum gauge, an air tight pump, dry gas meter, and an orifice meter. The outlet of the fourth impinger is connected to DGM for measuring sample gas temperature and pressure.

### 4.2.7. Particulate Collection System

In order to collect emissions effectively and control their discharge into the atmosphere, a two-stage particle collection system was installed downstream of the fan. The first stage consisted of changing the direction of flow to collect particles in a drum. The coarse particles are settled in the drum due to gravity and change of direction. In order to collect fine particles that do not settle during the first stage, an outlet from the drum was connected to fabric filter system. The fine particles In the second stage, a fabric filter was used to collect fine particles. In the study, four filter panels were used. The drum and the fabric filter system were periodically cleaned to maintain their efficiency. Each filter panel consisted of five individual filters. Clean air from the fabric filters was then released into air. This two-stage particle collection system is shown in Figure 4.

Figure 4: Two-Stage Particle Collection System (left: drum, right: fabric filter system)

## *4.3. Experimental Parameters*

As mentioned in Section 3.3.2, blast pressure and abrasive feed rate are important process parameters in dry abrasive blasting. Three most commonly used non-reusable abrasives were selected to study the effect of blast pressure and feed rate on performance of the abrasive materials. Based on literature review, it was evident that many industrial processes use blast pressures ranging from 80 to 120 PSI. Selection of feed rate depends on the valve size and abrasive material. Thus, from recommendations of equipment and material suppliers, feed rates ranging from 3 to 5 turns were selected. A detailed list of experimental parameters is given below:

### *4.3.1. Variable Parameters*

- ***Abrasive Material***: Coal Slag, Copper Slag, and Specialty Sand
- ***Blast Pressure:*** 80 PSI, 100 PSI, and 120 PSI
- ***Feed Rate:*** 3, 4, and 5 turns of opening of Schmidt feed valve

### *4.3.2. Constant Parameters*

- ***Abrasive Grade:*** Medium grade

- ***Blast Nozzle:*** Bazooka No.6 nozzle with 9.5 mm diameter (venturi nozzle)
- ***Angle of Deflection:*** $90^0$ (Nozzle held perpendicular to surface)
- ***Stand-off Distance:*** 12” was maintained between the test plate and the blast nozzle
- ***Exhaust Flow Rate:*** 3000 cfm (average volumetric flow rate)
- ***Surface Contamination:*** Paint with average thickness of 0.73 mill
- ***Surface Finish:*** Near-white finish (SP-10)

## *4.4. Experimental Procedure*

The experimental procedure is explained in two sections: abrasive blasting and PM sampling. PM sampling was performed while abrasive blasting was being carried out.

### *4.4.1. Abrasive Blasting*

The test plates were coated with a 1:1 mixture of commercially available Rust Oleum© Safety Yellow paint and a thinner. The paint was allowed to dry for 24 hours. Upon drying these plates were moved inside the test chamber with the help of a cart. The inside of the blast pot was checked for any foreign materials. Blast hose and air hose were connected to the blast pot and feed valve was closed tightly. Stack sampling equipment was assembled. A measured quantity of abrasive material (100 lbs in most cases) was added. Prior to adding, it was made sure that the material was free of lumps and moisture. In case of presence of moisture, the material was well dried and then added into the blast pot. Presence of lumps or moisture results in clogging the valve and non-uniform flow of material.

The compressor was turned on and the blasting pressure was set to desired setting (80, 100, or 120 PSI). The Schmidt feed valve was adjusted to a desired number of turns (3, 4, or 5). These blast pressure and feed rate settings were randomly chosen. The exhaust fan was turned on to draw the emissions from the chamber. Blaster, provided with professional training for abrasive blasting, then carried out blasting inside the chamber. During the whole time of abrasive blasting, the test chamber was kept enclosed. Blasting was carried out until the blast pot was emptied. The blaster visually ensured that the dwell time was sufficient to achieve a near-white surface finish. The compressor was then turned off and feed valve was closed. The time taken for each test run was recorded using a stopwatch and the area cleaned was measured using a measuring tape. For each combination of pressure and feed rate, three test runs were carried out to minimize experimental errors and test the repeatability of the results. Thus a total number of 27 experiments were performed for each material.

### *4.4.2. PM Sampling*

As the blasting was carried out inside the chamber, samples were drawn isokinetically through the sampling probe. A brief procedure for PM sampling is discussed in this section and a detailed procedure is available at http://www.epa.gov/ttn/emc.

#### *4.4.2.1. Selection of sampling ports and traverse points*

Based on the guidelines provided in EPA Method 1 (U.S. EPA 1997d), in order to minimize the effect of flow disturbances on sampling, a sampling port was located at point at least 8 diameters upstream (test chamber) and 2 diameters downstream (exhaust fan). For a circular duct with a diameter between 0.30 and 0.61 meter (12 and 24 inches), a total of eight traverse points must be selected. The location of these traverse points, along the plane perpendicular to direction of flow of exhaust gas, was calculated as per the guidelines and marked on sampling probe with a heat resistant tape to denote the distance into the duct for each traverse point. The purposes of sampling at various locations in the duct were to measure average stack gas velocity and obtain a representative sample for PM emissions.

#### *4.4.2.2. Stack gas velocity and flow rate measurements*

The average gas velocity in the duct was determined from measurement of average velocity head with the S-type pitot tube attached to the sampling probe. A temperature sensor attached to the sampling probe was used to measure the exhaust gas temperature at the traverse points. Atmospheric pressure was recorded from a nearby National Weather Service station. Leak checks were performed once the sampling train was assembled. The sample probe was sufficiently heated to prevent condensation of moisture present in the exhaust gas. At each traverse point, exhaust gas sample was collected for two minutes. Thus, total sampling time was sixteen minutes for each of the test runs. At the end of 16 minutes, sampling probe was withdrawn, and the exhaust fan was turned off. The measurements made at each traverse point, according EPA Method 2 (U.S. EPA 1997e), and equations used to calculate the stack gas velocity and flow rate for each experiment are given in Appendix A.

#### *4.4.2.3. Determination of moisture content*

The moisture content in the exhaust was determined according to the guidelines in EPA Method 4 (U.S. EPA 1997f). The exhaust gas, after passing through the filter paper is passed through a series of four impingers (first two filled with 100 ml water, third left empty and fourth filled with measured quantity of silica gel) to collect moisture present in the exhaust gas. These impingers were placed in an ice bath containing crushed ice, which helps in condensing the moisture. The weights of four impingers were recorded before and after each experiment. The increase in weight of each impinger was used to calculate weight of water collected. The exhaust gas was then passed through dry gas meter to determine volume and temperature of the gas. Moisture content was calculated using the equations given in EPA Method 4. These equations and calculations for each experiment are presented in Appendix A.

#### *4.4.2.4. Determination of PM emissions*

The particles were collected on a pre-weighed Whatman No. 10 filter paper that was already desiccated to eliminate moisture. The filter assembly box was maintained at a temperature of 120 ± 15°C to collect particulate matter from the sample gas stream while preventing moisture condensation. Once the sample was collected, the filter paper was removed from the filter box and placed in a dessicator. PM from the probe was collected in a beaker by rinsing the probe with acetone. The final weights of PM in filter paper and beaker were recorded after dessicating them for 24 hours. The sum of the weights of both containers was used to determine the actual mass of emissions in the stack gas using the equations in EPA Method 5 (U.S. EPA 1997g). The actual mass of PM collected in sample exhaust gas, equations used and total mass of PM in the exhaust gas for each experiment are presented in Appendix A.

## *4.5. Statistical Analysis*

The data collected from field measurements was transferred in Excel for analysis. Mean and standard deviation of three experimental runs were calculated were for each combination of blast pressure and feed rate. This data is presented in Section 5. In order to develop predictive models to estimate emission factors, productivity and consumption (performance parameters) at intermediate blast pressure and feed rate conditions (process parameters), multiple regression analysis was performed. Two-dimensional and three dimensional models were developed. Two-dimensional models were used to study the effect of a single process condition on performance parameter. In addition, these models were used compare the performance of the three abrasive materials at various operating conditions. DataFit$^{@}$, a curve fitting application, was used for developing three-dimensional models. These models were used to study the simultaneous effect of process parameters on performance parameters.

The best-fit models were selected based on the physical phenomenon discussed in Literature Review, $R^2$, and continuity of the curve (in case of 3-D models). The $R^2$ value, also known as the Coefficient of Determination, is an indicator that ranges in value from 0 to 1. This coefficient reveals how closely the estimated values for the regression correspond to the actual data. A regression is most reliable when its $R^2$ value is at or near 1 (Kleinbaum 1992, McBean and Rovers 1998). The value for $R^2$ was determined using the following equations:

Residual = $(Y_i - \hat{Y}_i)$

Sum of Residuals = $\sum (Y_i - \hat{Y}_i)$

Average Residual = $\sum (Y_i - \hat{Y}_i) / n$

Residual Sum of Squares, SSE = $\sum (Y_i - \hat{Y}_i)^2$

Regression Sum of Squares, SSR, $\sum (\hat{Y}_i - \overline{Y}_i)^2$

Total Sum of Squares, SST = SSE + SSR,

Coefficient of Multiple Determination, $R^2$ = SSR / SST

Two-way ANOVA was used to test the significance of the regression model. F static was calculated for $H_0 : a = 0, b = 0, c = 0, d = 0, e = 0$, and $f = 0$, where a, b, c, d, e, and f are coefficients in the regression model. Null hypothesis ($H_0$) was rejected if $\text{Prob}(F) < 0.025$. $\text{Prob}(F) = 0$ means the probability of obtaining data equal to more extreme under the null hypothesis is zero. In addition, t static was calculated for $H_0$: $a = 0, b = 0, c = 0, d = 0, e = 0$, or $f = 0$ to test the significance of each coefficient. Null hypothesis was rejected if $\text{Prob}(t) < 0.05$.

Since the analysis was performed assuming normal distribution of the data, residual plots were used check this assumption. The following scatter diagrams were plotted to check the normal distribution of the data:

- Residuals vs. Predicted Y: the residuals should not show any pattern or structure for normally distributed data.
- Residual Normality Plot: The plot must be a straight line for normally distributed data.

In addition, predicted values of performance parameters were plotted with observed values.

Detailed results of the statistical analysis of the data, ANOVA table, confidence intervals, and scatter diagrams are included in Appendix B. The Results and Discussion section includes the 2-D and 3-D models which will help understanding the effect of process parameters on performance parameters and compare the performance of three abrasive materials. The equations developed for calculating emission factors, productivity, and consumption at intermediate blast pressure and feed rate are presented in Section 5 along with the $R^2$ values and coefficients for 99% confidence levels. The confidence intervals are presented in Appendix B.

# 5. Results and Discussion

The fundamental goals of this study was to evaluate the performance of three non-reusable abrasives and study the effect of blast pressure and feed rate on performance of each material. In order to achieve these goals, the following parameters were calculated for each experiment performed:

- **Emission Factors:**
  - kg TPM per unit area cleaned: Mass of TPM emitted (kg) / Area cleaned ($m^2$)
  - kg TPM per unit mass of abrasive: Mass of TPM emitted (kg) / Quantity of abrasive used (kg)
- **Productivity:**
  - Area cleaned per unit time: Area cleaned ($m^2$) / Blasting time (hr)
- **Consumption:**
  - Mass of abrasive per unit area: Quantity of abrasive used (kg) / Area Cleaned ($m^2$)

It must be noted that the emission factors determined in this research correspond to uncontrolled emissions since samples were collected prior to applying any emission controls. Predictive mathematical models were developed to determine these parameters based on blast pressure and abrasive feed rate. Detailed information on the data collected, and calculation PM emissions is presented in Appendix A. The detailed results of statistical analysis performed for this data is presented in Appendix B. The results of the experiments, variation of performance of each abrasive with respect to blast pressure and feed rate, and predictive models developed are presented in this section.

Table 5: Experimental Results for Coal Slag

| Pressure | Feed Rate | Abrasive Quantity | Blasting Time | Area Cleaned | TPM Emissions | Productivity | Consumption | Emission Factor 1 | Emission Factor 2 |
|---|---|---|---|---|---|---|---|---|---|
| PSI | Turns | lbs | min | $ft^2$ | g | $m^2$/hr | kg/$m^2$ | kg/$m^2$ | kg/kg |
| 120 | 3 | 100 | 6 | 13.0 | 3604 | 12.08 | 37.57 | 2.984 | 0.0794 |
| 120 | 3 | 100 | 6 | 12.0 | 3590 | 11.15 | 40.70 | 3.221 | 0.0791 |
| 120 | 3 | 100 | 6 | 12.0 | 3562 | 11.15 | 40.70 | 3.195 | 0.0785 |
| 120 | 4 | 100 | 5 | 17.0 | 3349 | 18.95 | 28.73 | 2.121 | 0.0738 |
| 120 | 4 | 100 | 6 | 17.5 | 3388 | 16.26 | 27.91 | 2.084 | 0.0747 |
| 120 | 4 | 100 | 6 | 17.0 | 3371 | 15.79 | 28.73 | 2.135 | 0.0743 |
| 120 | 5 | 150 | 7 | 17.0 | 5526 | 13.54 | 43.10 | 3.499 | 0.0812 |
| 120 | 5 | 150 | 7 | 18.0 | 5839 | 14.33 | 40.70 | 3.492 | 0.0858 |
| 120 | 5 | 150 | 7 | 18.0 | 5780 | 14.33 | 40.70 | 3.456 | 0.0849 |
| 100 | 3 | 100 | 7 | 13.0 | 2849 | 10.35 | 37.57 | 2.358 | 0.0628 |
| 100 | 3 | 100 | 7 | 12.5 | 2693 | 9.95 | 39.07 | 2.319 | 0.0594 |
| 100 | 3 | 100 | 8 | 12.5 | 2785 | 8.71 | 39.07 | 2.398 | 0.0614 |
| 100 | 4 | 120 | 5 | 12.5 | 2345 | 13.94 | 46.88 | 2.019 | 0.0431 |
| 100 | 4 | 120 | 7 | 18.0 | 3327 | 14.33 | 32.56 | 1.990 | 0.0611 |
| 100 | 4 | 120 | 7 | 17.0 | 3172 | 13.54 | 34.48 | 2.009 | 0.0583 |
| 100 | 5 | 120 | 6 | 12.0 | 3372 | 11.15 | 48.84 | 3.025 | 0.0619 |
| 100 | 5 | 80 | 4 | 8.0 | 2368 | 11.15 | 48.84 | 3.186 | 0.0652 |
| 100 | 5 | 120 | 6 | 12.5 | 3499 | 11.61 | 46.88 | 3.013 | 0.0643 |
| 80 | 3 | 30 | 4 | 6.0 | 1045 | 8.36 | 24.42 | 1.875 | 0.0768 |
| 80 | 3 | 100 | 11 | 15.0 | 2679 | 7.60 | 32.56 | 1.922 | 0.0590 |
| 80 | 3 | 70 | 6 | 9.5 | 1634 | 8.83 | 35.98 | 1.851 | 0.0514 |
| 80 | 4 | 100 | 7 | 16.5 | 2003 | 13.14 | 29.60 | 1.307 | 0.0441 |
| 80 | 4 | 100 | 7 | 16.0 | 2041 | 12.74 | 30.52 | 1.373 | 0.0450 |
| 80 | 4 | 120 | 11 | 24.0 | 2912 | 12.16 | 24.42 | 1.306 | 0.0535 |
| 80 | 5 | 100 | 7 | 13.0 | 3004 | 10.35 | 37.57 | 2.488 | 0.0662 |
| 80 | 5 | 100 | 7 | 12.0 | 2689 | 9.56 | 40.70 | 2.412 | 0.0593 |
| 80 | 5 | 80 | 5 | 9.5 | 2160 | 10.59 | 41.13 | 2.448 | 0.0595 |

Table 6: Mean and Standard Deviation (SD) of Experimental Results for Coal Slag

| Pressure | Feed Rate | Productivity | | | Consumption | | | Emission Factor 1 | | | Emission Factor 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSI | Turns | m$^2$/hr | Mean | SD | kg/m$^2$ | Mean | SD | kg/m$^2$ | Mean | SD | kg/kg | Mean | SD |
| 120 | 3 | 12.08 | 11.46 | 0.54 | 37.57 | 39.65 | 1.81 | 2.984 | 3.133 | 0.130 | 0.0794 | 0.0790 | 0.0005 |
| 120 | 3 | 11.15 | | | 40.70 | | | 3.221 | | | 0.0791 | | |
| 120 | 3 | 11.15 | | | 40.70 | | | 3.195 | | | 0.0785 | | |
| 120 | 4 | 18.95 | 17.00 | 1.71 | 28.73 | 28.45 | 0.47 | 2.121 | 2.113 | 0.026 | 0.0738 | 0.0743 | 0.0004 |
| 120 | 4 | 16.26 | | | 27.91 | | | 2.084 | | | 0.0747 | | |
| 120 | 4 | 15.79 | | | 28.73 | | | 2.135 | | | 0.0743 | | |
| 120 | 5 | 13.54 | 14.07 | 0.46 | 43.10 | 41.50 | 1.38 | 3.499 | 3.483 | 0.023 | 0.0812 | 0.0840 | 0.0024 |
| 120 | 5 | 14.33 | | | 40.70 | | | 3.492 | | | 0.0858 | | |
| 120 | 5 | 14.33 | | | 40.70 | | | 3.456 | | | 0.0849 | | |
| 100 | 3 | 10.35 | 9.67 | 0.86 | 37.57 | 38.57 | 0.87 | 2.358 | 2.358 | 0.040 | 0.0628 | 0.0612 | 0.0017 |
| 100 | 3 | 9.95 | | | 39.07 | | | 2.319 | | | 0.0594 | | |
| 100 | 3 | 8.71 | | | 39.07 | | | 2.398 | | | 0.0614 | | |
| 100 | 4 | 13.94 | 13.94 | 0.40 | 46.88 | 37.97 | 7.78 | 2.019 | 2.006 | 0.015 | 0.0431 | 0.0541 | 0.0097 |
| 100 | 4 | 14.33 | | | 32.56 | | | 1.990 | | | 0.0611 | | |
| 100 | 4 | 13.54 | | | 34.48 | | | 2.009 | | | 0.0583 | | |
| 100 | 5 | 11.15 | 11.30 | 0.27 | 48.84 | 48.19 | 1.13 | 3.025 | 3.075 | 0.097 | 0.0619 | 0.0638 | 0.0017 |
| 100 | 5 | 11.15 | | | 48.84 | | | 3.186 | | | 0.0652 | | |
| 100 | 5 | 11.61 | | | 46.88 | | | 3.013 | | | 0.0643 | | |
| 80 | 3 | 8.36 | 8.26 | 0.62 | 24.42 | 30.99 | 5.94 | 1.875 | 1.883 | 0.036 | 0.0768 | 0.0624 | 0.0130 |
| 80 | 3 | 7.60 | | | 32.56 | | | 1.922 | | | 0.0590 | | |
| 80 | 3 | 8.83 | | | 35.98 | | | 1.851 | | | 0.0514 | | |
| 80 | 4 | 13.14 | 12.68 | 0.49 | 29.60 | 28.18 | 3.29 | 1.307 | 1.329 | 0.039 | 0.0441 | 0.0475 | 0.0052 |
| 80 | 4 | 12.74 | | | 30.52 | | | 1.373 | | | 0.0450 | | |
| 80 | 4 | 12.16 | | | 24.42 | | | 1.306 | | | 0.0535 | | |
| 80 | 5 | 10.35 | 10.17 | 0.54 | 37.57 | 39.80 | 1.94 | 2.488 | 2.449 | 0.038 | 0.0662 | 0.0617 | 0.0039 |
| 80 | 5 | 9.56 | | | 40.70 | | | 2.412 | | | 0.0593 | | |
| 80 | 5 | 10.59 | | | 41.13 | | | 2.448 | | | 0.0595 | | |

Table 7: Experimental Results for Copper Slag

| Pressure | Feed Rate | Abrasive Quantity | Blasting Time | Area Cleaned | TPM Emissions | Productivity | Consumption | Emission Factor 1 | Emission Factor 2 |
|---|---|---|---|---|---|---|---|---|---|
| PSI | Turns | lbs | min | $ft^2$ | g | $m^2/hr$ | $kg/m^2$ | $kg/m^2$ | kg/kg |
| 120 | 3 | 100 | 7 | 8.5 | 2060 | 6.77 | 57.46 | 2.609 | 0.0454 |
| 120 | 3 | 100 | 8 | 9.0 | 2165 | 6.27 | 54.26 | 2.589 | 0.0477 |
| 120 | 3 | 50 | 5 | 6.0 | 1431 | 6.69 | 40.70 | 2.567 | 0.0631 |
| 120 | 4 | 150 | 10 | 20.0 | 2725 | 11.15 | 36.63 | 1.466 | 0.0400 |
| 120 | 4 | 100 | 6 | 12.0 | 1754 | 11.15 | 40.70 | 1.573 | 0.0387 |
| 120 | 4 | 50 | 4 | 8.0 | 1163 | 11.15 | 30.52 | 1.565 | 0.0513 |
| 120 | 5 | 120 | 6 | 10.0 | 2823 | 9.29 | 58.61 | 3.039 | 0.0518 |
| 120 | 5 | 80 | 4 | 7.0 | 1962 | 9.75 | 55.82 | 3.017 | 0.0540 |
| 120 | 5 | 100 | 4 | 7.3 | 2053 | 10.10 | 67.36 | 3.048 | 0.0452 |
| 100 | 3 | 100 | 8 | 13.5 | 2463 | 9.41 | 36.17 | 1.964 | 0.0543 |
| 100 | 3 | 50 | 4 | 7.0 | 1256 | 9.75 | 34.89 | 1.932 | 0.0554 |
| 100 | 3 | 75 | 6 | 10.3 | 1859.5 | 9.58 | 35.53 | 1.948 | 0.0548 |
| 100 | 4 | 150 | 7 | 18.0 | 2946 | 14.33 | 40.70 | 1.762 | 0.0433 |
| 100 | 4 | 150 | 7 | 17.8 | 2938 | 14.18 | 41.13 | 1.775 | 0.0432 |
| 100 | 4 | 120 | 6 | 15.0 | 2438 | 13.94 | 39.07 | 1.749 | 0.0448 |
| 100 | 5 | 120 | 8 | 15.8 | 3105 | 10.97 | 37.21 | 2.122 | 0.0570 |
| 100 | 5 | 50 | 4 | 8.0 | 1538 | 11.15 | 30.52 | 2.070 | 0.0678 |
| 100 | 5 | 50 | 4 | 8.0 | 1518 | 11.15 | 30.52 | 2.043 | 0.0669 |
| 80 | 3 | 50 | 6 | 6.0 | 1560 | 5.57 | 40.70 | 2.800 | 0.0688 |
| 80 | 3 | 50 | 7 | 6.5 | 1581 | 5.18 | 37.57 | 2.618 | 0.0697 |
| 80 | 3 | 50 | 6 | 6.5 | 1591 | 6.04 | 37.57 | 2.634 | 0.0701 |
| 80 | 4 | 150 | 12 | 19.0 | 3729 | 8.83 | 38.56 | 2.113 | 0.0548 |
| 80 | 4 | 100 | 6 | 9.8 | 1861 | 9.06 | 50.09 | 2.055 | 0.0410 |
| 80 | 4 | 125 | 9 | 14.4 | 2795 | 8.94 | 44.33 | 2.084 | 0.0479 |
| 80 | 5 | 80 | 8 | 9.0 | 2957 | 6.27 | 43.41 | 3.537 | 0.0815 |
| 80 | 5 | 80 | 6 | 7.0 | 2306 | 6.50 | 55.82 | 3.546 | 0.0635 |
| 80 | 5 | 80 | 7 | 8.0 | 2631.5 | 6.39 | 49.62 | 3.541 | 0.0725 |

Table 8: Mean and Standard Deviation (SD) of Experimental Results for Copper Slag

| Pressure | Feed Rate | Productivity | | | Consumption | | | Emission Factor 1 | | | Emission Factor 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PSI | Turns | $m^2$/hr | Mean | SD | kg/$m^2$ | Mean | SD | kg/$m^2$ | Mean | SD | kg/kg | Mean | SD |
| 120 | 3 | 6.77 | 6.58 | 0.27 | 57.46 | 50.81 | 8.90 | 2.609 | 2.588 | 0.021 | 0.0454 | 0.0521 | 0.0096 |
| 120 | 3 | 6.27 | | | 54.26 | | | 2.589 | | | 0.0477 | | |
| 120 | 3 | 6.69 | | | 40.70 | | | 2.567 | | | 0.0631 | | |
| 120 | 4 | 11.15 | 11.15 | 0.00 | 36.63 | 35.95 | 5.12 | 1.466 | 1.535 | 0.059 | 0.0400 | 0.0433 | 0.0069 |
| 120 | 4 | 11.15 | | | 40.70 | | | 1.573 | | | 0.0387 | | |
| 120 | 4 | 11.15 | | | 30.52 | | | 1.565 | | | 0.0513 | | |
| 120 | 5 | 9.29 | 9.72 | 0.41 | 58.61 | 60.60 | 6.02 | 3.039 | 3.035 | 0.016 | 0.0518 | 0.0504 | 0.0046 |
| 120 | 5 | 9.75 | | | 55.82 | | | 3.017 | | | 0.0540 | | |
| 120 | 5 | 10.10 | | | 67.36 | | | 3.048 | | | 0.0452 | | |
| 100 | 3 | 9.41 | 9.58 | 0.17 | 36.17 | 35.53 | 0.64 | 1.964 | 1.948 | 0.016 | 0.0543 | 0.0548 | 0.0006 |
| 100 | 3 | 9.75 | | | 34.89 | | | 1.932 | | | 0.0554 | | |
| 100 | 3 | 9.58 | | | 35.53 | | | 1.948 | | | 0.0548 | | |
| 100 | 4 | 14.33 | 14.15 | 0.20 | 40.70 | 40.30 | 1.08 | 1.762 | 1.762 | 0.013 | 0.0433 | 0.0437 | 0.0009 |
| 100 | 4 | 14.18 | | | 41.13 | | | 1.775 | | | 0.0432 | | |
| 100 | 4 | 13.94 | | | 39.07 | | | 1.749 | | | 0.0448 | | |
| 100 | 5 | 10.97 | 11.09 | 0.10 | 37.21 | 32.75 | 3.86 | 2.122 | 2.078 | 0.040 | 0.0570 | 0.0639 | 0.0060 |
| 100 | 5 | 11.15 | | | 30.52 | | | 2.070 | | | 0.0678 | | |
| 100 | 5 | 11.15 | | | 30.52 | | | 2.043 | | | 0.0669 | | |
| 80 | 3 | 5.57 | 5.60 | 0.43 | 40.70 | 38.61 | 1.81 | 2.800 | 2.684 | 0.101 | 0.0688 | 0.0695 | 0.0007 |
| 80 | 3 | 5.18 | | | 37.57 | | | 2.618 | | | 0.0697 | | |
| 80 | 3 | 6.04 | | | 37.57 | | | 2.634 | | | 0.0701 | | |
| 80 | 4 | 8.83 | 8.94 | 0.12 | 38.56 | 44.32 | 5.77 | 2.113 | 2.084 | 0.029 | 0.0548 | 0.0479 | 0.0069 |
| 80 | 4 | 9.06 | | | 50.09 | | | 2.055 | | | 0.0410 | | |
| 80 | 4 | 8.94 | | | 44.33 | | | 2.084 | | | 0.0479 | | |
| 80 | 5 | 6.27 | 6.39 | 0.12 | 43.41 | 49.62 | 6.20 | 3.537 | 3.541 | 0.004 | 0.0815 | 0.0725 | 0.0090 |
| 80 | 5 | 6.50 | | | 55.82 | | | 3.546 | | | 0.0635 | | |
| 80 | 5 | 6.39 | | | 49.62 | | | 3.541 | | | 0.0725 | | |

Table 9: Experimental Results for Specialty Sand

| **Pressure** | **Feed Rate** | **Abrasive Quantity** | **Blasting Time** | **Area Cleaned** | **TPM Emissions** | **Productivity** | **Consumption** | **Emission Factor 1** | **Emission Factor 2** |
|---|---|---|---|---|---|---|---|---|---|
| **PSI** | **Turns** | **lbs** | **min** | **ft$^2$** | **g** | **m$^2$/hr** | **kg/m$^2$** | **kg/m$^2$** | **kg/kg** |
| 120 | 3 | 50 | 6 | 11.5 | 3034 | 10.68 | 21.23 | 2.840 | 0.1337 |
| 120 | 3 | 100 | 8 | 15.0 | 4242 | 10.45 | 32.56 | 3.044 | 0.0935 |
| 120 | 3 | 50 | 3 | 5.8 | 1615 | 10.68 | 42.47 | 3.024 | 0.0712 |
| 120 | 4 | 50 | 4 | 10.0 | 4005 | 13.94 | 24.42 | 4.311 | 0.1766 |
| 120 | 4 | 50 | 3 | 7.8 | 3611 | 14.40 | 31.51 | 5.015 | 0.1592 |
| 120 | 4 | 100 | 9 | 22.0 | 9578 | 13.63 | 22.20 | 4.687 | 0.2111 |
| 120 | 5 | 100 | 7 | 22.5 | 8042 | 17.92 | 21.70 | 3.847 | 0.1772 |
| 120 | 5 | 100 | 5 | 15.0 | 5161 | 16.72 | 32.56 | 3.704 | 0.1137 |
| 120 | 5 | 100 | 6 | 18.8 | 6586 | 17.42 | 26.05 | 3.781 | 0.1452 |
| 100 | 3 | 50 | 4 | 10.5 | 1298 | 14.63 | 23.26 | 1.330 | 0.0572 |
| 100 | 3 | 50 | 4 | 10.0 | 1365 | 13.94 | 24.42 | 1.469 | 0.0601 |
| 100 | 3 | 50 | 3 | 7.5 | 681 | 13.94 | 32.56 | 0.976 | 0.0300 |
| 100 | 4 | 50 | 4 | 11.8 | 3214 | 16.37 | 20.78 | 2.944 | 0.1417 |
| 100 | 4 | 50 | 4 | 12.0 | 3298 | 16.72 | 20.35 | 2.958 | 0.1454 |
| 100 | 4 | 100 | 7 | 21.5 | 6165 | 17.12 | 22.71 | 3.087 | 0.1359 |
| 100 | 5 | 50 | 4 | 6.5 | 2148 | 9.06 | 37.57 | 3.556 | 0.0947 |
| 100 | 5 | 50 | 3 | 5.3 | 1977 | 9.75 | 46.51 | 4.054 | 0.0871 |
| 100 | 5 | 100 | 10 | 17.0 | 5722 | 9.48 | 28.73 | 3.623 | 0.1261 |
| 80 | 3 | 50 | 4 | 8.8 | 846 | 12.19 | 27.91 | 1.041 | 0.0373 |
| 80 | 3 | 100 | 8 | 14.5 | 1500 | 10.10 | 33.68 | 1.114 | 0.0331 |
| 80 | 3 | 100 | 8 | 15.0 | 1679 | 10.45 | 32.56 | 1.204 | 0.0370 |
| 80 | 4 | 50 | 4 | 8.8 | 1116 | 12.19 | 27.91 | 1.373 | 0.0492 |
| 80 | 4 | 50 | 5 | 10.0 | 1449 | 11.15 | 24.42 | 1.560 | 0.0639 |
| 80 | 4 | 100 | 8 | 18.0 | 2464 | 12.54 | 27.13 | 1.474 | 0.0543 |
| 80 | 5 | 50 | 5 | 7.1 | 1480 | 7.94 | 34.27 | 2.236 | 0.0652 |
| 80 | 5 | 50 | 5 | 8.0 | 1824 | 8.92 | 30.52 | 2.453 | 0.0804 |
| 80 | 5 | 100 | 8 | 13.8 | 3228 | 9.58 | 35.52 | 2.526 | 0.0711 |

Table 10: Mean and Standard Deviation (SD) of Experimental Results for Specialty Sand

| **Pressure** | **Feed Rate** | **Productivity** | | | **Consumption** | | | **Emission Factor 1** | | | **Emission Factor 2** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PSI** | **Turns** | **$m^2$/hr** | **Mean** | **SD** | **kg/$m^2$** | **Mean** | **SD** | **kg/$m^2$** | **Mean** | **SD** | **kg/kg** | **Mean** | **SD** |
| 120 | 3 | 10.68 | 10.61 | 0.13 | 21.23 | 32.09 | 10.63 | 2.840 | 2.969 | 0.113 | 0.1337 | 0.0995 | 0.0317 |
| 120 | 3 | 10.45 | | | 32.56 | | | 3.044 | | | 0.0935 | | |
| 120 | 3 | 10.68 | | | 42.47 | | | 3.024 | | | 0.0712 | | |
| 120 | 4 | 13.94 | 13.99 | 0.39 | 24.42 | 26.04 | 4.86 | 4.311 | 4.671 | 0.352 | 0.1766 | 0.1823 | 0.0264 |
| 120 | 4 | 14.40 | | | 31.51 | | | 5.015 | | | 0.1592 | | |
| 120 | 4 | 13.63 | | | 22.20 | | | 4.687 | | | 0.2111 | | |
| 120 | 5 | 17.92 | 17.35 | 0.60 | 21.70 | 26.77 | 5.46 | 3.847 | 3.777 | 0.072 | 0.1772 | 0.1454 | 0.0317 |
| 120 | 5 | 16.72 | | | 32.56 | | | 3.704 | | | 0.1137 | | |
| 120 | 5 | 17.42 | | | 26.05 | | | 3.781 | | | 0.1452 | | |
| 100 | 3 | 14.63 | 14.17 | 0.40 | 23.26 | 26.75 | 5.07 | 1.330 | 1.259 | 0.254 | 0.0572 | 0.0491 | 0.0166 |
| 100 | 3 | 13.94 | | | 24.42 | | | 1.469 | | | 0.0601 | | |
| 100 | 3 | 13.94 | | | 32.56 | | | 0.976 | | | 0.0300 | | |
| 100 | 4 | 16.37 | 16.74 | 0.37 | 20.78 | 21.28 | 1.26 | 2.944 | 2.996 | 0.079 | 0.1417 | 0.1410 | 0.0048 |
| 100 | 4 | 16.72 | | | 20.35 | | | 2.958 | | | 0.1454 | | |
| 100 | 4 | 17.12 | | | 22.71 | | | 3.087 | | | 0.1359 | | |
| 100 | 5 | 9.06 | 9.43 | 0.35 | 37.57 | 37.60 | 8.89 | 3.556 | 3.744 | 0.270 | 0.0947 | 0.1026 | 0.0207 |
| 100 | 5 | 9.75 | | | 46.51 | | | 4.054 | | | 0.0871 | | |
| 100 | 5 | 9.48 | | | 28.73 | | | 3.623 | | | 0.1261 | | |
| 80 | 3 | 12.19 | 10.92 | 1.12 | 27.91 | 31.38 | 3.06 | 1.041 | 1.120 | 0.082 | 0.0373 | 0.0358 | 0.0024 |
| 80 | 3 | 10.10 | | | 33.68 | | | 1.114 | | | 0.0331 | | |
| 80 | 3 | 10.45 | | | 32.56 | | | 1.204 | | | 0.0370 | | |
| 80 | 4 | 12.19 | 11.96 | 0.73 | 27.91 | 26.49 | 1.83 | 1.373 | 1.469 | 0.093 | 0.0492 | 0.0558 | 0.0074 |
| 80 | 4 | 11.15 | | | 24.42 | | | 1.560 | | | 0.0639 | | |
| 80 | 4 | 12.54 | | | 27.13 | | | 1.474 | | | 0.0543 | | |
| 80 | 5 | 7.94 | 8.81 | 0.82 | 34.27 | 33.44 | 2.60 | 2.236 | 2.405 | 0.151 | 0.0652 | 0.0723 | 0.0076 |
| 80 | 5 | 8.92 | | | 30.52 | | | 2.453 | | | 0.0804 | | |
| 80 | 5 | 9.58 | | | 35.52 | | | 2.526 | | | 0.0711 | | |

## *5.1. Emission Factors*

### *5.1.1. Emission Factors in kg/m$^2$*

#### *5.1.1.1. Variation of emission factors (kg/m$^2$) with pressure*

Velocity of abrasive particles is determined by blast pressure. Higher the pressure, greater will be the velocity and hence greater impact on base plate. Although this may increase productivity, at very high velocity, the abrasive particles suffer more damage, thus breakdown into smaller particles. This causes increased emissions at high pressure. Figure 5 shows the variation of emission factors (kg/m$^2$) with pressure at 3 turns of feed rate. It was observed that emission factors increased with pressure for coal slag and specialty sand. This may be due to more number of particles undergoing damage with increase in pressure.

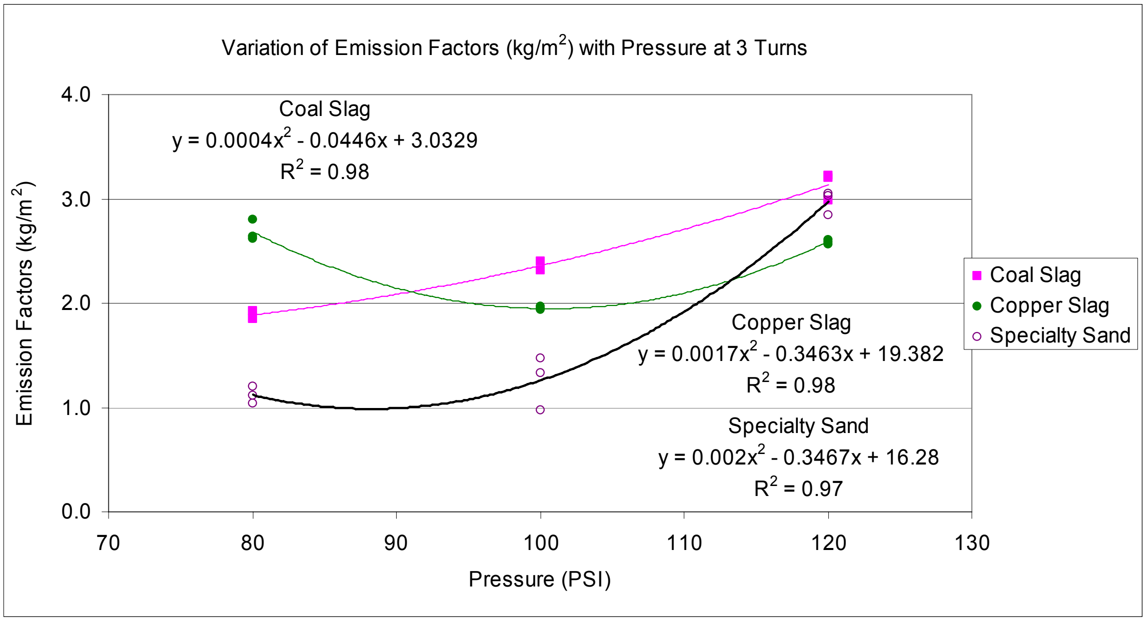


Figure 5: Variation of Emission Factors (kg/m2) with Pressure at 3 Turns

In case of copper slag, emission factors decreased with increase in pressure from 80 PSI to 100 PSI and then increased with further increase in pressure. This may be because at lower pressure, although emissions may be less, emission factors will be high because of less productivity and more consumption at lower velocity. It can be observed from the graph that at lower pressure, emission factors varied significantly from one material to another, highest being copper slag. At very high pressure, all three materials have less comparable emission factors, especially for coal slag and specialty sand. The regression equations developed and corresponding $R^2$ values are shown in Figure 5.

Variation of emission factors (kg/m$^2$) with pressure at 4 turns of feed rate is shown in Figure 6. Emission factors for coal slag and specialty sand increased with pressure similar to the variation at 3 turns. However, for copper slag, emission factors decreased with increase in pressure.

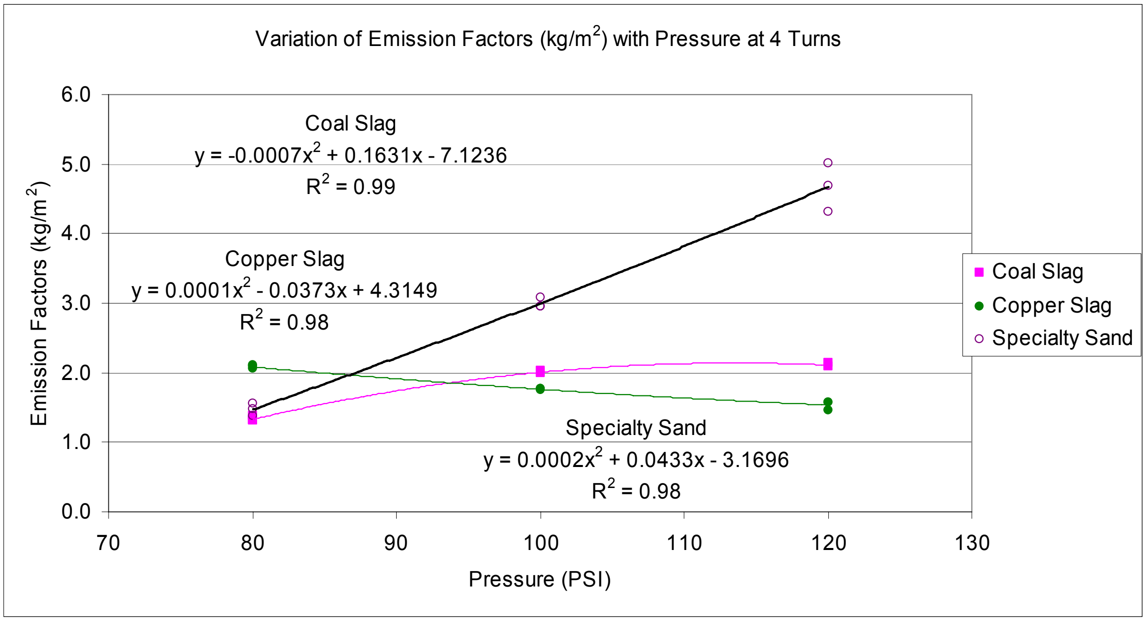


Figure 6: Variation of Emission Factors (kg/m2) with Pressure at 4 Turns

It can be observed from Figure 6 that increase in emission factors for specialty sand was significantly higher while in case of coal slag and copper slag, a slight variation of emission factors was observed. $R^2$ values obtained for the three materials were very close (0.98 and 0.99)

Figure 7 shows the variation of emission factors with pressure at 5 turns of feed rate. The variation emission factors at 5 turns were observed to be similar to the variation at 3 turns. While copper slag has highest emission factors at 80 PSI, with increase in pressure, emission factors were observed to be lesser than coal slag and specialty sand. The regression equations to calculate emission factors at intermediate blast pressures ranging from 80 to 120 PSI are also shown in Figure 10. $R^2$ value for specialty sand (0.95) was lesser as compared to coal slag and copper slag (0.99).

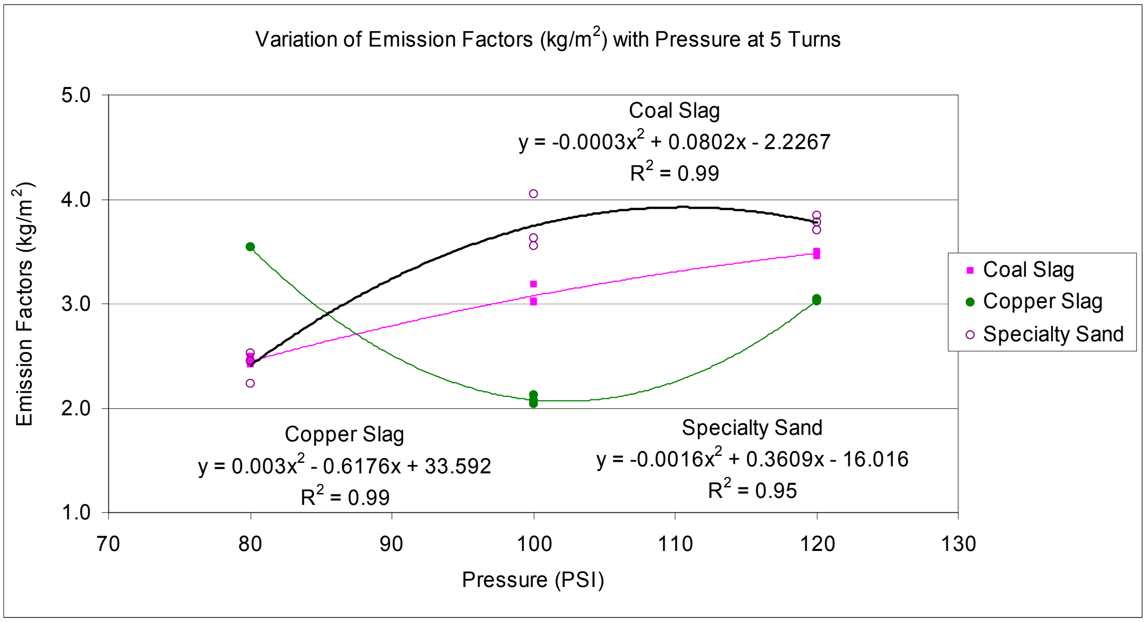


Figure 7: Variation of Emission Factors (kg/m2) with Pressure at 5 Turns

#### *5.1.1.2. Variation of emission factors (kg/m$^2$) with feed rate*

Controlling feed rate is an important factor in abrasive blasting since it determines the mass of abrasive released from the nozzle. Figures 8, 9, and 10 show the variation of emission factors with feed rate at 80, 100, and 120 PSI for coal slag, copper slag, and specialty sand. It can be observed that for coal slag and copper slag, the emission factors initially decreased with increase in feed rate and then increased with further increase in feed rate. This may be due to more material consumption at lower feed rate to clean a unit area. i.e., at lower feed rate, less number of particles impacts the unit surface and consumes more material to achieve desired surface finish.

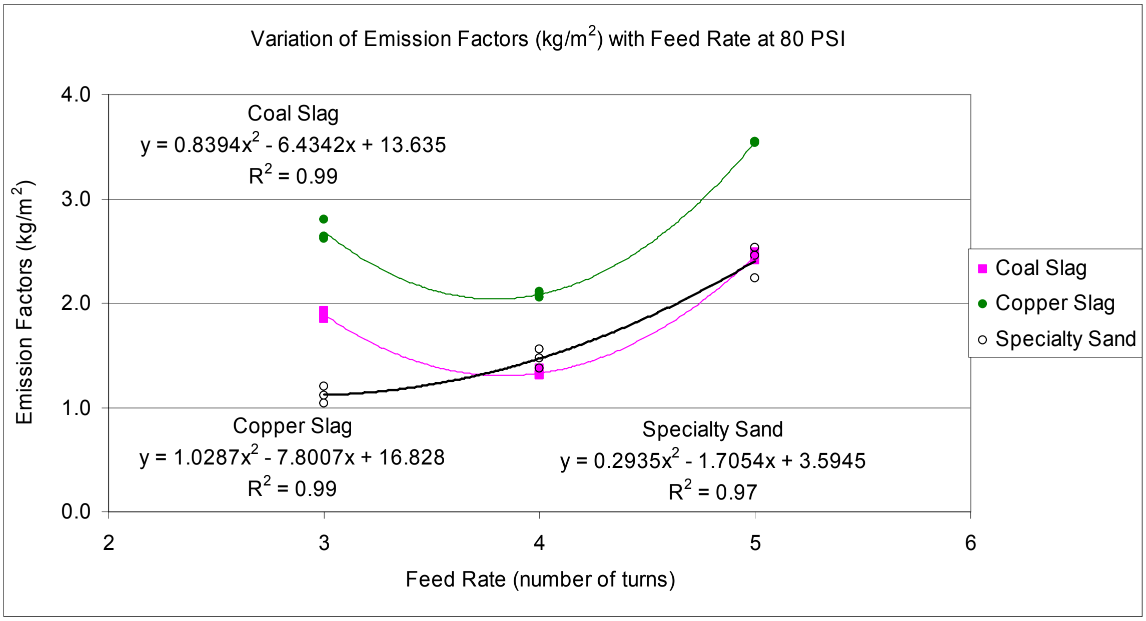


Figure 8: Variation of Emission Factors (kg/m2) with Feed Rate at 80 PSI

With increase in feed rate, more uniform flow of material occurs and less material is consumed to clean a unit area, thus resulting in less emission factors. However, at very high feed rates, the particles traveling from the nozzle interact with the rebounding particles from the base plate and breakdown resulting in higher emissions and consuming more material. In addition, at high feed rates, flow of material may turbulent rather than uniform. This increases emission factors with increase in feed rate.

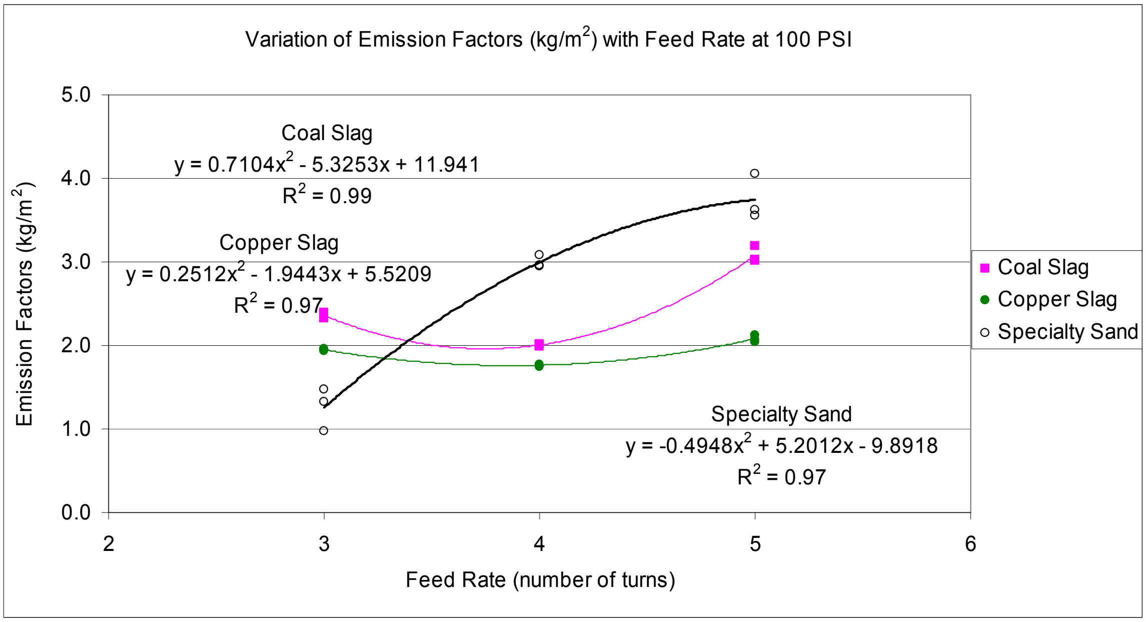


Figure 9: Variation of Emission Factors (kg/m2) with Feed Rate at 100 PSI

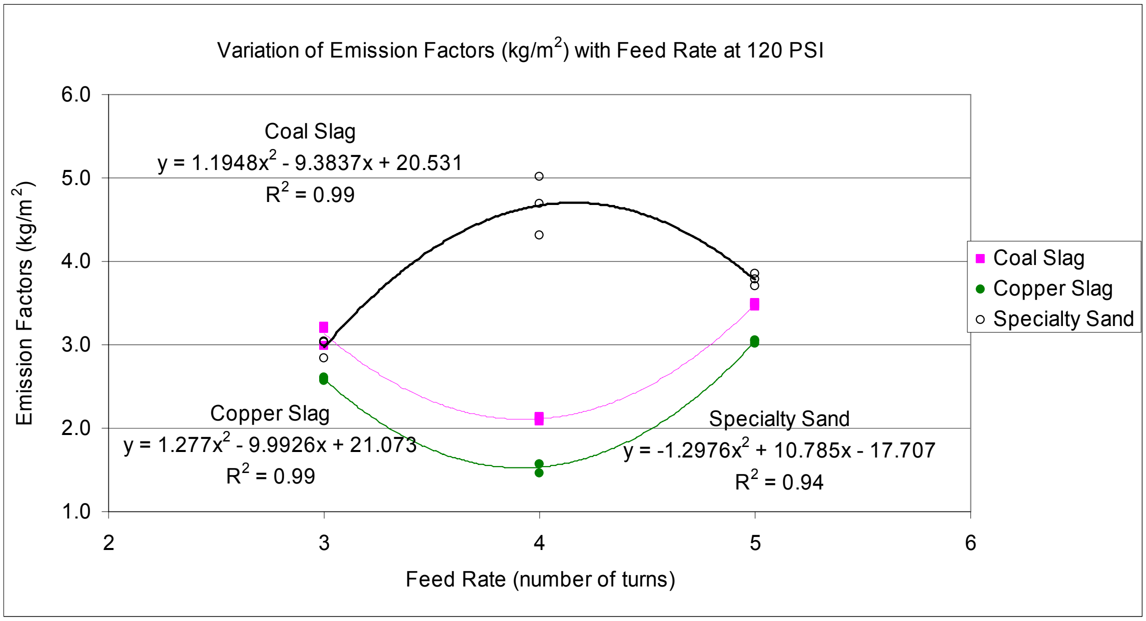


Figure 10: Variation of Emission Factors (kg/m2) with Feed Rate at 120 PSI

Emission factors for specialty sand were observed to increase with feed rate at 80 and 100 PSI. This may be due to higher breakdown rate of abrasive particles at higher feed rate. At 120 PSI, the emission factors increased with feed rate from 3 to 4 turns and then decreased with increase in feed rate to 5 turns. Specialty sand may have more uniform flow of material at higher pressure and feed rate conditions, resulting in lower emissions which can be observed from Figures 7 and 10. At 80 PSI, copper slag has higher emission factors than coal slag and at 100 and 120 PSI, copper slag has lower emission factors than coal slag. In case of sand, lower emission factors were observed at low pressure (80 PSI). The regression equations to determine emission factors at intermediate feed rates for blast pressures of 80, 100, and 120 PSI are also shown in Figures 8, 9, and 10 respectively.

### *5.1.1.3. Variation of emission factors (kg/m$^2$) with pressure and feed rate*

The variations and equations discussed above depict either effect of pressure on emissions at a given feed rate or effect of feed rate at a specific pressure. In order to study simultaneous effects of both, pressure and feed rate on emissions, three-dimensional models were developed. Datafit © curve fitting application was used for regression analysis and for plotting three-dimensional charts. Figure 11, 12, and 13 demonstrates the variation of emission factors with pressure and feed rate for coal slag, copper slag, and specialty sand respectively.

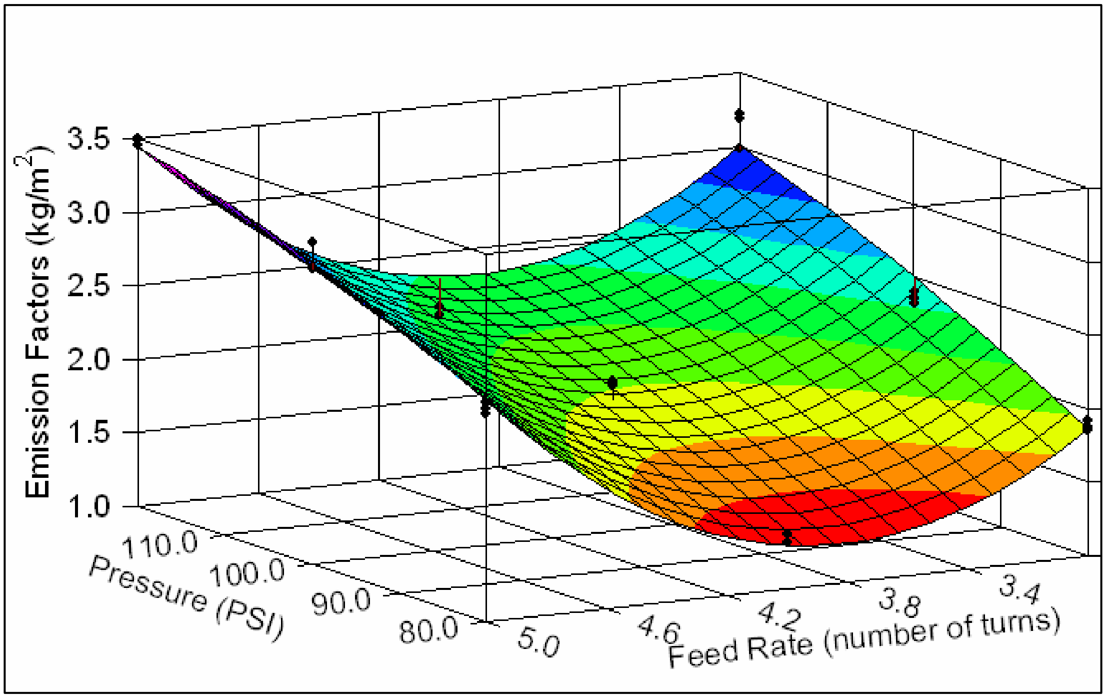


Figure 11: Coal Slag - Variation of Emission Factors (kg/m2) with Pressure and Feed Rate

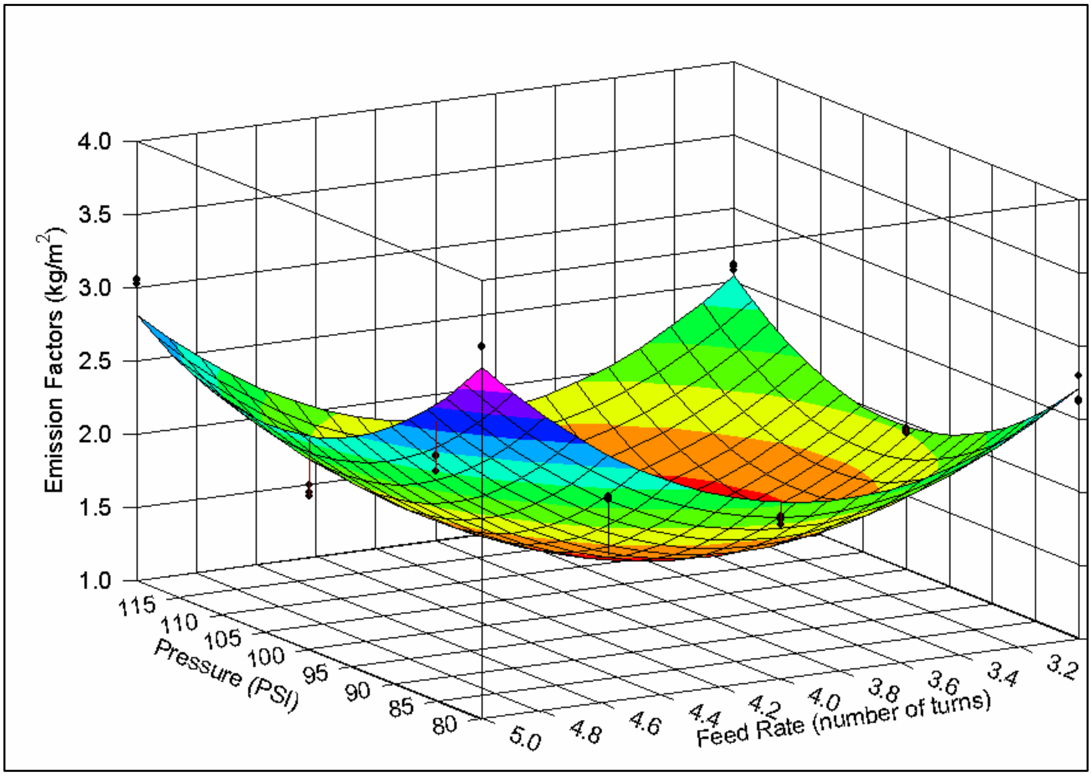


Figure 12: .Copper Slag - Variation of Emission Factors (kg/m2) with Pressure and Feed Rate

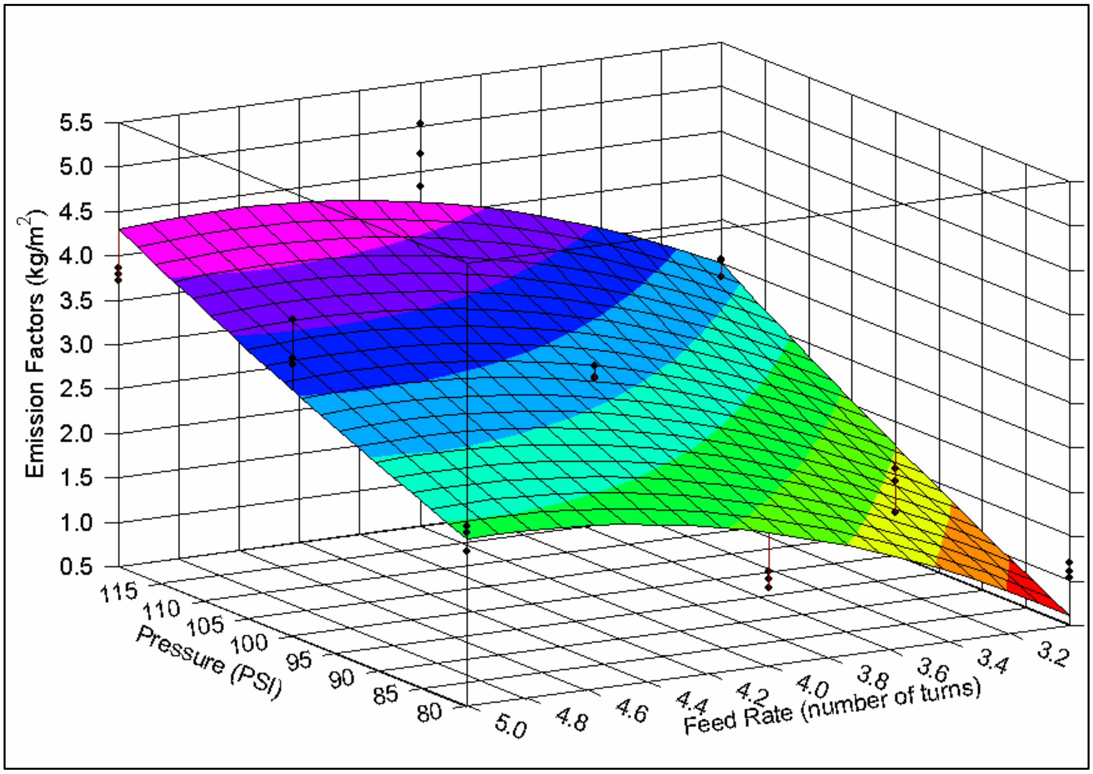


Figure 13: Specialty Sand - Variation of Emission Factors (kg/m2) with Pressure and Feed Rate

The regression model developed to determine emission factors at intermediate pressure and feed rate is:

$$EF = a + (b * P) + (c * F) + (d * P^2) + (e * F^2) + (f * P * F) \qquad (2)$$

Where,

EF = Emission Factor in kg/m$^2$,

P = Blast Pressure in PSI, (80 to 120 PSI),

F = Feed Rate in Number of Turns of Schmidt Feed Valve (3 to 5), and

a, b, c, d, e, and f are coefficients, given in Table 11.

Table 11: Coefficients for Emission Factors in (kg/m$^2$) for Equation 2

| **Abrasive Material** | **a** | **b** | **c** | **d** | **e** | **f** | **R$^2$** |
|---|---|---|---|---|---|---|---|
| Coal Slag | 9.61E+00 | 7.18E-02 | -6.58E+00 | -1.75E-04 | 8.90E-01 | -2.67E-03 | 0.97 |
| Copper Slag | 2.92E+01 | -3.13E-01 | -6.07E+00 | 1.62E-03 | 8.52E-01 | -5.14E-03 | 0.86 |
| Specialty Sand | -1.41E+01 | 4.30E-02 | 5.36E+00 | 1.72E-04 | -5.00E-01 | -5.97E-03 | 0.86 |

### *5.1.2. Emission Factors in kg/kg*

#### *5.1.2.1. Variation of emission factors (kg/kg) with pressure*

As mentioned earlier, abrasive particles breakdown at higher rate with increase in pressure due to greater impact with which they strike the base plate. Thus, emissions increase with blast pressure. This trend can be observed for coal slag and specialty sand in Figure 14 at 3 turns of feed rate. However, in some cases, at higher pressure, the self abrasion of particles causes breakdown of particles before striking the plate. Because smaller particles may not be efficient in removing the paint from the surface, more material is required to achieve required finish. This results in decrease of emission factors per unit mass of abrasive consumed. This trend is observed in case of copper slag. At 80 and 100 PSI, coal slag, copper slag, and specialty sand have comparable emission factors while at higher pressure, copper slag resulted in significantly lesser emission factors. The $R^2$ values obtained from the regression analysis were lower for coal slag and specialty sand.

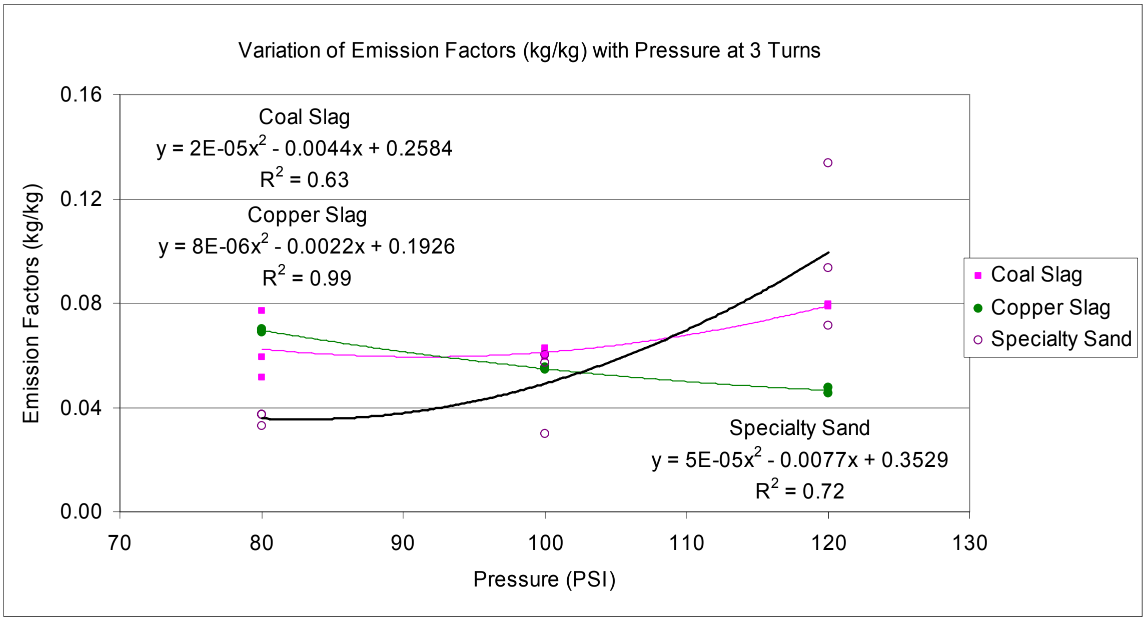


Figure 14: Variation of Emission Factors (kg/kg) with Pressure at 3 turns

Figure 15 shows the variation of emission factors with pressure at 4 turns of feed rate. Similar to variation at 3 turns, emission factors for coal slag and specialty sand. Increase in emission factors for specialty sand was considerably higher as compared to coal slag.

In case of copper slag, emission factors decreased with increase in blast pressure, which may be sue to the effect of self abrasion of particles as explained earlier. At 80 PSI, all three materials were observed to have almost same emission factors. With increase in pressure, emission factors for specialty sand increased significantly than for coal slag and copper slag. At 120 PSI, copper slag was observed to have the lowest emission factors and specialty sand, highest emission factors. Regression equations to calculate emission factors at intermediate blast pressure are also given in Figure 15. Copper slag had notably lower $R^2$ (0.48) compared to coal slag and specialty sand.

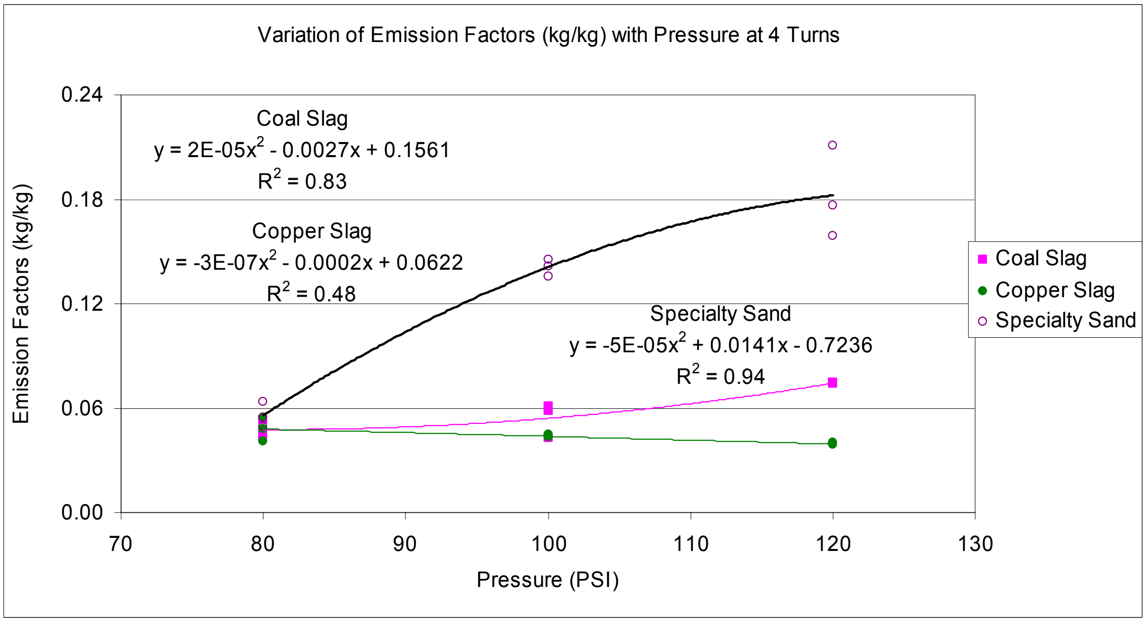


Figure 15: Variation of Emission Factors (kg/kg) with Pressure at 4 turns

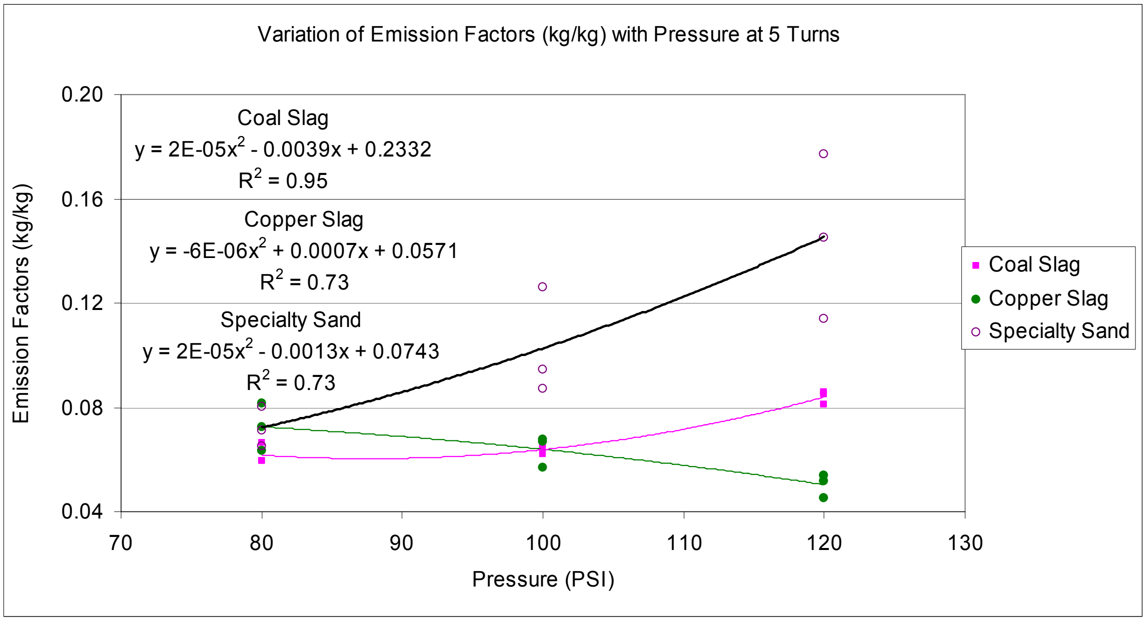


Figure 16: Variation of Emission Factors (kg/kg) with Pressure at 5 turns

Variation of emission factors with pressure at 5 turns of feed rate Figure 15 was similar to the variation at 4 turns. Specialty sand had higher emission factors at higher blast pressure. Emission factors for copper slag decreased with increase in pressure. Regression equations for determining emission factors at intermediate feed rates are also shown in Figure 16. $R^2$ values for copper slag and specialty sand were 0.73, and higher for coal slag, 0.95.

### *5.1.2.2. Variation of emission factors (kg/kg) with feed rate*

At higher feed rates, the particles traveling from the nozzle interact with the rebounding particles from the base plate and breakdown resulting in higher emissions. In addition, higher feed rates may result in turbulent flow which results in self-abrasion of particles and reduction in velocity. Thus, a uniform flow results in less emissions while cleaning more area and consuming less material.

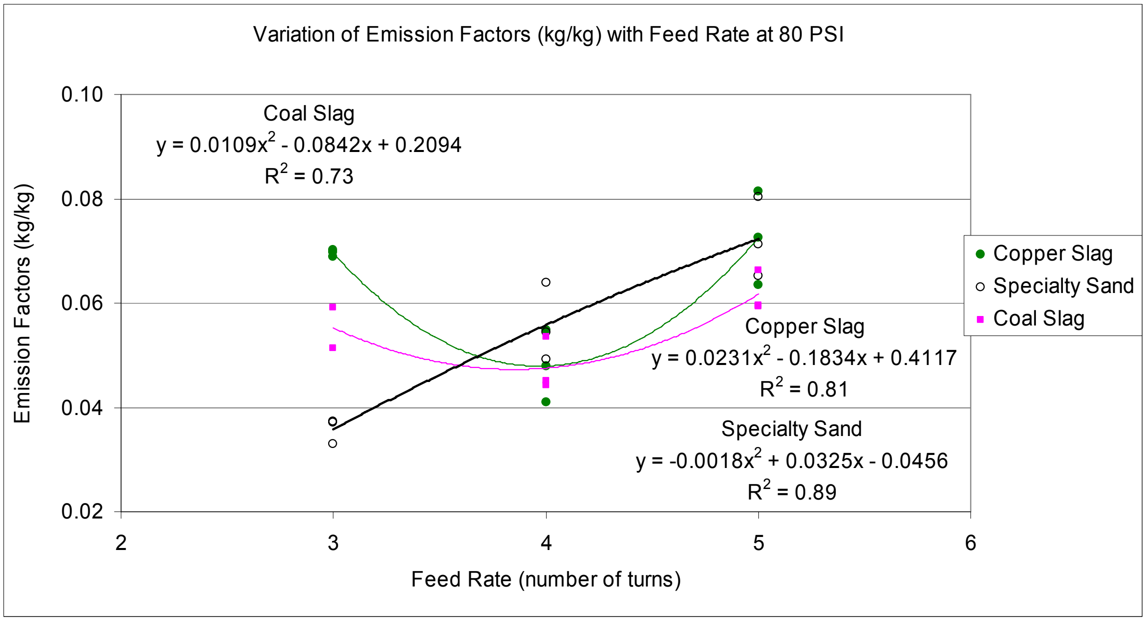


Figure 17: Variation of Emission Factors (kg/kg) with Feed Rate at 80 PSI

The effect of feed rate on emission factors at 80 PSI is shown in Figure 17. At 3 turns of feed rate, copper slag had highest emission factors and specialty sand had lowest emission factors. However, with increase in feed rate, all three materials had comparable average emission factors. In case of copper slag, emission factors decreased with increase in feed rate from 3 to 4 turns and then increased with further increase in feed rate. This may be due to uniform flow and effective cleaning at 4 turns of feed rate. For coal slag, although average emission factor showed similar trend as copper slag, the variation was not significant. In case of specialty sand, emission factors increased with increase in feed rate, which may be due to self-abrasion of particles and non-uniform flow of material at higher feed rates. The regression equations for estimating emission factors at intermediate feed rates for blast pressure of 80 PSI are also shown in Figure 17. $R^2$ values obtained for these variations were less than 0.90.

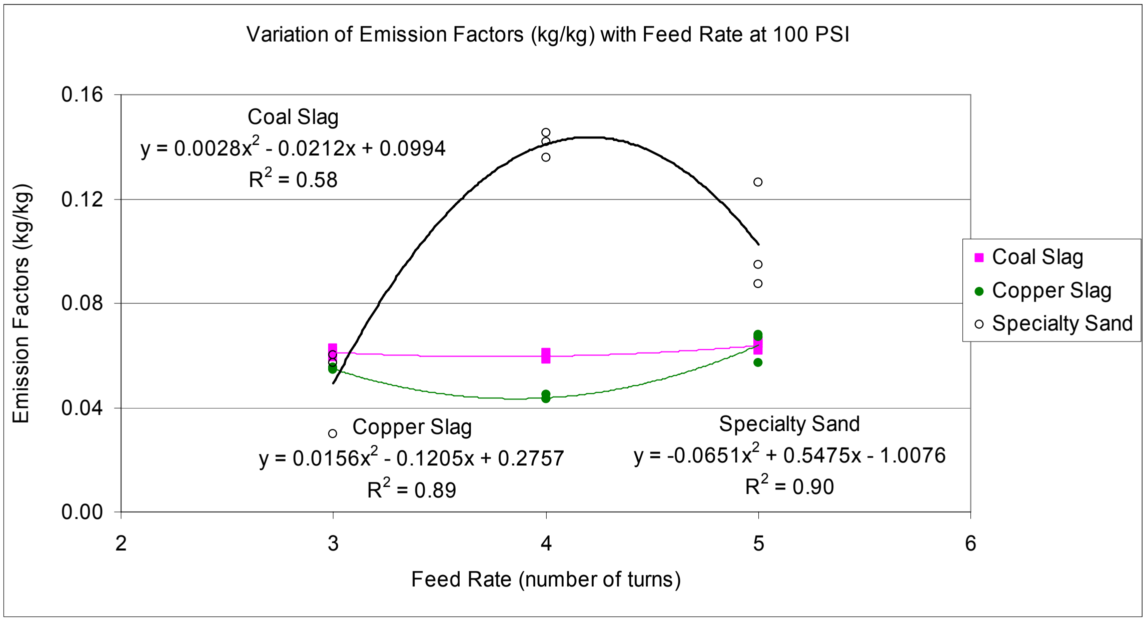


Figure 18: Variation of Emission Factors (kg/kg) with Feed Rate at 100 PSI

Figures 18 and 19 show the variation of emission factors with feed rate at 100 and 120 PSI respectively. Coal slag showed an insignificant variation in emission factors with feed rate. Copper slag emission factors decreased with increase in feed rate and then increased at 100 PSI similar to the variation at 80 PSI, which may be due to more uniform flow at 4 turns. However, at 120 PSI, this variation was not significant. This may be because of lesser effect of feed rate at higher pressures. In case specialty sand, emission factors increased with increase in feed rate from 3 to 4 turns and then decreased with further increase in feed rate. A more uniform flow and less consumption of material at higher feed rates may have resulted in decreased emission factors at 100 and 120 PSI. The equations to determine emission factors at intermediate feed rates for 100 and 120 PSI are also shown in Figures 18 and 19.

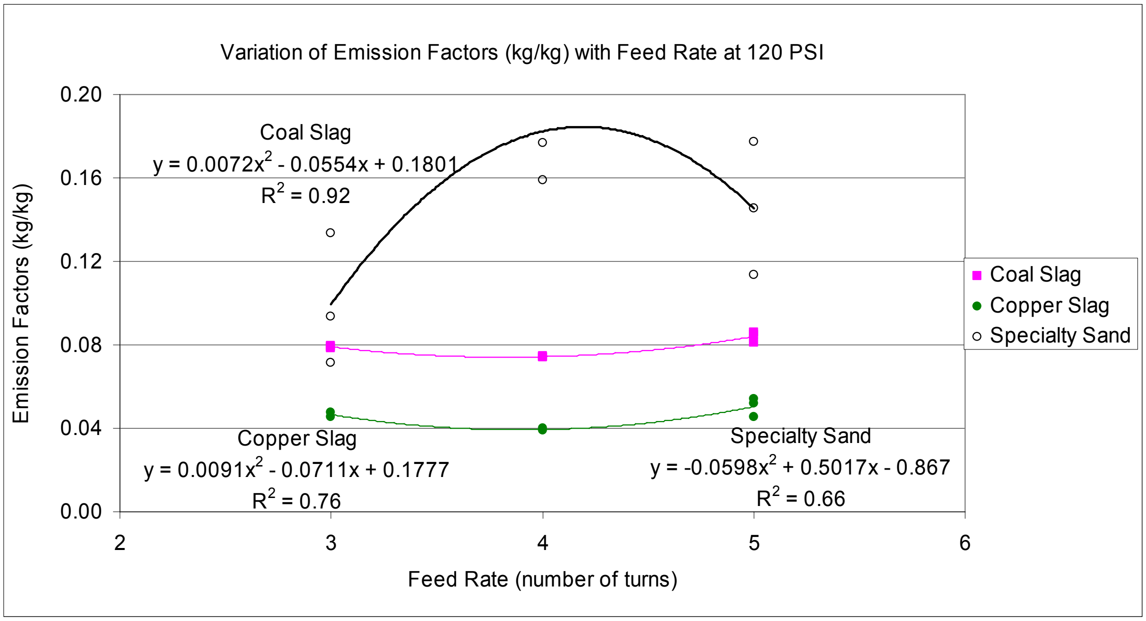


Figure 19: Variation of Emission Factors (kg/kg) with Feed Rate at 120 PSI

### *5.1.2.3. Variation of emission factors (kg/kg) with pressure and feed rate*

Figures 20, 21, and 22 show variation of emission factors with both pressure and feed rate. The regression model developed to determine emission factors at intermediate pressure and feed rate is:

$$EF = a + (b * P) + (c * F) + (d * P^2) + (e * F^2) + (f * P * F) \qquad (3)$$

Where,

EF = Emission Factor in kg/kg,

P = Blast Pressure in PSI, (80 to 120 PSI),

F = Feed Rate in Number of Turns of Schmidt Feed Valve (3 to 5), and

a, b, c, d, e, and f are coefficients, given in Table 12.

Table 12: Coefficients for Emission Factors in (kg/kg) for Equation 3

| **Abrasive Material** | **a** | **b** | **c** | **d** | **e** | **f** | **$R^2$** |
|---|---|---|---|---|---|---|---|
| Coal Slag | 2.38E-01 | -2.20E-03 | -5.37E-02 | 1.46E-05 | 7.32E-03 | -2.47E-05 | 0.94 |
| Copper Slag | 3.48E-01 | -5.15E-04 | -1.31E-01 | 8.93E-08 | 1.65E-02 | 9.52E-06 | 0.83 |
| Specialty Sand | -7.90E-01 | 1.26E-03 | 3.49E-01 | 2.29E-06 | -4.23E-02 | 1.18E-04 | 0.82 |

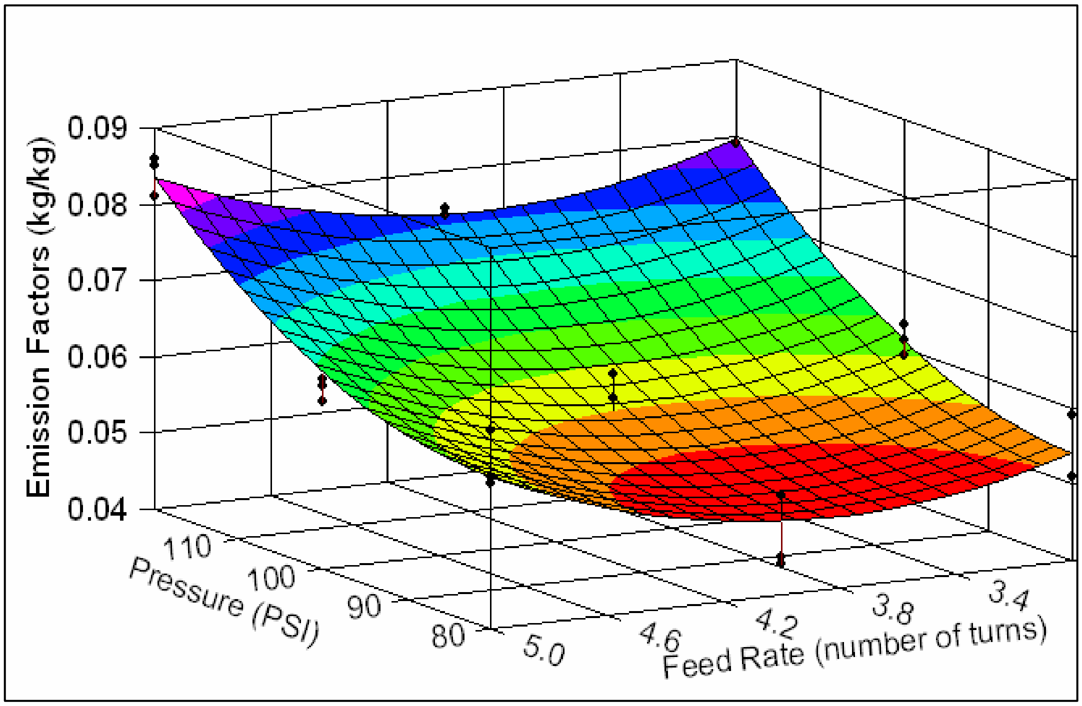


Figure 20: Coal Slag - Variation of Emission Factors (kg/kg) with Pressure and Feed Rate

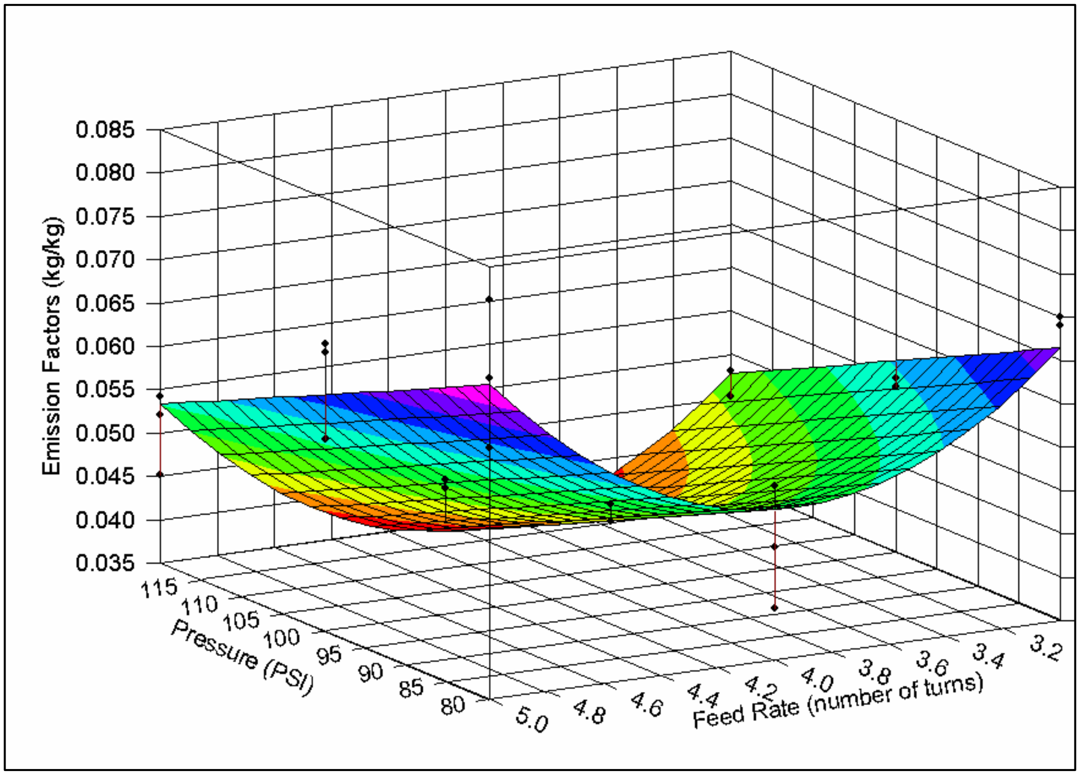


Figure 21: Copper Slag - Variation of Emission Factors (kg/kg) with Pressure and Feed Rate

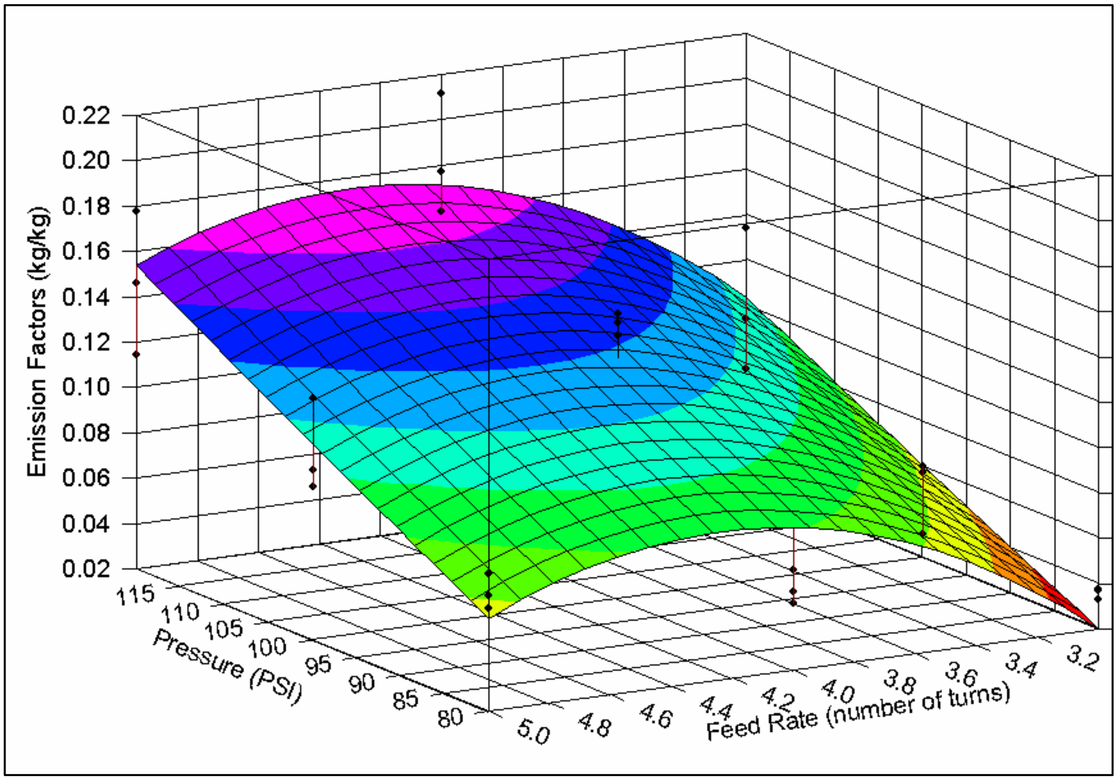


Figure 22: Specialty Sand - Variation of Emission Factors (kg/kg) with Pressure and Feed Rate

## *5.2. Productivity*

### *5.1.1. Variation of Productivity with Pressure*

The variation of productivity with pressure at 3, 4, and 5 turns of feed rate is shown in Figures 23, 26, and 25, respectively. Productivity of coal slag increased with increase in pressure at 3, 4, and 5 turns. An increase in pressure results in higher velocities and a significant increase in the kinetic energy of abrasive particles since kinetic energy imparted to the abrasive material is proportional to square of the velocity ($V^2$) of the material. Thus, a greater impact is created upon striking the plate resulting in lesser dwell time to remove paint from the surface. Hence, productivity increased with increase in blast pressure. While this trend was observed for copper slag and specialty sand from blast pressures 80 to 100 PSI, the productivity decreased with further increase in pressure to 120 PSI at 3 and 4 turns. At very high pressures, the particles undergo more damage due to self-abrasion of abrasive particles and impact of rebounding particles causes loss of energy. Thus, kinetic energy of particles striking the plate decreases, resulting in decreased productivity at very high pressures. In addition, worker fatigue at high blast pressures causes decrease in productivity.

At 5 turns of feed rate, while coal slag and copper slag followed similar trends as at 3 and 4 turns, productivity of sand increased with increase in pressure. This may be due to lesser effect of self-abrasion and rebounding particles and greater abrasive flow rate at 5 turns, which resulted in more number of particles impacting the surface with higher kinetic energy. Specialty sand was more effective in removing paint at a faster rate than coal slag and copper in most cases. Higher hardness of sand grains due to improved abrasive qualities by processing from the suppliers may have resulted in higher productivity. While coal slag and copper slag had approximately same productivity at 100 PSI, coal slag resulted in higher productivity than copper slag at 80 and 120 PSI for 3, 4, and 5 turns of feed rate.

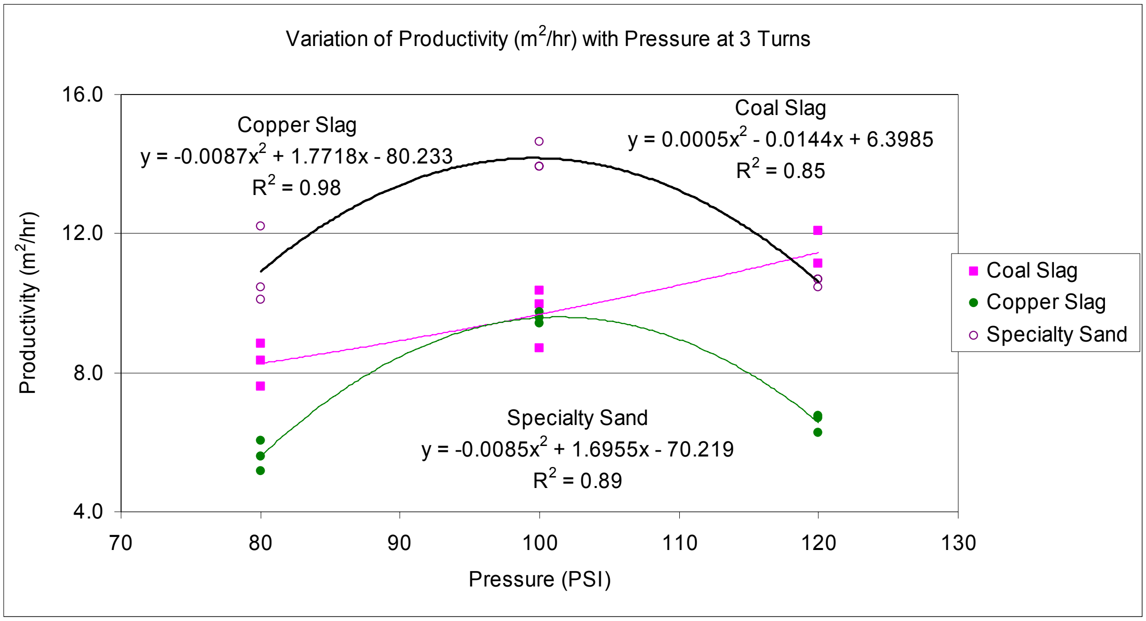


Figure 23: Variation of Productivity with Pressure at 3 Turns

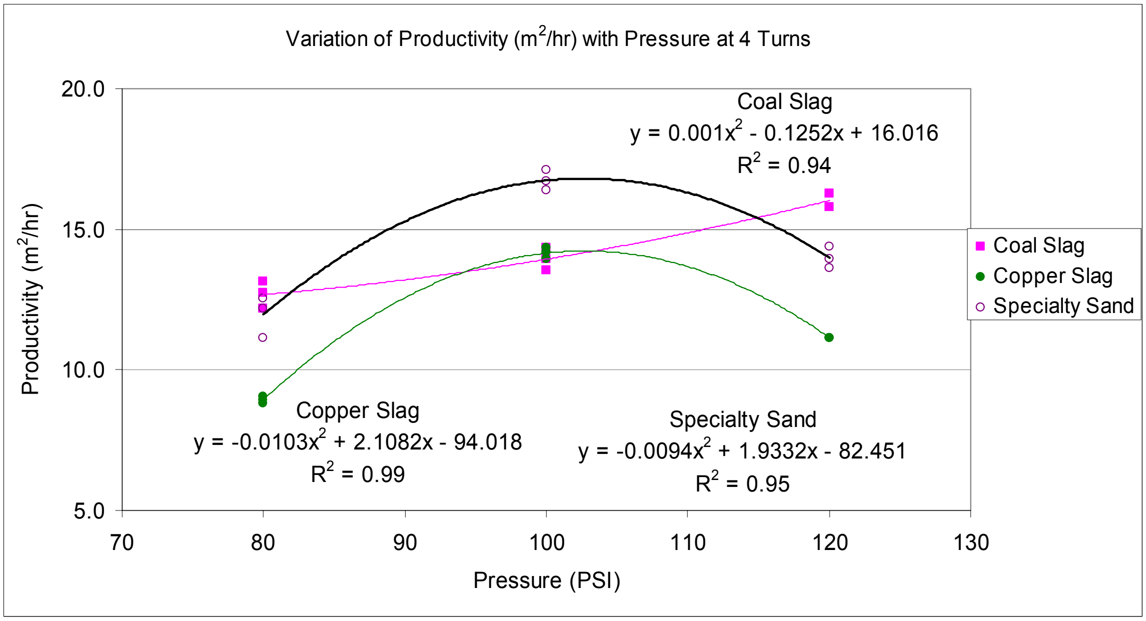


Figure 24: Variation of Productivity with Pressure at 4 Turns

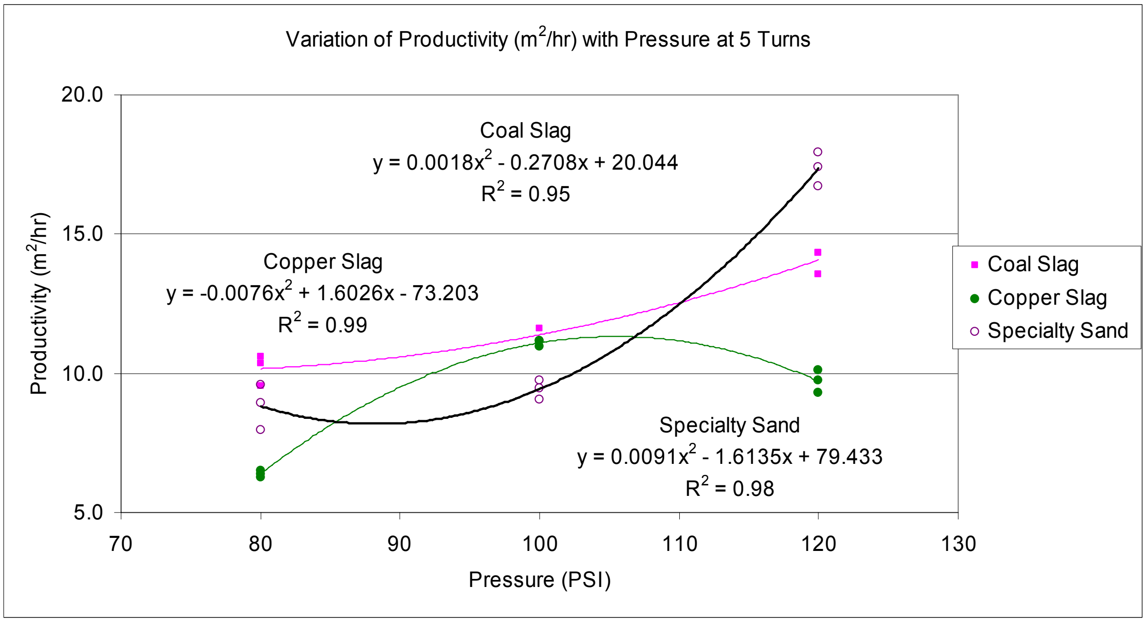


Figure 25: Variation of Productivity with Pressure at 5 Turns

### *5.1.2. Variation of Productivity with Feed Rate*

Variation of productivity with feed rate at 80 PSI is shown in Figure 26. It can seen from the figure that productivity increased with feed rate from 3 to 4 turns and then decreased. With increase in feed rate more number of particles per unit area strikes the plate, increasing the productivity. However, at very high feed rates, the velocity of particles is decreased due to over burdening of the air with more number of particles. In addition, with more particles released from the nozzle, self-abrasion of particles causes damage to the particles. Thus, productivity decreased with increase in feed rate from 4 to 5 turns.

Copper slag resulted in lowest productivity compared to coal slag and specialty sand. While productivity of specialty sand was higher than that of coal slag at 3 turns, with increase in feed rate, productivity of these two materials was comparable.

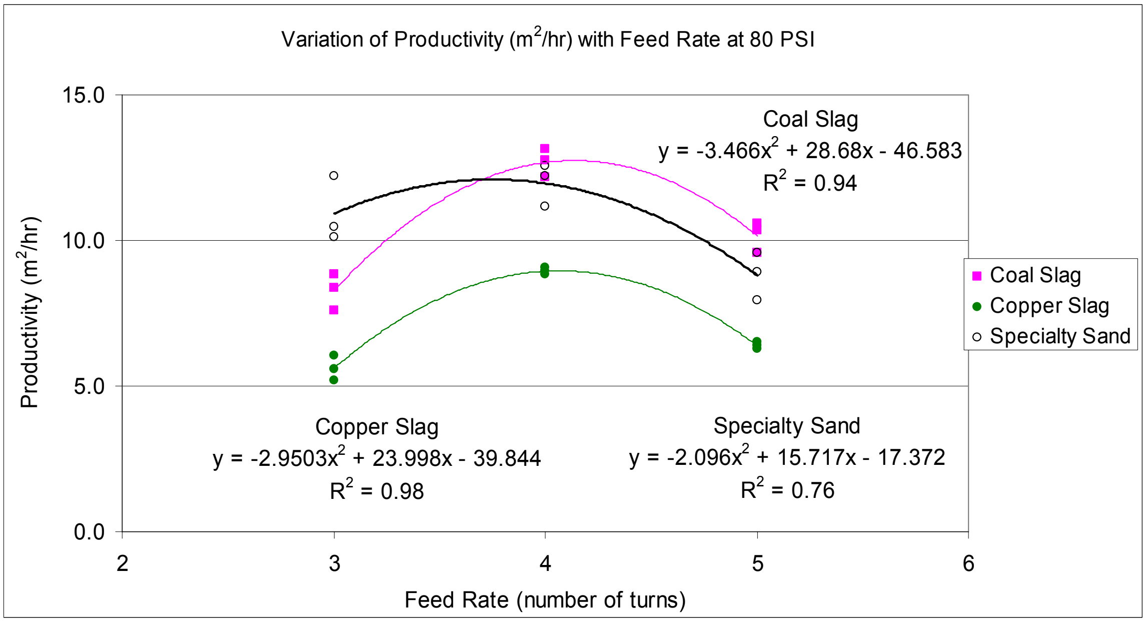


Figure 26: Variation of Productivity with Feed Rate at 80 PSI

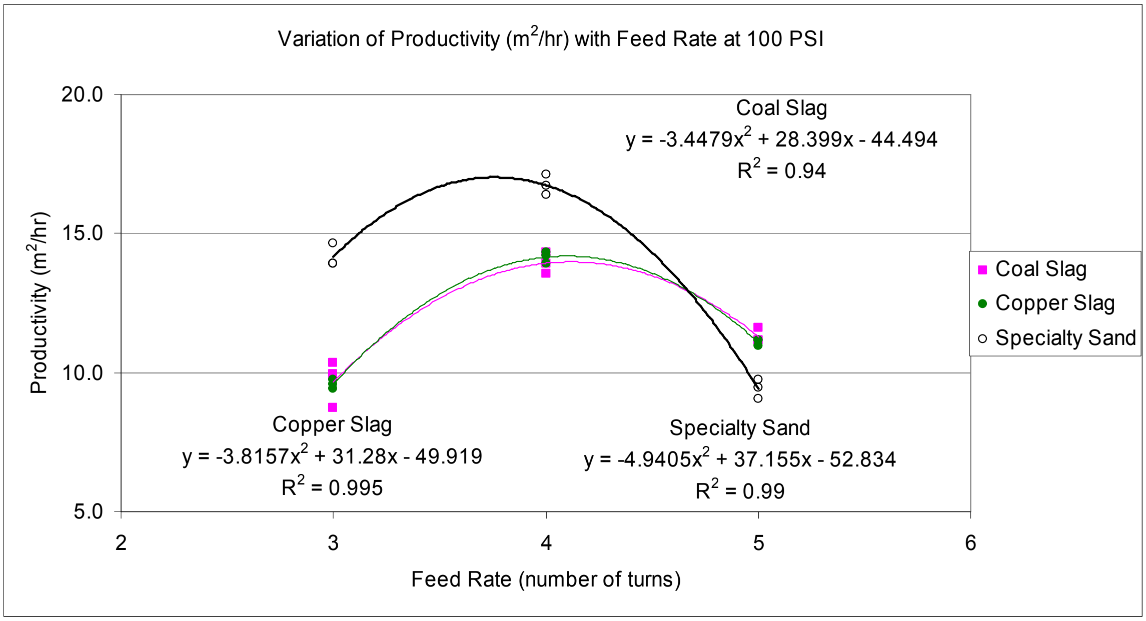


Figure 27: Variation of Productivity with Feed Rate at 100 PSI

Similar to variation at 80 PSI, the productivity of coal slag, copper slag, and specialty sand at 100 PSI increased with increase in feed rate to an optimum value and then decreased with further increase in feed rate (Figure 27). Coal slag and copper slag showed almost the same productivity, while productivity of specialty was observed to be considerably higher from 3 to 4 turns. The equations to estimate productivity at intermediate feed rates are shown in also shown in Figure 27.

The variation of productivity of three materials with feed rate at 120 PSI is shown in Figure 28. While coal slag and copper slag showed a similar trend as previous two pressure conditions with change in feed rate, productivity of specialty sand did not show the decreasing trend at higher feed rates. This may be due to combined effect of higher pressure and feed rate conditions, resulting greater velocity and higher number of particles participating in abrading action for specialty sand compared to coal slag and copper slag. Lowest productivity was observed for copper slag. Coal slag showed higher productivity than specialty sand at 4 turns, but lower at 5 turns.

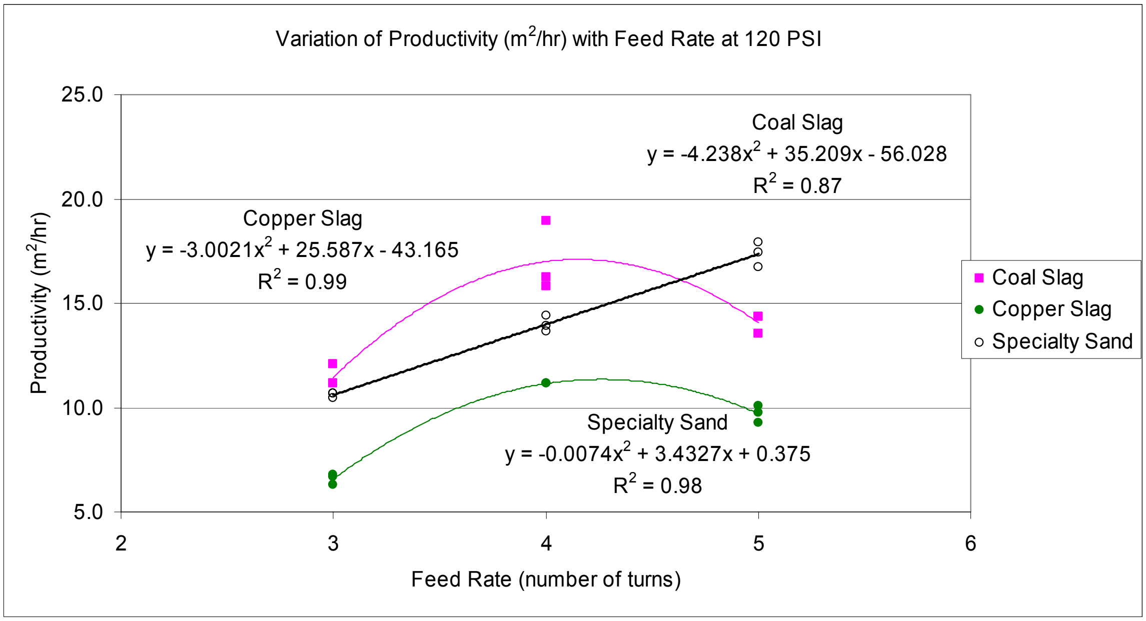


Figure 28: Variation of Productivity with Feed Rate at 120 PSI

### *5.1.3. Variation of Productivity with Pressure and Feed Rate*

Figures 28, 30, and 31 show simultaneous effect of blast pressure and feed rate on productivity for coal slag, copper slag, and specialty sand respectively.

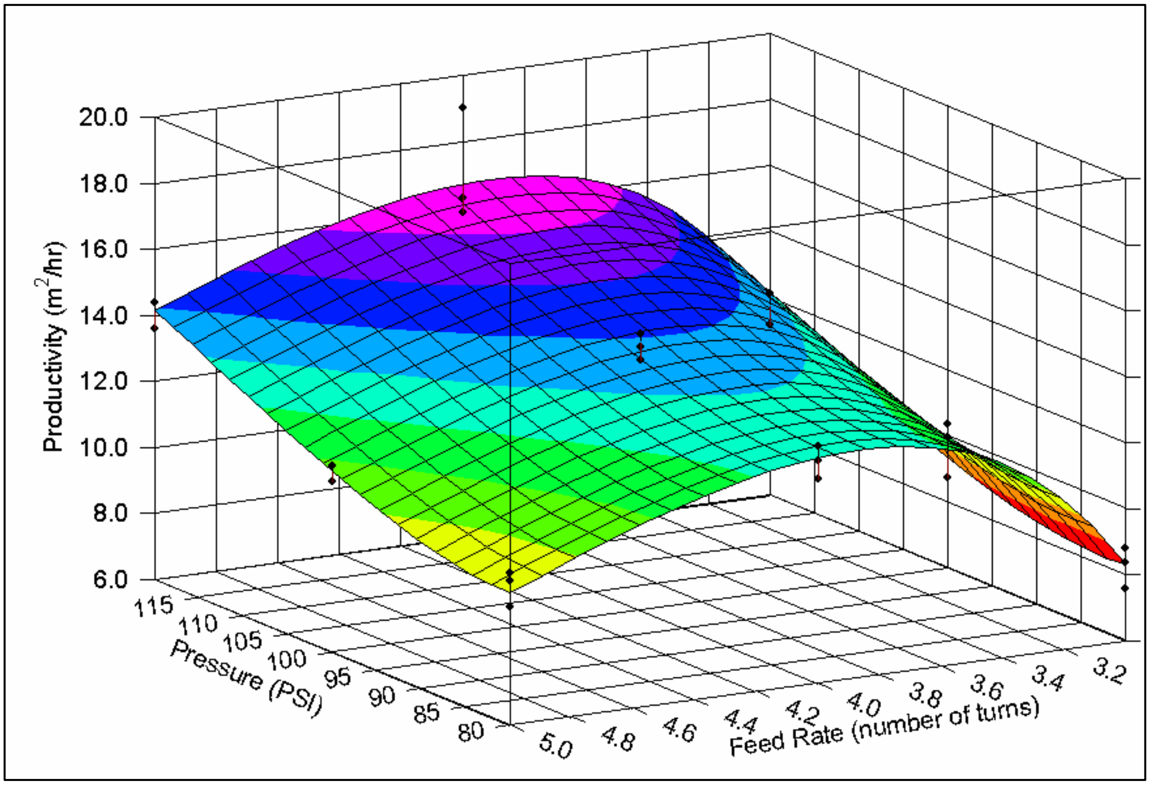


Figure 29: Coal Slag - Variation of Productivity with Pressure and Feed Rate

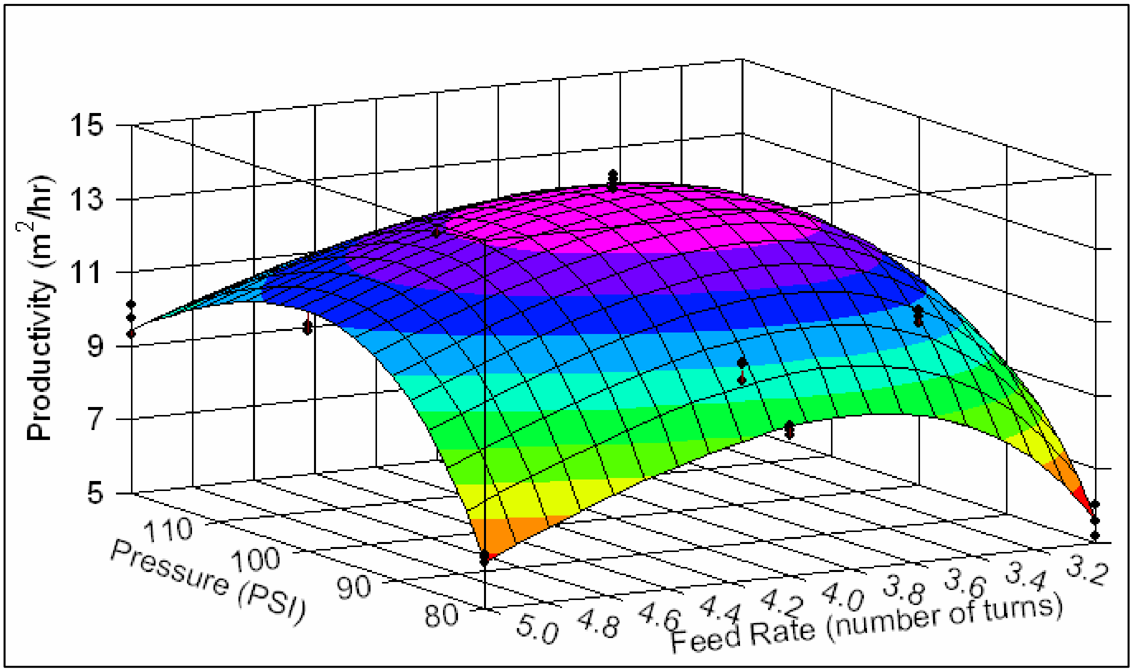


Figure 30: Copper Slag - Variation of Productivity with Pressure and Feed Rate

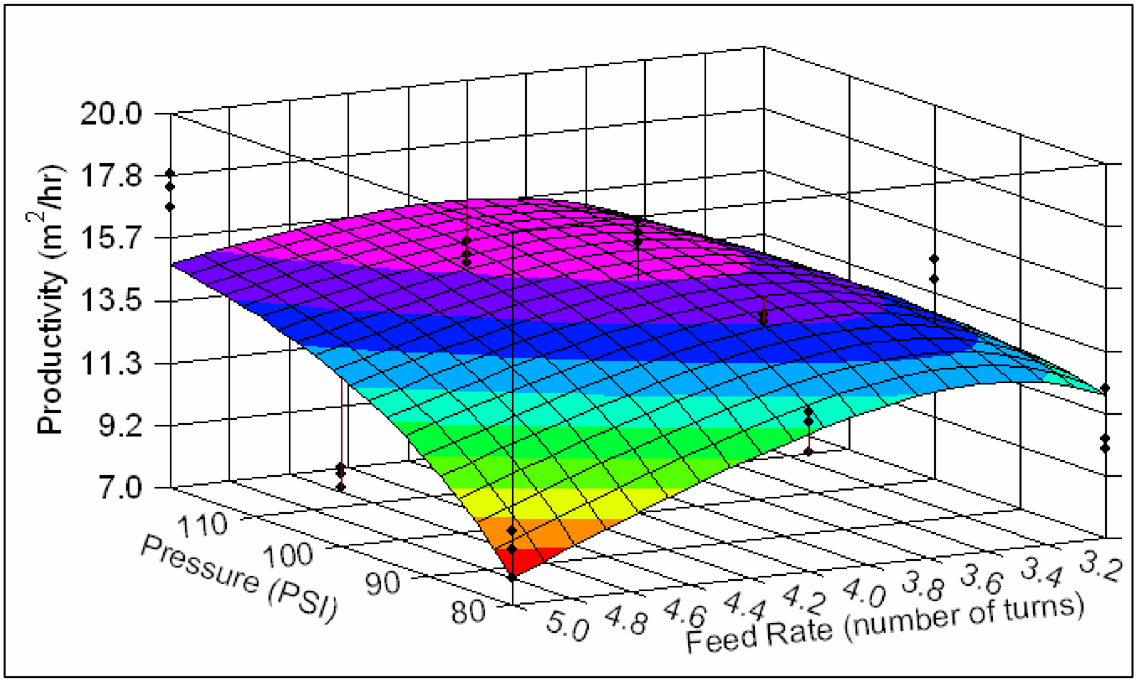


Figure 31: Specialty Sand - Variation of Productivity with Pressure and Feed Rate

The regression model developed to determine productivity at intermediate pressure and feed rate is:

$$\mathrm{Productivity} = a + (b/P) + (c/F) + (d/P^2) + (e/F^2) + f/(P*F) \qquad (4)$$

Where,

Productivity in $m^2$/hr

P = Blast Pressure in PSI, (80 to 120 PSI),

F = Feed Rate in Number of Turns of Schmidt Feed Valve (3 to 5), and

a, b, c, d, e, and f are coefficients, given in Table 13.

Table 13: Coefficients for Productivity ($m^2$/hr) for Equation 4

| **Abrasive Material** | **a** | **b** | **c** | **d** | **e** | **f** | **$R^2$** |
|---|---|---|---|---|---|---|---|
| Coal Slag | -1.85E+00 | -6.33E+03 | 4.14E+02 | 2.44E+05 | -8.31E+02 | 1.29E+03 | 0.94 |
| Copper Slag | -1.05E+02 | 1.51E+04 | 3.33E+02 | -7.99E+05 | -7.27E+02 | 4.03E+03 | 0.99 |
| Specialty Sand | -2.73E+00 | -1.38E+02 | 1.65E+02 | -2.00E+05 | -5.65E+02 | 1.33E+04 | 0.58 |

## 5.3. Consumption

### 5.3.1. Variation of Consumption with Pressure

The variation of abrasive consumption with pressure at 3 turns of feed rate is shown in Figure 32. Consumption of copper slag and specialty sand decreased with increase in blast pressure and then increased with further increase in pressure. Due to lower velocity at low pressure, the kinetic energy possessed by the abrasive particles is less. Thus, more material was required to remove paint and achieve desired profile. With increase in blast pressure, kinetic energy increased, which resulted a decrease in consumption. However, at very high pressures, particles undergo more damage at higher velocities due to self-abrasion., which resulted in increased consumption for coal slag and copper slag.

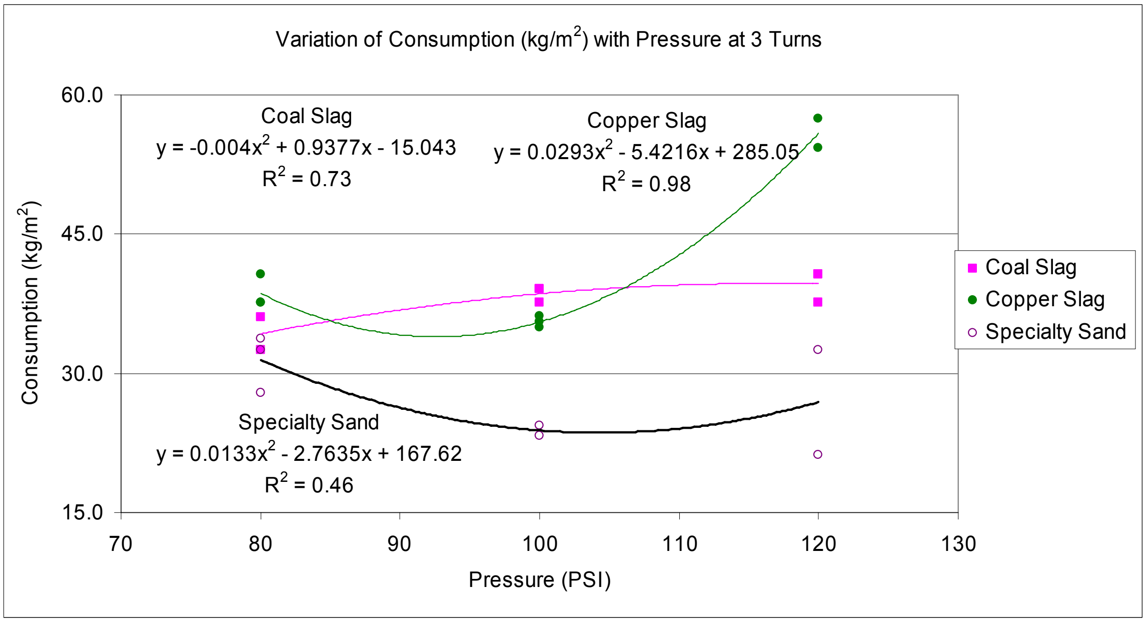


Figure 32: Variation of Consumption with Pressure at 3 Turns

Although an increase in consumption of specialty sand was observed with increase pressure from 100 to 120 PSI, the variation was not significant. Minimum consumption of material was observed in case of specialty sand at 3 turns. While coal slag and copper slag consumed comparable quantities of material from 80 to 100 PSI, at higher pressure, copper slag showed a significant increase in consumption. This may be due to greater damage of particles for copper slag compared to coal slag. $R^2$ value obtained for specialty sand was considerably lower than the values for coal slag and copper slag at 3 turns.

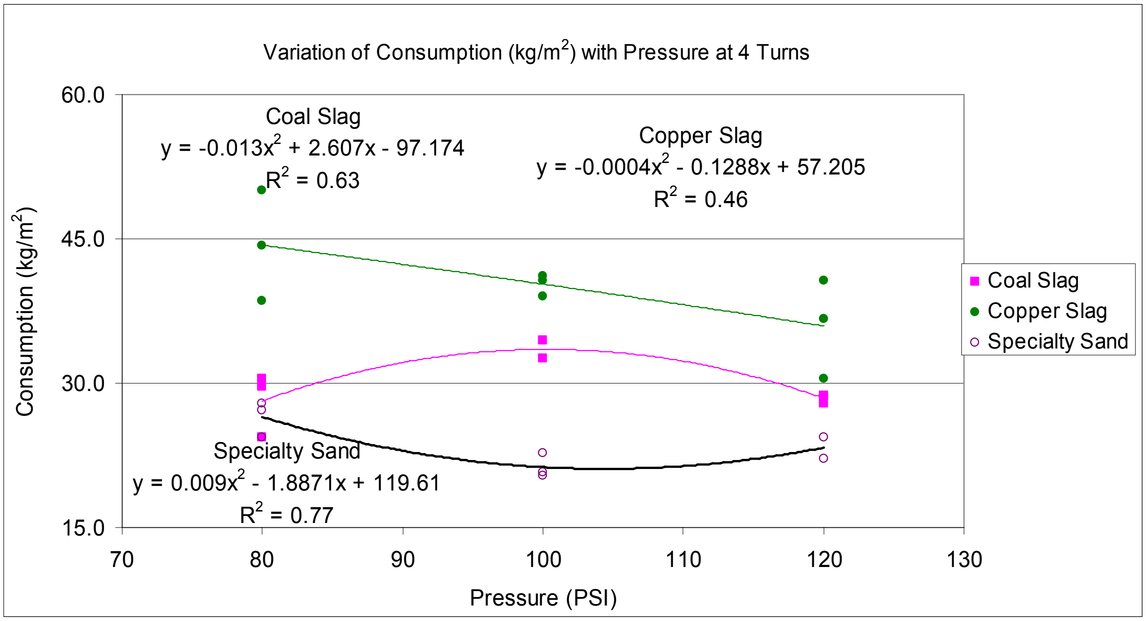


Figure 33: Variation of Consumption with Pressure at 4 Turns

Figure 33 shows the variation of consumption with pressure at 4 turns. It can be observed from the figure that effect of pressure on consumption was not significant in case of all three materials, which may be due to more uniform flow of material at turns. However, consumption of copper slag was higher than coal slag and specialty sand. Minimum material was consumed in case of specialty sand. The equations to determine material consumption for coal slag, copper slag, and specialty sand are shown in Figure 33 and lower $R^2$ values (<0.80) were obtained for all three materials.

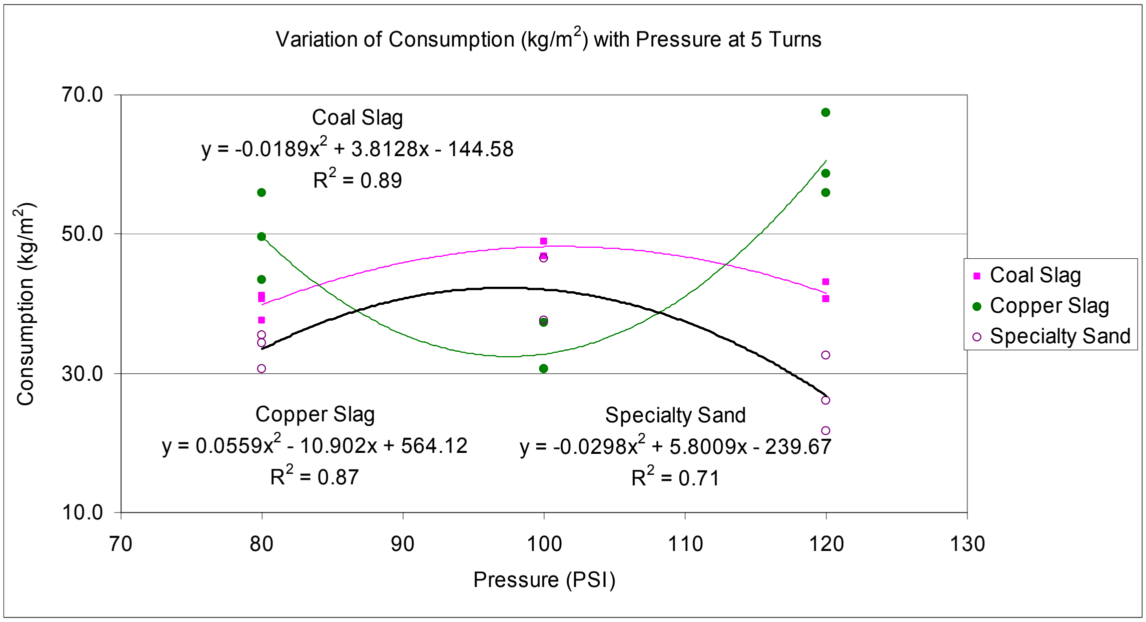


Figure 34: Variation of Consumption with Pressure at 5 Turns

An increase pressure at 5 turns showed varying effects on the abrasive materials. Increase in pressure from 80 to 100 PSI resulted in decreased consumption and with further increase in pressure, consumption of more material in case of copper slag (Figure 34). As explained earlier, this may be due to increasing velocity effect from 80 to 100 PSI and effect of damage of particles at higher pressure. An opposite effect of pressure was observed for consumption of coal slag and specialty sand. However, the variation was not as significant for specialty sand as for coal slag.

### *5.3.2. Variation of Consumption with Feed Rate*

The variation of consumption with feed rate at 80, 100, and 120 PSI are shown in Figures 35, 36, and 37, respectively. The consumption of abrasive initially decreased with increased feed rate and then increased with further increase in feed rate in most of the cases for coal slag and specialty sand. This is because of more uniform flow of abrasive at 4 turns than at 3 or 5 turns. In addition, very high feed rates cause self-abrasion of particles and uneven distribution of material due to turbulent flow and thus require more material to remove paint from a unit area.

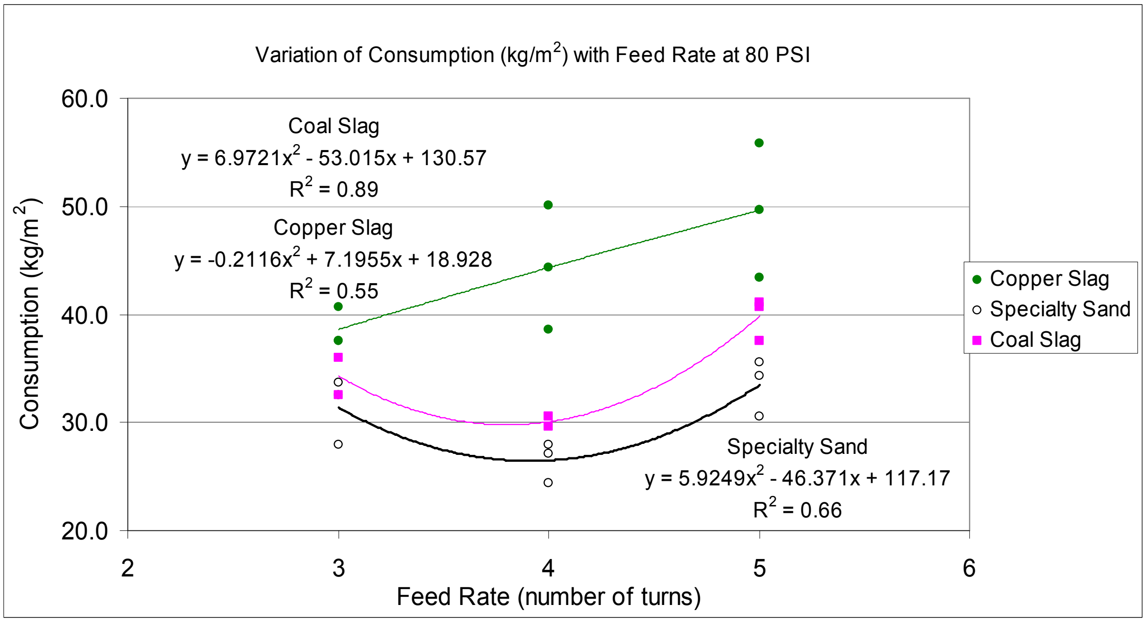


Figure 35: Variation of Consumption with Feed Rate at 80 PSI

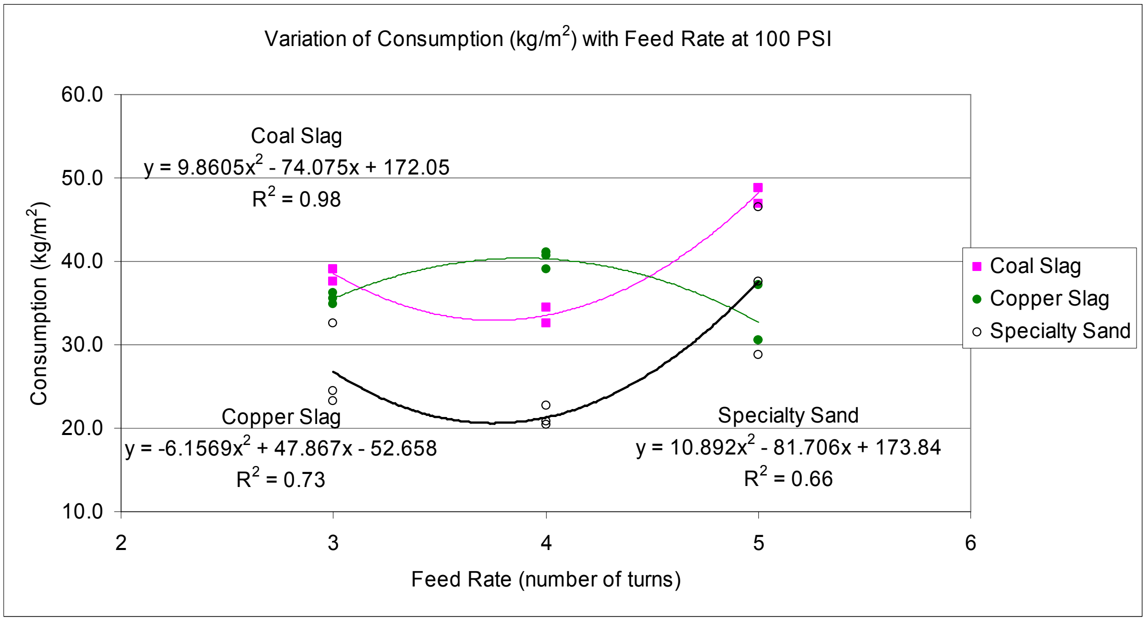


Figure 36: Variation of Consumption with Feed Rate at 100 PSI

However, in case of copper slag, average consumption increased with in feed rate at 80 PSI. This may be due to overload of abrasive particles at this lower pressure, which caused a decrease in velocity of particles, and hence the kinetic energy of the particles. At 100 PSI, consumption of copper slag increased with feed rate from 3 to 4 turns and then decreased. With increase in feed rate, more number of particles participated in abrading action per unit area, which may have resulted in decrease of consumption at higher feed rate for 100 PSI.

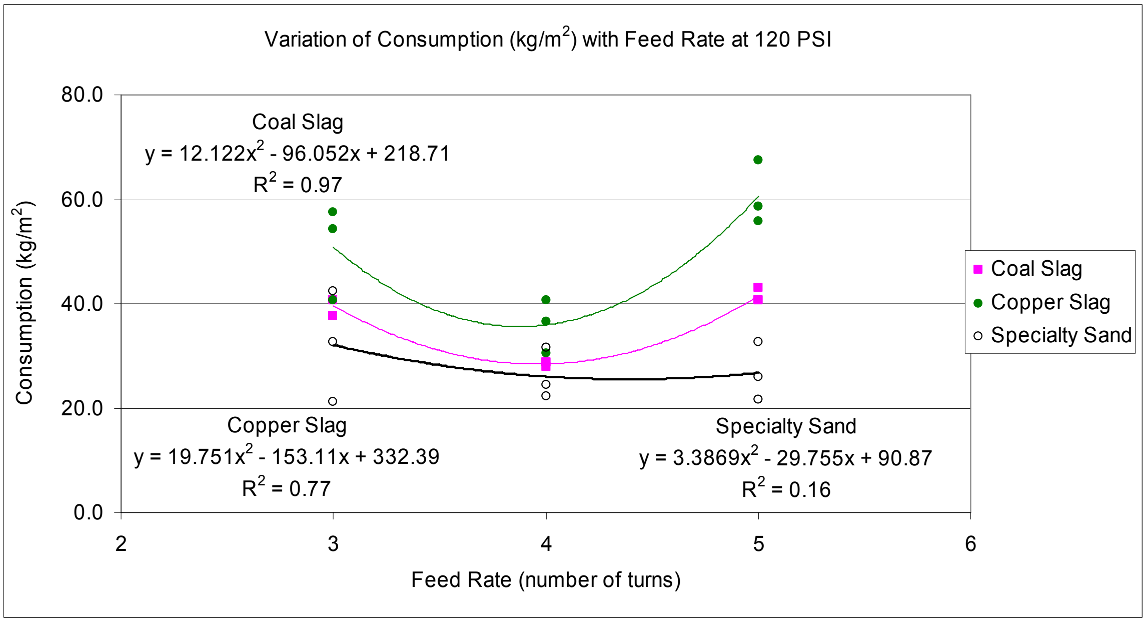


Figure 37: Variation of Consumption with Feed Rate at 120 PSI

Copper slag resulted in higher consumption than coal slag and specialty sand at 80 and 120 PSI. While minimum consumption was observed for specialty sand at 80 and 120 PSI, the consumption of abrasives demonstrated a mixed effect at 100 PSI for the three materials. The equations and $R^2$ values obtained from regression analysis for these variations are shown in the figures above.

### *5.3.3. Variation of Consumption with Pressure and Feed Rate*

The variation of consumption with both pressure and feed rate for coal slag, copper slag, and specialty sand are shown in Figures 38, 39, and 40.

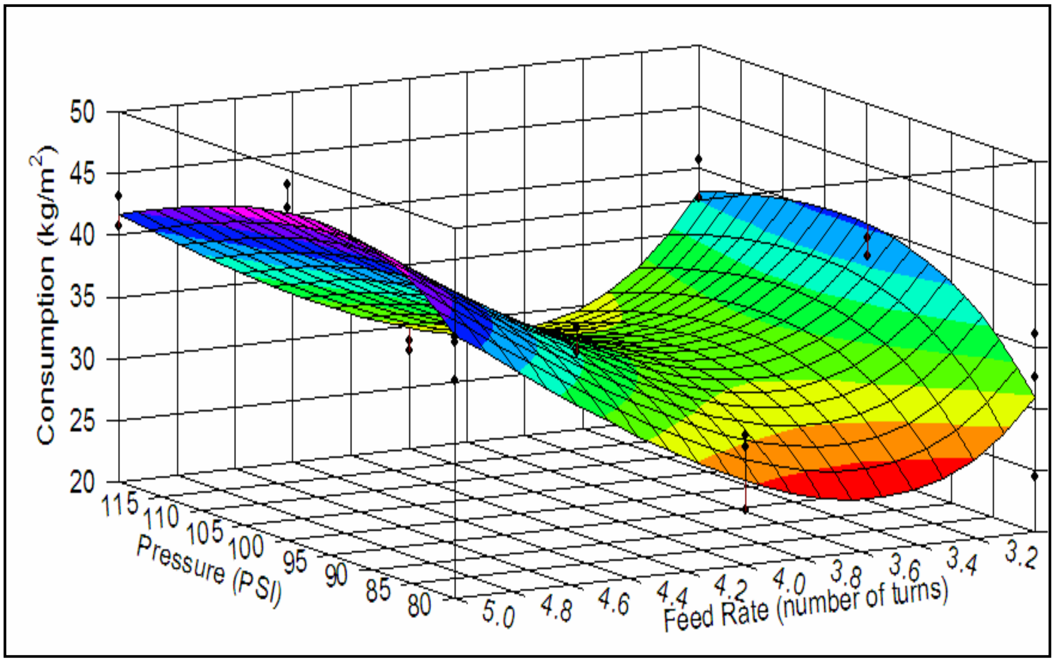


Figure 38: Coal Slag - Variation of Consumption with Pressure and Feed Rate

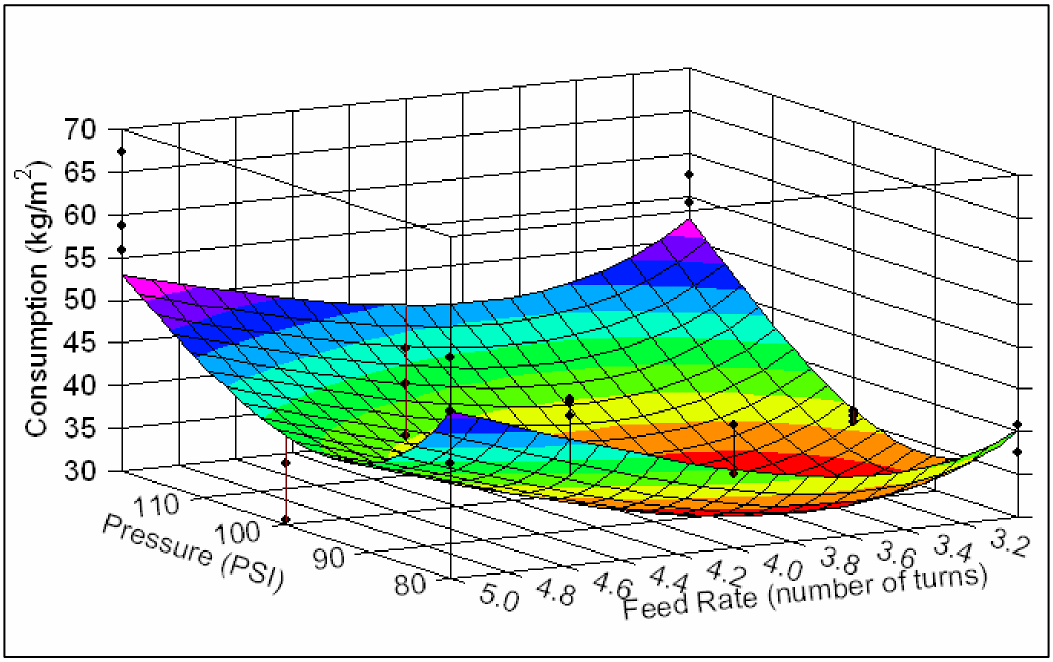


Figure 39: Copper Slag - Variation of Consumption with Pressure and Feed Rate

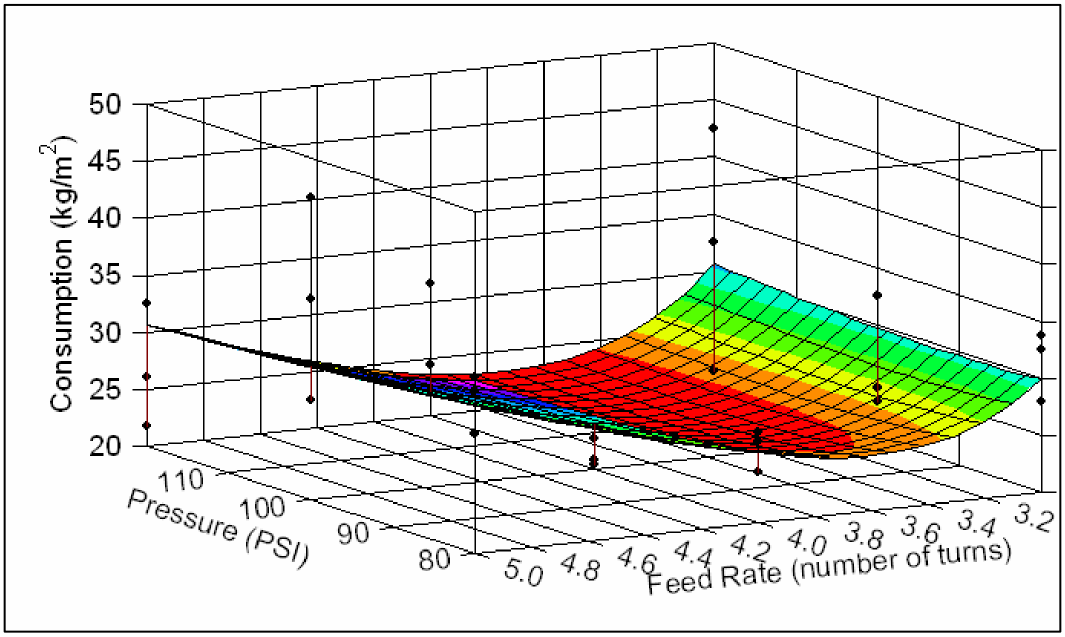


Figure 40: Specialty Sand - Variation of Consumption with Pressure and Feed Rate

The regression model developed to determine consumption at intermediate pressure and feed rate is:

$$Consumption = a + (b/P) + (c/F) + (d/P^2) + (e/F^2) + f/(P*F) \qquad (5)$$

Where,

Consumption in kg/m$^2$

P = Blast Pressure in PSI, (80 to 120 PSI),

F = Feed Rate in Number of Turns of Schmidt Feed Valve (3 to 5), and

a, b, c, d, e, and f are coefficients, given in Table 14.

Table 14: Coefficients for Consumption (kg/m$^2$) for Equation 5

| **Abrasive Material** | **a** | **b** | **c** | **d** | **e** | **f** | **R$^2$** |
|---|---|---|---|---|---|---|---|
| Coal Slag | 7.13E+01 | 2.73E+04 | -1.27E+03 | -1.20E+06 | 2.54E+03 | -1.26E+04 | 0.86 |
| Copper Slag | 4.25E+02 | -5.38E+04 | -7.55E+02 | 2.70E+06 | 1.66E+03 | -1.61E+04 | 0.51 |
| Specialty Sand | 1.34E+02 | -7.91E+01 | -8.25E+02 | 1.47E+05 | 1.69E+03 | -9.43E+03 | 0.30 |

# 6. Conclusions and Recommendations

Performance of coal slag, copper slag, and specialty sand for removal of paint from mild steel surfaces was evaluated in this research. While several factors affect the performance of an abrasive, blast pressure and feed rate are two important process conditions that can be optimized easily to achieve maximum efficiency from an abrasive material. Thus, effect of two important process parameters, namely, blast pressure (80 -120 PSI) and feed rate (3 – 5 turns of opening of Schmidt feed valve) on productivity, consumption and total PM emission factors (performance parameters) was studied to evaluate the performance. Two dimensional and three dimensional models were developed to estimate the performance parameters at intermediate blast pressure and feed rate conditions.

Based on the overall performance, the three abrasive materials are ranked as follows:

- Emission Factors in $kg/m^2$:

  Copper Slag < Coal Slag < Specialty Sand

- Emission Factors in kg/kg:

  Copper Slag < Coal Slag < Specialty Sand

- Productivity:

  Copper Slag < Coal Slag < Specialty Sand

- Consumption:

  Specialty Sand < Coal Slag < Copper Slag

At a specific blast pressure and feed rate condition, the materials may not follow the same order. In order to determine these performance parameters at a specific blast pressure and feed rate condition, the regression models were developed:

$$EF = a + (b * P) + (c * F) + (d * P^2) + (e * F^2) + (f * P * F)$$
$$Y = a + (b / P) + (c / F) + (d / P^2) + (e / F^2) + f / (P * F)$$

Where,

EF = Emission Factor in $kg/m^2$ or kg/kg

Y = Productivity in $m^2/hr$ or Consumption in $kg/m^2$

P = Blast Pressure in PSI, (80 to 120 PSI)

F = Feed Rate in Number of Turns of Schmidt Feed Valve (3 to 5)

a, b, c, d, e, and f are coefficients, which vary for each material and performance parameter.

Due caution must be employed while using these equations. The results are valid within the tested ranges of blast pressure and feed rate.

Emission quantities and health risk can be estimated using the emission factors developed in this research. Spent abrasive quantities can be estimated by estimating the quantity of abrasive used from the consumption models developed in this research. With additional information on specific costs, emission factors, productivity and consumption models can be used to determine material costs, labor costs, equipment costs, energy costs, emission control & compliance costs, waste disposal costs, and health risk costs. An example of application of these equations in cost calculations is shown in Appendix D.

It is evident from the above results that specialty sand is cost-effective with respect to production costs due to highest productivity and lowest consumption. However, it also has highest emission potential, which increases emission control and compliance costs, health risk to workers. Moreover, emissions from sand are of great concern due to silicosis caused by silica emissions and many health and regulatory agencies require the use of substitute materials to reduce the risk of silicosis.

While coal slag has higher emission factors than copper slag, overall life cycle costs may be lower than copper slag because of higher productivity and lower consumption of coal slag. With increasing concern on environmental and health effects due to PM emissions, it is important to evaluate pollution prevention, cost reduction options and health risk of alternative materials prior to selecting an abrasive.

Size distribution and metal analysis of total PM emissions will greatly enhance the health risk evaluation due to metal and particulate emissions. This research was focused on effect of blast pressure and feed rate on performance of medium grade, non-reusable abrasives. It is recommended to study the effect of other parameters such as nozzle size, and abrasive grade on the performance.

The exhaust flow rate is important when emissions are estimated. With higher flow rate, more particles get airborne due to higher suction in the test chamber. Thus, emission factors may be higher. Effect of exhaust flow rate on emission factors may be studied in future research. Since thickness of surface contamination affects the performance of an abrasive, effect of varying paint thickness may be studied.

Since the blasting operations were carried in an enclosed chamber emission factors developed in this research must be extrapolated for other sizes of blast chambers and open-air blasting due to effect of wind velocity in case of outdoor blasting.

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# APPENDIX A: Field Observations and Stack Calculations

Table: Coal Slag: CO 120-4-1 Field Observations

| | | | | | |
|---|---|---|---|---|---|
| **Date** | 6/14/2004 | | | | |
| **Type of Abrasive =** | Coal Slag | | **Mass of Abrasive =** | 100 | lbs |
| **Area Cleaned =** | 17 | sqft | **Blast Time =** | 5 | mins |
| **Finish =** | Near White | | **Abrasive Grade =** | Medium | |
| **K factor =** | 1.13 | | **Blast Pressure =** | 120 | psi |
| **Run No =** | 1 | | **Abrasive feed rate =** | 4 | # turns of on Schmidt valve |
| **Initial meter reading =** | **161.81** | | | | |

| **Traverse Pt** | **Meter Reading** | **Delta P** | **Delta H** | **DGM in** | **DGM Out** | **Avg Meter Temp (°F)** | **Stack Temp** | | **Vacuum** | **Hot Box Temp (°F)** | **Cold Box Temp (°F)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **°C** | **°F** | | | |
| 1 | 162.51 | 0.37 | 0.418 | 107 | 105 | 106 | 27 | 80.6 | 3 | 190 | 50 |
| 2 | 163.18 | 0.39 | 0.440 | 106 | 104 | 105 | 27 | 80.6 | 3 | 210 | 48 |
| 3 | 163.86 | 0.38 | 0.429 | 104 | 102 | 103 | 26 | 78.8 | 3 | 210 | 48 |
| 4 | 164.51 | 0.38 | 0.429 | 104 | 102 | 103 | 26 | 78.8 | 3 | 205 | 48 |
| 5 | 166.28 | 0.6 | 0.677 | 103 | 101 | 102 | 26 | 78.8 | 3 | 200 | 46 |
| 6 | 168.15 | 0.61 | 0.688 | 103 | 101 | 102 | 26 | 78.8 | 4 | 190 | 44 |
| 7 | 169.17 | 1.1 | 1.241 | 103 | 101 | 102 | 26 | 78.8 | 5 | 175 | 45 |
| 8 | 170.02 | 0.99 | 1.117 | 103 | 102 | 102.5 | 26.5 | 79.7 | 5 | 165 | 45 |
| **V dgm =** | 8.21 | | | | | | | | | | |
| | **Average =** | **0.603** | 0.680 | | **Avg Temp =** | **103.1875** | | **79.3625** | | | |

| **Impinger Data** | **Impinger 1** | **Impinger 2** | **Impinger 3** | **Impinger 4** |
|---|---|---|---|---|
| | | | | (Silica Gel) |
| **Final** | **530** | **549** | **433.5** | **544.5** |
| **Initial** | **528** | **548** | **433.5** | **543** |
| | | | | |
| **Difference** | 2 | 1 | 0 | 1.5 |
| Volume of Water Condensed, $V_{wc}$ | 3 | ml | | |
| Mass increase in Silica gel, $(m_f - m_i)$ | 1.5 | g | | |

| **Particulate Mass Collected** | | |
|---|---|---|
| | Filter | Beaker |
| Initial Mass (g) | 0.8242 | 112.7509 |
| Final mass (g) | 0.8298 | 113.5333 |
| Mass Collected | 0.0056 | 0.7824 |
| **Total** | **0.7880** | **g** |

| Symbol | Description | Comments | Units | Value |
|---|---|---|---|---|
| **$V_1$** | Initial Meter Reading | | dcf | 161.810 |
| **V2** | Final Meter Reading | | dcf | 170.020 |
| **Vm** | Actual Volume of gas measured by the DGM | (Final-Initial) meter reading | dcf | 8.210 |
| **Tstd** | Standard Temperature | ~~25°C = 298°K~~ | R | 536.690 |
| | Conversion factor (in.of Hg to mm.of Hg) | | | 25.400 |
| **Y** | Y(DGM correction factor: 0.95-1.05) | | | 0.990 |
| **$P_B$** | Barometric Pressure | Assumed to be 30.06 | in Hg | 30.060 |
| **Δ P** | Average Δ P | | in. $H_20$ | 0.603 |
| | | = 0.763/13.6 | in Hg | 0.044 |
| **$P_{std}$** | Standard Pressure | | in Hg | 29.920 |
| **Δ H@** | Reference Δ H | From DGM Calibration | in. H20 | 1.80 |
| **K** | K Factor for Δ H | Assuming Pdgm ~ Pbar | | 1.13 |
| **Δ H** | Average Δ H | K*Δ P | in. H20 | 0.68 |
| **Pdgm** | Pressyre of the DGM | $P_B + (\Delta P/13.6)$ | in Hg | 30.104 |
| **$T_{dgm}$** | Temperature of the DGM | | F | 103.188 |
| | | | R | 562.878 |
| **$V_{dgm(std)}$** | Volume of gas at standard conditions | $\frac{V_{dgm}*Y*(P_{dgm}*T_{std})}{(P_{std}*T_{dgm})}$ | SCF | 7.797 |
| **$V_{wc}$** | Volume of water vapor condensed | From Impingers 1, 2, & 3 | ml | 3.000 |
| **$V_{wc(std)}$** | Volume of water vapour at Standard Conditions | $K_1$*(Vw) where $K_1$=0.04707 | | 0.141 |
| **$m_f - m_i$** | Mass increase in Silica Gel | From Impinger 4 | g | 1.500 |
| **$V_{wsg(std)}$** | Volume of vapor absorbed onto the silica gel | $K_2*(m_f - m_i)$ where $K_2$=0.04715 | ml | 0.071 |
| **$B_{H2O}$** | Mole fraction of dry gas | $\frac{[V_{wc(std)} + V_{wsg(std)}] X 100}{[V_{wc(std)} + V_{wsg(std)} + V_{dgm(std)}]}$ | % | 2.646 |
| **PMOS** | | | | 0.974 |
| **Mdry** | Molecular Weight Dry Gas | Assumed to be 28.6 | | 28.600 |
| **Mgas** | Total Molecular Weight of Gas | $M_{gas} = M_{dry} X (1-B_{H2O}) + (18 X B_{H2O})$ | | 28.320 |
| **DPS** | √(ΔP) | | in $H_20$ | 0.776 |
| **$T_S$** | Average Stack Temp | | DEG F | 79.363 |
| | | | R | 539.053 |
| **$P_S$** | Stack Pressure Absolute ($P_{stat}$) | $P_B + (\Delta H/13.6)$ | in Hg | 30.109 |
| **Cp** | Pitot Tube Coeff | | | 0.840 |
| **$V_S$** | Average Stack Gas Velocity | $K_p * C_p$* sqrt($T_{gas}$*Δ P/($P_{stat}$ *$M_{gas}$) where $K_p$ = 85.49* 60 | fpm | 2659.199 |
| **Dia(stack)** | Inside Diameter of Stack | | in | 12.000 |
| **$A_S$** | Stack Area(sq.in) | | sq in. | 113.097 |
| **$A_S$** | Stack Area(sq ft) | | sq.ft | 0.785 |

| Symbol | Description | Comments | Units | Value |
|---|---|---|---|---|
| **$Q_{s,\ actual}$** | Stack Flow Rate Actual Conditions | $V_S$ X $A_S$ | cfm | 2088.530 |
| **$Q_{s,\ std,\ dry}$** | Stack Flow Rate Dry, Std Conditions | $\frac{v_s * A_s * (1 - B_{H2O}) * (P_{stat} * T_{std})}{(P_{std} * T_{gas})}$ | dscfm | 2037.124 |
| **TT = $\Theta$** | Net time of run | sampling time = (2min*8 traverse points) | min | 16.000 |
| **Dia(nozzle)** | Nozzle Diameter | | in | 0.180 |
| **$A_n$** | Nozzle Area | | sqft | 0.0002 |
| **$v_n$** | Nozzle average velocity | $\frac{V_{dgm} * Y * P_{dgm} * T_{gas}}{T_{dgm} * P_{stat} * \Theta * A_n * (1-B_{H2O})}$ | fpm | 2827.39 |
| **$Q_n$** | Nozzle flow rate | $v_n * A_n$ | cfm | 0.50 |
| **$Q_{n,\ std,\ dry}$** | Nozzle flow rate at standard conditions | $\frac{Q_n * P_{dgm} * T_{std}}{P_{std} * T_{dgm}}$ | dscfm | 0.48 |
| **% Iso-Kinetic** | Percent Isokinetic | $\frac{V_{dgm,std} * P_{std} * T_{gas} * 100}{T_{std} * v_s * \Theta * A_n * P_{stat} * (1-B_{H2O})}$ | % | 106.325 |
| **$P_{mass}$** | Particulate Weight ( Total) | On the Filter Paper + In the beaker | g | 0.7880 |
| **TPM** | Total Particulate Emissions | $\frac{Q_{s,\ std,\ dry} * P_{mass}}{Q_{n,\ std,\ dry}}$ | g | 3348.952 |
| **BT** | Blasting Time | | min | 5.00 |
| **$M_{abrasive}$** | Mass of abrasive | | lb | 100.00 |
| **Area cleaned** | | 5' X 2' 9" | sqft | 17.00 |
| **Total Gas Sampled** | Flow rate in the nozzle * Sampling time | $Q_{n,\ std\ dry} * \Theta$ | dscf | 7.99 |
| | | dscm = dscf * 0.02832 | dscm | 0.23 |
| **Total exhaust gas from emissions test chamber** | Flow rate in the stack * Sampling time | $Q_{s,\ std\ dry} * \Theta$ | dscf | 32593.98 |
| | | dscm = dscf * 0.02832 | dscm | 923.06 |
| **EF (mg/sq.ft)** | Emission factor for TPM (per unit area cleaned) | TPM *1000 / Area cleaned | mg/sq.ft | 196997.18 |
| **EF (lb/ton)** | Emission factor for TPM (per ton of abrasive used) | (TPM / 453.59) * 2000 / 100 | lb/ton | 147.66 |

# APPENDIX B: Results of Statistical Analysis

# Regression Analysis for Two Dimensional Analysis

## DataFit Results for Feed Rate vs. Productivity of Copper Slag at 120 PSI

Number of observations = 9
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 11
Residual tolerance = 0.0000000001
Sum of Residuals = -3.64153152077051E-14
Average Residual = -4.04614613418946E-15
Residual Sum of Squares (Absolute) = 0.474333333333334
Residual Sum of Squares (Relative) = 0.474333333333334
Standard Error of the Estimate = 0.281168197980418
Coefficient of Multiple Determination (R^2) = 0.9857525041
Proportion of Variance Explained = 98.57525041%
Adjusted coefficient of multiple determination (Ra^2) = 0.9810033388
Durbin-Watson statistic = 2.00819864136802

| **Regression Variable Results** | | | | |
|---|---|---|---|---|
| Variable | Value | Standard Error | t-ratio | Prob(t) |
| a | -3.005 | 0.198816 | -15.1145 | 0.00001 |
| b | 25.60833 | 1.594664 | 16.05876 | 0 |
| c | -43.2033 | 3.084318 | -14.0074 | 0.00001 |

| **68% Confidence Intervals** | | | | |
|---|---|---|---|---|
| Variable | Value | 68% (+/-) | Lower Limit | Upper Limit |
| a | -3.005 | 0.215516 | -3.22052 | -2.78948 |
| b | 25.60833 | 1.728616 | 23.87972 | 27.33695 |
| c | -43.2033 | 3.343401 | -46.5467 | -39.8599 |

| **90% Confidence Intervals** | | | | |
|---|---|---|---|---|
| Variable | Value | 90% (+/-) | Lower Limit | Upper Limit |
| a | -3.005 | 0.386339 | -3.39134 | -2.61866 |
| b | 25.60833 | 3.098751 | 22.50958 | 28.70708 |
| c | -43.2033 | 5.993447 | -49.1968 | -37.2099 |

| **95% Confidence Intervals** | | | | |
|---|---|---|---|---|
| Variable | Value | 95% (+/-) | Lower Limit | Upper Limit |
| a | -3.005 | 0.486483 | -3.49148 | -2.51852 |

| | | | | |
|---|---|---|---|---|
| b | 25.60833 | 3.901984 | 21.70635 | 29.51032 |
| c | -43.2033 | 7.547018 | -50.7504 | -35.6563 |

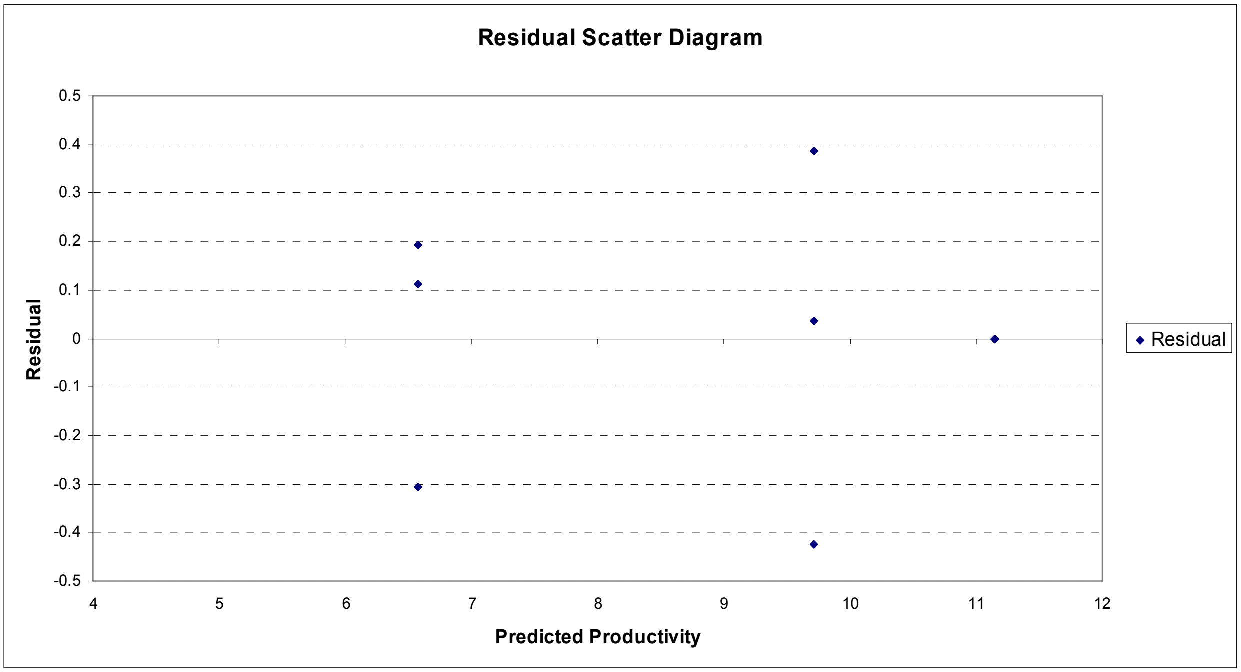
| **99% Confidence Intervals** | | | | |
|---|---|---|---|---|
| Variable | Value | 99% (+/-) | Lower Limit | Upper Limit |
| a | -3.005 | 0.73709 | -3.74209 | -2.26791 |
| b | 25.60833 | 5.912058 | 19.69628 | 31.52039 |
| c | -43.2033 | 11.4348 | -54.6381 | -31.7685 |

| **Variance Analysis** | | | | | |
|---|---|---|---|---|---|
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob(F) |
| Regression | 2 | 32.81807 | 16.40903 | 207.5633 | 0 |
| Error | 6 | 0.474333 | 7.91E-02 | | |
| Total | 8 | 33.2924 | | | |

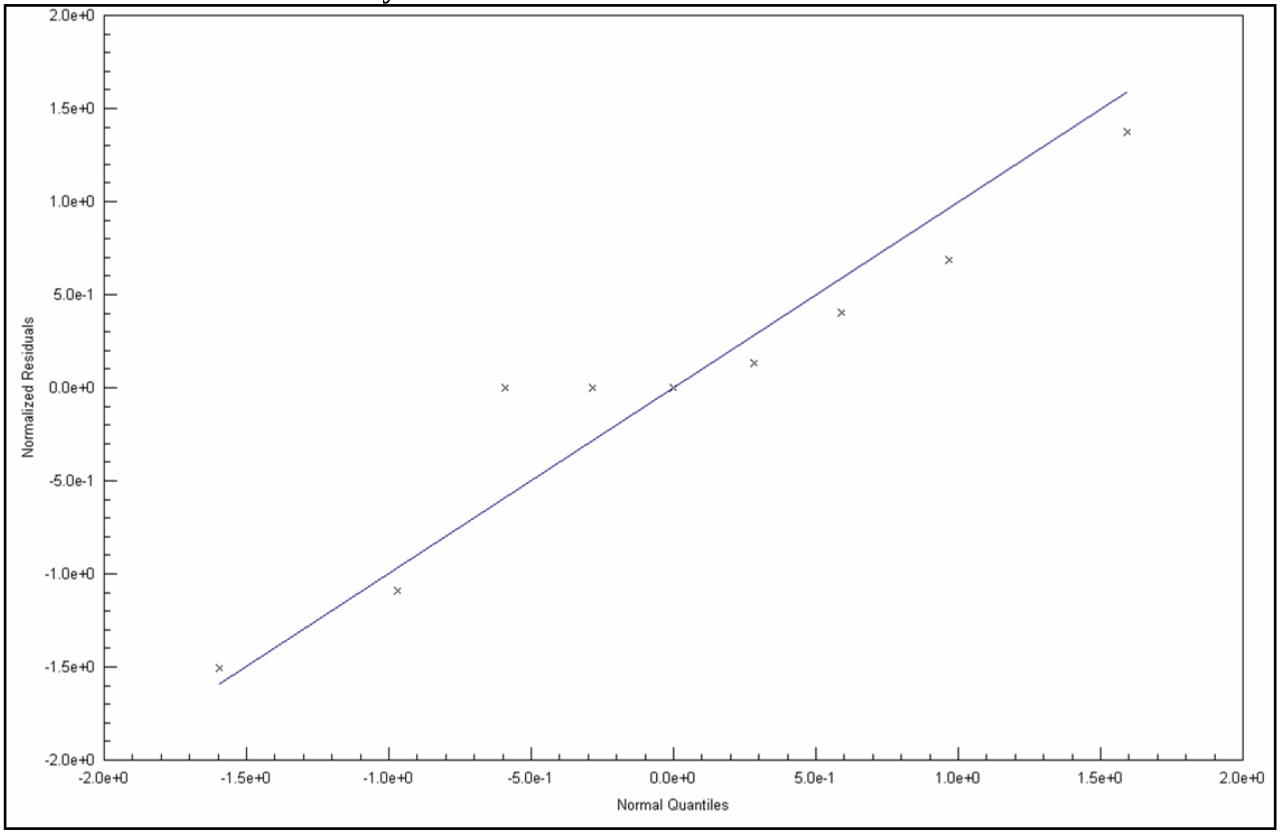
## Residuals for Two Dimensional Analyses for Feed Rate vs. Productivity of Copper Slag

| Feed Rate (No. of turns) | Observed Productivity ($m^2$/hr) | Predicted Productivity | Residual | % Error | Absolute Residual | Min. Residual | Max. Residual |
|---|---|---|---|---|---|---|---|
| 3 | 6.77 | 6.576666667 | 0.193333 | 2.855736 | 0.193333 | -0.42333 | 0.386667 |
| 3 | 6.27 | 6.576666667 | -0.30667 | -4.89102 | 0.306667 | | |
| 3 | 6.69 | 6.576666667 | 0.113333 | 1.694071 | 0.113333 | | |
| 4 | 11.15 | 11.15 | -5.33E-15 | -4.78E-14 | 5.33E-15 | | |
| 4 | 11.15 | 11.15 | -5.33E-15 | -4.78E-14 | 5.33E-15 | | |
| 4 | 11.15 | 11.15 | -5.33E-15 | -4.78E-14 | 5.33E-15 | | |
| 5 | 9.29 | 9.713333333 | -0.42333 | -4.55687 | 0.423333 | | |
| 5 | 9.75 | 9.713333333 | 0.036667 | 0.376068 | 0.036667 | | |
| 5 | 10.1 | 9.713333333 | 0.386667 | 3.828383 | 0.386667 | | |

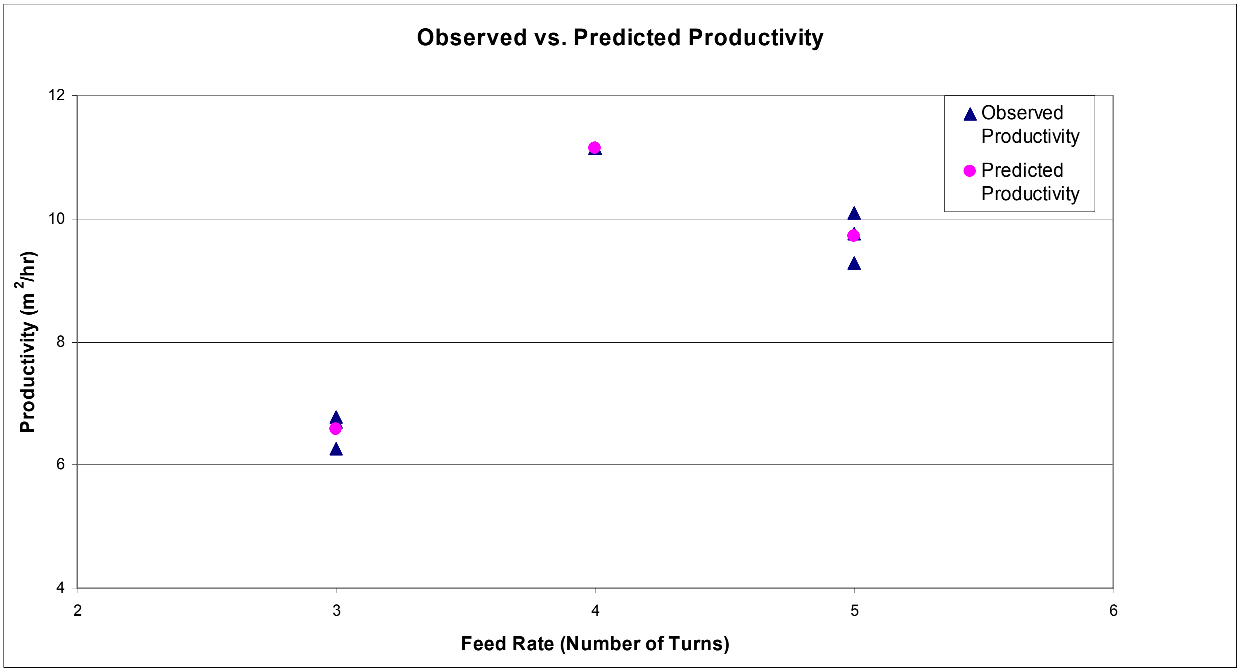
## Residual Scatter Diagram



## Residual Normal Probability Plot



## Observed vs. Predicted Productivity



# Regression Analysis for Three Dimensional Analysis

## DataFit Results for Productivity of Copper Slag

```
Equation ID: a+b/x1+c/x2+d/x1^2+e/x2^2+f/(x1*x2)
Model Definition:
Y = a+b/x1+c/x2+d/x1^2+e/x2^2+f/(x1*x2)
Number of observations = 27
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 6
Residual tolerance = 0.0000000001
Sum of Residuals = 8.33999536098418E-13
Average Residual = 3.08888717073488E-14
Residual Sum of Squares (Absolute) = 2.44553862036037
Residual Sum of Squares (Relative) = 2.44553862036037
Standard Error of the Estimate = 0.341253893775823
Coefficient of Multiple Determination (R^2) = 0.9865185275
Proportion of Variance Explained = 98.65185275%
Adjusted coefficient of multiple determination (Ra^2) = 0.983308653
Durbin-Watson statistic = 1.62549133011123
```

| Regression Variable Results | | | | |
|---|---|---|---|---|
| Variable | Value | Standard Error | t-ratio | Prob(t) |
| a | -104.87 | 4.711905267 | -22.25645432 | 0 |
| b | 15069.92 | 729.7634256 | 20.65042365 | 0 |
| c | 332.959 | 19.58728221 | 16.9987317 | 0 |
| d | -798827 | 33658.0845 | -23.73357482 | 0 |
| e | -727.367 | 33.78241194 | -21.53092763 | 0 |
| f | 4025.994 | 697.3742432 | 5.773074636 | 0.00001 |

| 68% Confidence Intervals | | | | |
|---|---|---|---|---|
| Variable | Value | 68% (+/-) | Lower Limit | Upper Limit |
| a | -104.87 | 4.799546705 | -109.669851 | -100.0707576 |
| b | 15069.92 | 743.3370253 | 14326.58688 | 15813.26093 |
| c | 332.959 | 19.95160566 | 313.0073495 | 352.9105608 |
| d | -798827 | 34284.12487 | -833110.7915 | -764542.5418 |
| e | -727.367 | 34.4107648 | -761.7774315 | -692.9559019 |
| f | 4025.994 | 710.3454041 | 3315.648151 | 4736.338959 |
| | | | | |
| 90% Confidence Intervals | | | | |
| Variable | Value | 90% (+/-) | Lower Limit | Upper Limit |
| a | -104.87 | 8.107775394 | -112.9780797 | -96.76252894 |
| b | 15069.92 | 1255.703926 | 13814.21998 | 16325.62783 |
| c | 332.959 | 33.7038365 | 299.2551186 | 366.6627916 |

|  |  |  |  |  |
|---|---|---|---|---|
| d | -798827 | 57915.466 | -856742.1327 | -740911.2007 |
| e | -727.367 | 58.12939622 | -785.4960629 | -669.2372705 |
| f | 4025.994 | 1199.97186 | 2826.021695 | 5225.965415 |

| 95% Confidence Intervals |  |  |  |  |
|---|---|---|---|---|
| Variable | Value | 95% (+/-) | Lower Limit | Upper Limit |
| a | -104.87 | 9.798878194 | -114.6691825 | -95.07142614 |
| b | 15069.92 | 1517.61602 | 13552.30789 | 16587.53992 |
| c | 332.959 | 40.73371209 | 292.225243 | 373.6926672 |
| d | -798827 | 69995.35253 | -868822.0192 | -728831.3141 |
| e | -727.367 | 70.25390386 | -797.6205705 | -657.1127628 |
| f | 4025.994 | 1450.259476 | 2575.734079 | 5476.253031 |

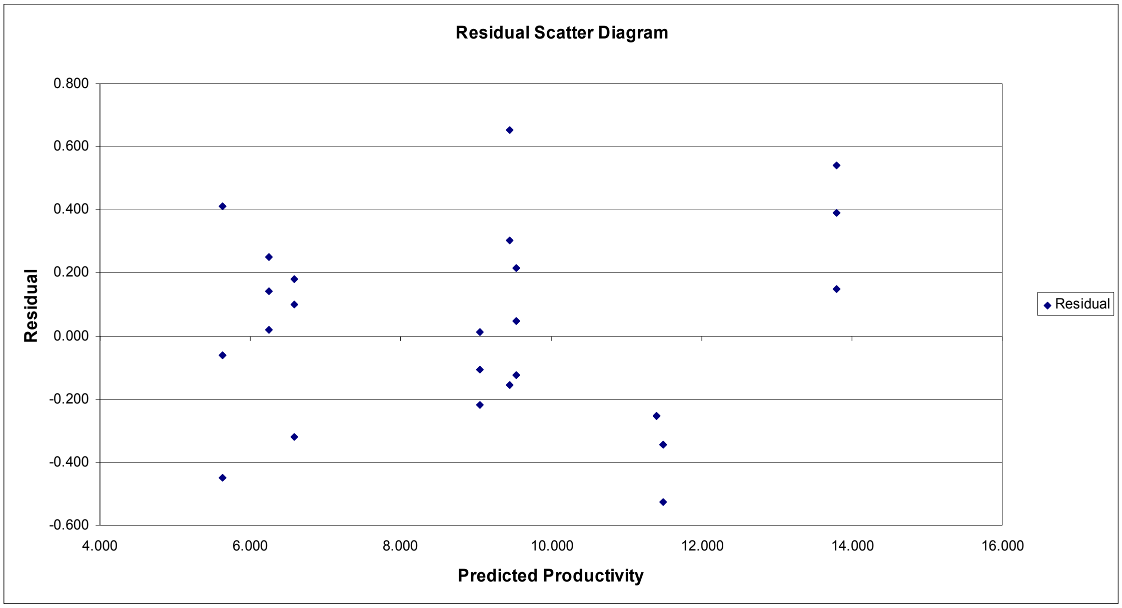
| 99% Confidence Intervals |  |  |  |  |
|---|---|---|---|---|
| Variable | Value | 99% (+/-) | Lower Limit | Upper Limit |
| a | -104.87 | 13.34128857 | -118.2115929 | -91.52901576 |
| b | 15069.92 | 2066.252163 | 13003.67174 | 17136.17607 |
| c | 332.959 | 55.45943086 | 277.4995243 | 388.418386 |
| d | -798827 | 95299.50046 | -894126.1671 | -703527.1662 |
| e | -727.367 | 95.65152115 | -823.0181878 | -631.7151455 |
| f | 4025.994 | 1974.545432 | 2051.448123 | 6000.538987 |

| Variance Analysis |  |  |  |  |  |
|---|---|---|---|---|---|
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob(F) |
| Regression | 5 | 178.9544243 | 35.79088487 | 307.338668 | 0 |
| Error | 21 | 2.44553862 | 0.11645422 |  |  |
| Total | 26 | 181.399963 |  |  |  |

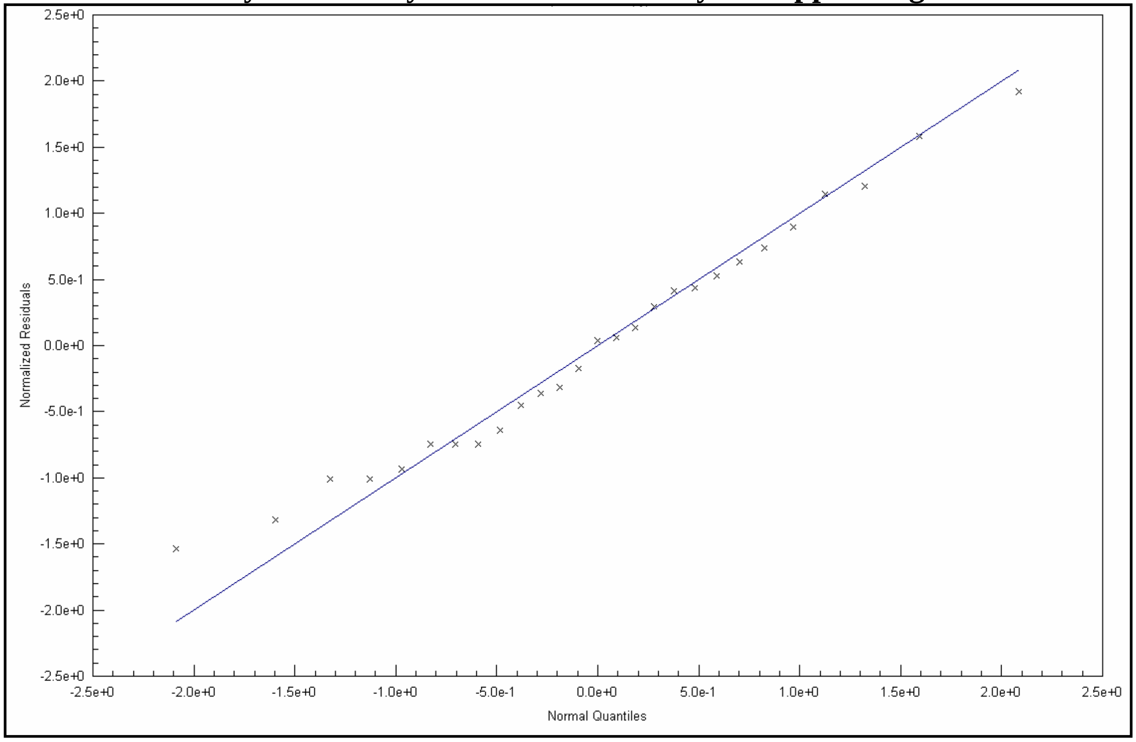
## Residuals for Three Dimensional Analyses for Productivity of Copper Slag

| Pressure (PSI) | Feed Rate (No. of turns) | Productivity ($m^2$/hr) | Predicted Productivity | Residual | % Error | Absolute Residual | Min. Residual | Max. Residual |
|---|---|---|---|---|---|---|---|---|
| 120 | 3 | 6.77 | 6.589 | 0.181 | 2.667 | 0.181 | -0.525 | 0.655 |
| 120 | 3 | 6.27 | 6.589 | -0.319 | -5.095 | 0.319 | | |
| 120 | 3 | 6.69 | 6.589 | 0.101 | 1.503 | 0.101 | | |
| 120 | 4 | 11.15 | 11.405 | -0.255 | -2.288 | 0.255 | | |
| 120 | 4 | 11.15 | 11.405 | -0.255 | -2.288 | 0.255 | | |
| 120 | 4 | 11.15 | 11.405 | -0.255 | -2.288 | 0.255 | | |
| 120 | 5 | 9.29 | 9.445 | -0.155 | -1.673 | 0.155 | | |
| 120 | 5 | 9.75 | 9.445 | 0.305 | 3.124 | 0.305 | | |
| 120 | 5 | 10.1 | 9.445 | 0.655 | 6.481 | 0.655 | | |
| 100 | 3 | 9.41 | 9.534 | -0.124 | -1.318 | 0.124 | | |
| 100 | 3 | 9.75 | 9.534 | 0.216 | 2.215 | 0.216 | | |
| 100 | 3 | 9.58 | 9.534 | 0.046 | 0.480 | 0.046 | | |
| 100 | 4 | 14.33 | 13.791 | 0.539 | 3.764 | 0.539 | | |
| 100 | 4 | 14.18 | 13.791 | 0.389 | 2.746 | 0.389 | | |
| 100 | 4 | 13.94 | 13.791 | 0.149 | 1.072 | 0.149 | | |
| 100 | 5 | 10.97 | 11.495 | -0.525 | -4.789 | 0.525 | | |
| 100 | 5 | 11.15 | 11.495 | -0.345 | -3.098 | 0.345 | | |
| 100 | 5 | 11.15 | 11.495 | -0.345 | -3.098 | 0.345 | | |
| 80 | 3 | 5.57 | 5.630 | -0.060 | -1.075 | 0.060 | | |
| 80 | 3 | 5.18 | 5.630 | -0.450 | -8.684 | 0.450 | | |
| 80 | 3 | 6.04 | 5.630 | 0.410 | 6.791 | 0.410 | | |
| 80 | 4 | 8.83 | 9.048 | -0.218 | -2.465 | 0.218 | | |
| 80 | 4 | 9.06 | 9.048 | 0.012 | 0.137 | 0.012 | | |
| 80 | 4 | 8.94 | 9.048 | -0.108 | -1.204 | 0.108 | | |
| 80 | 5 | 6.27 | 6.249 | 0.021 | 0.332 | 0.021 | | |
| 80 | 5 | 6.5 | 6.249 | 0.251 | 3.859 | 0.251 | | |
| 80 | 5 | 6.39 | 6.249 | 0.141 | 2.204 | 0.141 | | |

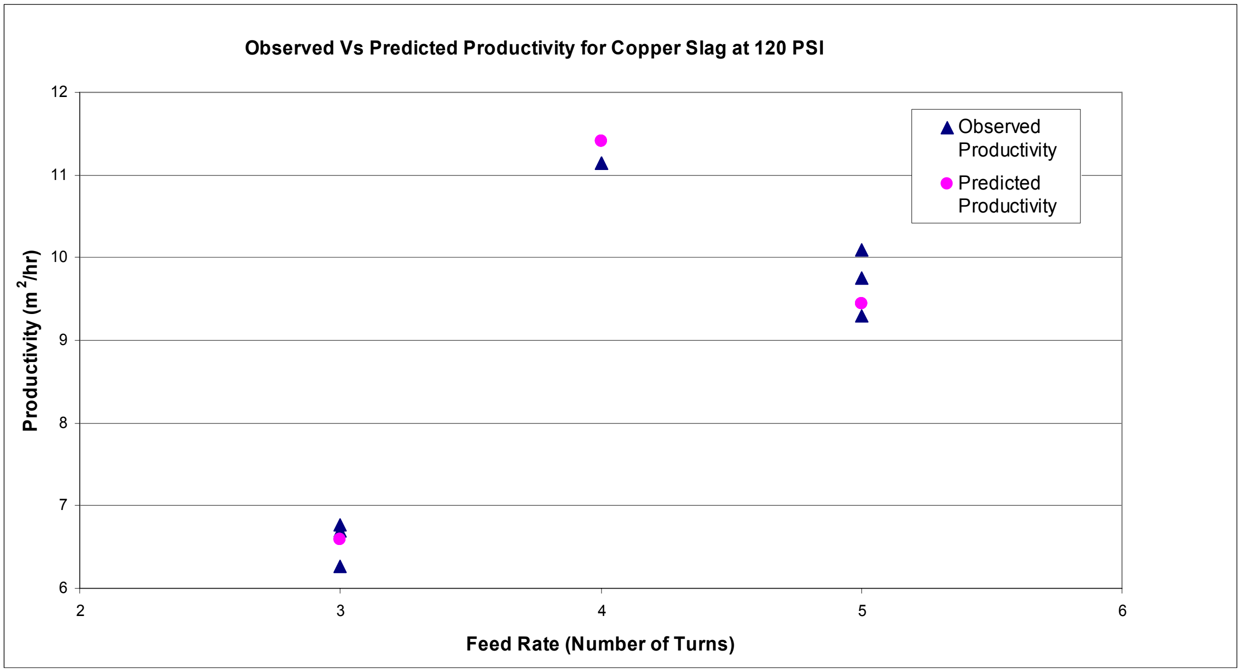
## Residual Scatter Diagram for Productivity of Copper Slag



## Residual Normality Probability Plot for Productivity of Copper Slag



## Observed vs. Predicted values of Productivity for Copper Slag at 120 PSI



# APPENDIX C: Material Data Safety Sheets

# MSDS for Coal Slag

## MATERIAL SAFETY DATA SHEET

## SECTION I – GENERAL

Reed Minerals, Harsco Corporation
P.O. Box 0515
Camp Hill, PA 17001-0515
**Emergency Telephone Number**
(717) 763-4200

**Product Name:** Black Beauty Abrasives and Reed Minerals Roofing Products
**CAS Number:** 68476-96-0
**Common Name:** Slag, Coal
**Date:** August 05, 2005

## SECTION II – PRODUCT COMPOSITION

| Component | Normal Composition (WT %) Range | CAS Number | OSHA PEL (mg/m$^3$) |
|---|---|---|---|
| Silicon Dioxide [$SiO_2$] | 41-53% | 7631-86-9 | $\frac{80\ mg/m^3}{\%SiO_2}$ |
| Quartz<br>[Respirable Dust] | <0.1% | 14808-60-7 | $\frac{10\ mg/m^3}{\%SiO_2+2}$ |
| Cristobalite<br>Total Dust] | ND | 14464-46-1 | $\frac{30\ mg/m^3}{\%SiO_2+2}$ [Quartz |
| Tridymite<br>[Respirable Dust] | ND | 15468-32-3 | $\frac{80\ mg/m^3}{\%SiO_2}$ |
| Aluminum Oxide [$Al_2O_3$] | 17-25% | 1344-28-1 | 15 mg/m$^3$ |
| Calcium Oxide [CaO] | 3-15% | 1305-78-8 | 5 mg/m$^3$ |
| Magnesium Oxide [MgO] | 0-4% | 1309-48-4 | 15 mg/m$^3$ (Fume) |
| Iron Oxide [FeO] | 7-31% | 1309-37-1 | 10 mg/m$^3$ |
| Potassium Oxide [$K_2O$] | 0-3% | 12136-45-7 | NE |
| Titanium Dioxide [$TiO_2$] | 0-2% | 13463-67-7 | 15 mg/m$^3$ |

**ND** - Not Detectable
**NE** - Not Established

## SECTION III – PHYSICAL DATA

| | |
|---|---|
| **Physical Form:** | Solid (Angular Granules) |
| **Boiling Temperature:** | N/A |
| **Melting Temperature:** | > 2500° F |
| **Vapor Pressure/Density:** | N/A |
| **Evaporation Rate:** | N/A |
| **Specific Gravity:** | 2.7 g/cc Typical |
| **Water Solubility:** | Negligible |
| **Color:** | Black Coarse Solid |
| **Odor:** | None |

## SECTION IV – FIRE/EXPLOSION/ REACTIVITY DATA

Product is nonflammable, non-explosive and stable under normal conditions of use, storage and transportation.

## SECTION V – HEALTH HAZARD DATA

**EXPOSURE LIMITS:** Refer to Section II which highlights the Permissible Exposure Limit (PEL). This limit is published and enforced by OSHA as a legal standard. Most PELs are expressed as eight hour average airborne concentrations. The nuisance dust exposure standard should be followed if exceeded than the appropriate respiratory protection equipment should be worn.

**ACUTE and CHRONIC TOXICITY:** Exposure to and contact from dust may irritate the respiratory system, eyes, or skin. Coal slag is not listed on the NTP, IARC, or OSHA list of carcinogens. If ingested it may cause nausea and vomiting.

**FIRST AID:**

1. Eye Contact – Immediately flush eyes thoroughly with water or an ophthalmic saline solution.*
2. Skin Contact – Wash skin with soap and water if irritation occurs.*
3. Inhalation – Remove affected person(s) to fresh air source.*
4. Oral intake – Rinse mouth out with water.*

***Note: if symptoms persist, contact a physician or other medical personnel.**

## SECTION VI – CONTROL MEASURES

**RESPIRATOR PROTECTION:** If airborne concentrations exceed recommended exposure limits, a suitable NIOSH/MSHA approved filter respirator should be worn. General ventilation or local exhaust is normally adequate to control dust emissions, if not engineering controls should be utilized.

**EYE:** Safety glasses with side shields should be worn as minimum protection from impact. Dust goggles should be worn when excessively dusty conditions are present or anticipated.

**GENERAL:** The use of hard hats and hard toe shoes is recommended. Gloves may be worn to protect from abrasion as well as long sleeve shirts to minimize dermal exposure and potential skin irritation.

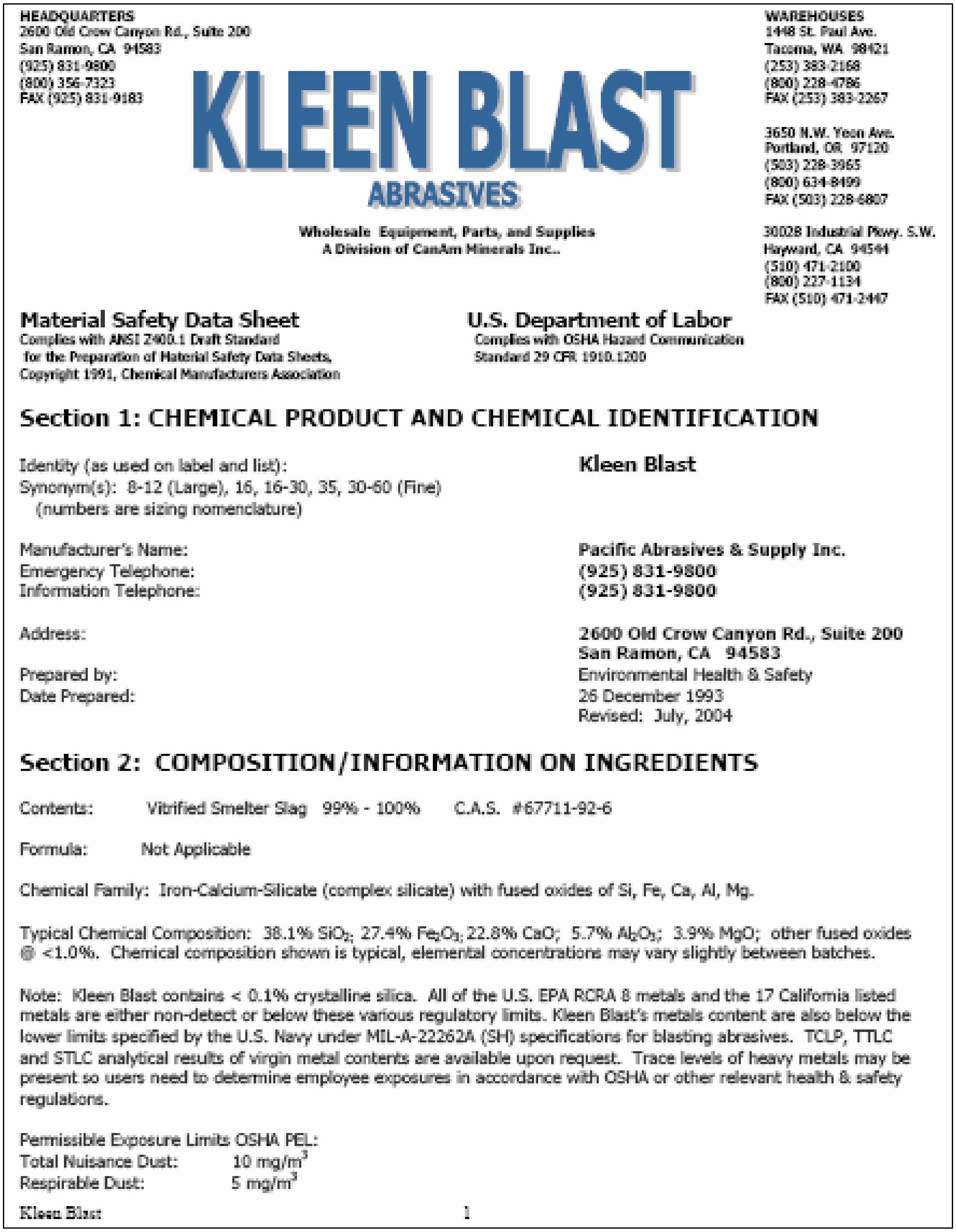
## SECTION VII – SPILL, LEAK, AND DISPOSAL PROCEDURES

No special procedures required for clean-up, but it is recommended that this is done mechanically or through the use of hand tools. Wetting with water will reduce any airborne dust. Uncontaminated product does not exceed Toxicity Characteristic Leaching Procedure (TCLP) limits and may be disposed of as an inert material in an appropriate solid waste landfill according to applicable Federal, State and Local regulations.

### Disclaimer

The opinions expressed herein are those of competent personnel within Harsco Corporation. Harsco believes that the information contained herein is current and accurate for the normal and intended use of this product as of the date of this Material Safety Data Sheet. Since the use of this information and of those opinions or the conditions of use of the product are not within the control of Harsco Corporation, it is the user's obligation to determine and observe the conditions of safe use and disposal of the product by their operations. Harsco Corporation will not be liable for any loss, damage or injury arising out of the use thereof.

# MSDS for Copper Slag



**HEADQUARTERS**
2600 Old Crow Canyon Rd., Suite 200
San Ramon, CA 94583
(925) 831-9800
(800) 356-7323
FAX (925) 831-9183

**KLEEN BLAST**
**ABRASIVES**

**Wholesale Equipment, Parts, and Supplies**
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**WAREHOUSES**
1448 St. Paul Ave.
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(800) 228-4786
FAX (253) 383-2267

3650 N.W. Yeon Ave.
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(503) 228-3965
(800) 634-8499
FAX (503) 228-6807

30028 Industrial Pkwy. S.W.
Hayward, CA 94544
(510) 471-2100
(800) 227-1134
FAX (510) 471-2447

**Material Safety Data Sheet**
Complies with ANSI Z400.1 Draft Standard
for the Preparation of Material Safety Data Sheets,
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**U.S. Department of Labor**
Complies with OSHA Hazard Communication
Standard 29 CFR 1910.1200

## Section 1: CHEMICAL PRODUCT AND CHEMICAL IDENTIFICATION

Identity (as used on label and list): **Kleen Blast**
Synonym(s): 8-12 (Large), 16, 16-30, 35, 30-60 (Fine)
(numbers are sizing nomenclature)

Manufacturer's Name: **Pacific Abrasives & Supply Inc.**
Emergency Telephone: **(925) 831-9800**
Information Telephone: **(925) 831-9800**

Address: **2600 Old Crow Canyon Rd., Suite 200**
**San Ramon, CA 94583**
Prepared by: Environmental Health & Safety
Date Prepared: 26 December 1993
Revised: July, 2004

## Section 2: COMPOSITION/INFORMATION ON INGREDIENTS

Contents: Vitrified Smelter Slag 99% - 100% C.A.S. #67711-92-6

Formula: Not Applicable

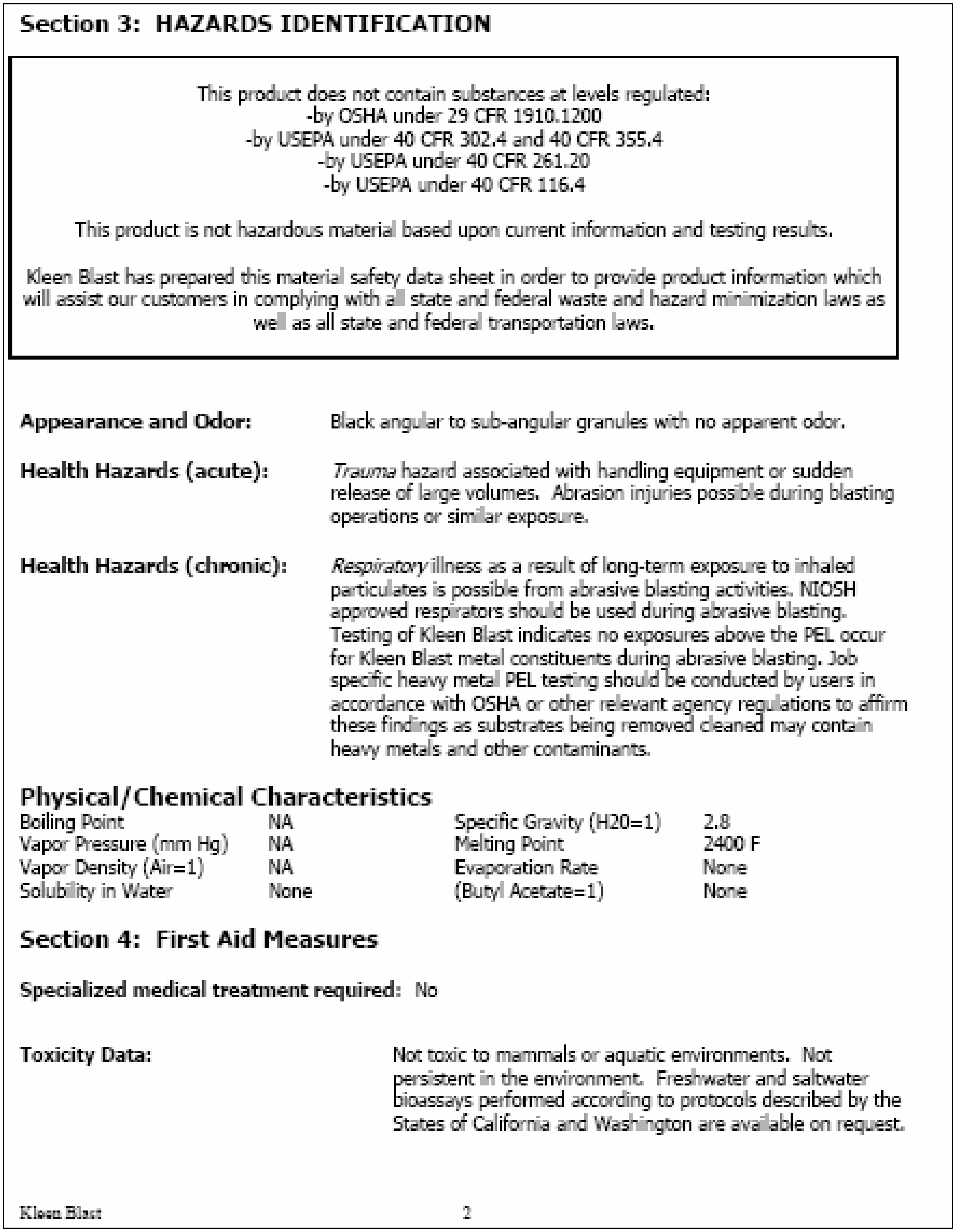
Chemical Family: Iron-Calcium-Silicate (complex silicate) with fused oxides of Si, Fe, Ca, Al, Mg.

Typical Chemical Composition: 38.1% $SiO_2$; 27.4% $Fe_2O_3$; 22.8% CaO; 5.7% $Al_2O_3$; 3.9% MgO; other fused oxides @ <1.0%. Chemical composition shown is typical, elemental concentrations may vary slightly between batches.

Note: Kleen Blast contains < 0.1% crystalline silica. All of the U.S. EPA RCRA 8 metals and the 17 California listed metals are either non-detect or below these various regulatory limits. Kleen Blast's metals content are also below the lower limits specified by the U.S. Navy under MIL-A-22262A (SH) specifications for blasting abrasives. TCLP, TTLC and STLC analytical results of virgin metal contents are available upon request. Trace levels of heavy metals may be present so users need to determine employee exposures in accordance with OSHA or other relevant health & safety regulations.

Permissible Exposure Limits OSHA PEL:
Total Nuisance Dust: 10 mg/$m^3$
Respirable Dust: 5 mg/$m^3$

Kleen Blast 1



## Section 3: HAZARDS IDENTIFICATION

This product does not contain substances at levels regulated:
-by OSHA under 29 CFR 1910.1200
-by USEPA under 40 CFR 302.4 and 40 CFR 355.4
-by USEPA under 40 CFR 261.20
-by USEPA under 40 CFR 116.4

This product is not hazardous material based upon current information and testing results.

Kleen Blast has prepared this material safety data sheet in order to provide product information which will assist our customers in complying with all state and federal waste and hazard minimization laws as well as all state and federal transportation laws.

**Appearance and Odor:** Black angular to sub-angular granules with no apparent odor.

**Health Hazards (acute):** *Trauma* hazard associated with handling equipment or sudden release of large volumes. Abrasion injuries possible during blasting operations or similar exposure.

**Health Hazards (chronic):** *Respiratory* illness as a result of long-term exposure to inhaled particulates is possible from abrasive blasting activities. NIOSH approved respirators should be used during abrasive blasting. Testing of Kleen Blast indicates no exposures above the PEL occur for Kleen Blast metal constituents during abrasive blasting. Job specific heavy metal PEL testing should be conducted by users in accordance with OSHA or other relevant agency regulations to affirm these findings as substrates being removed cleaned may contain heavy metals and other contaminants.

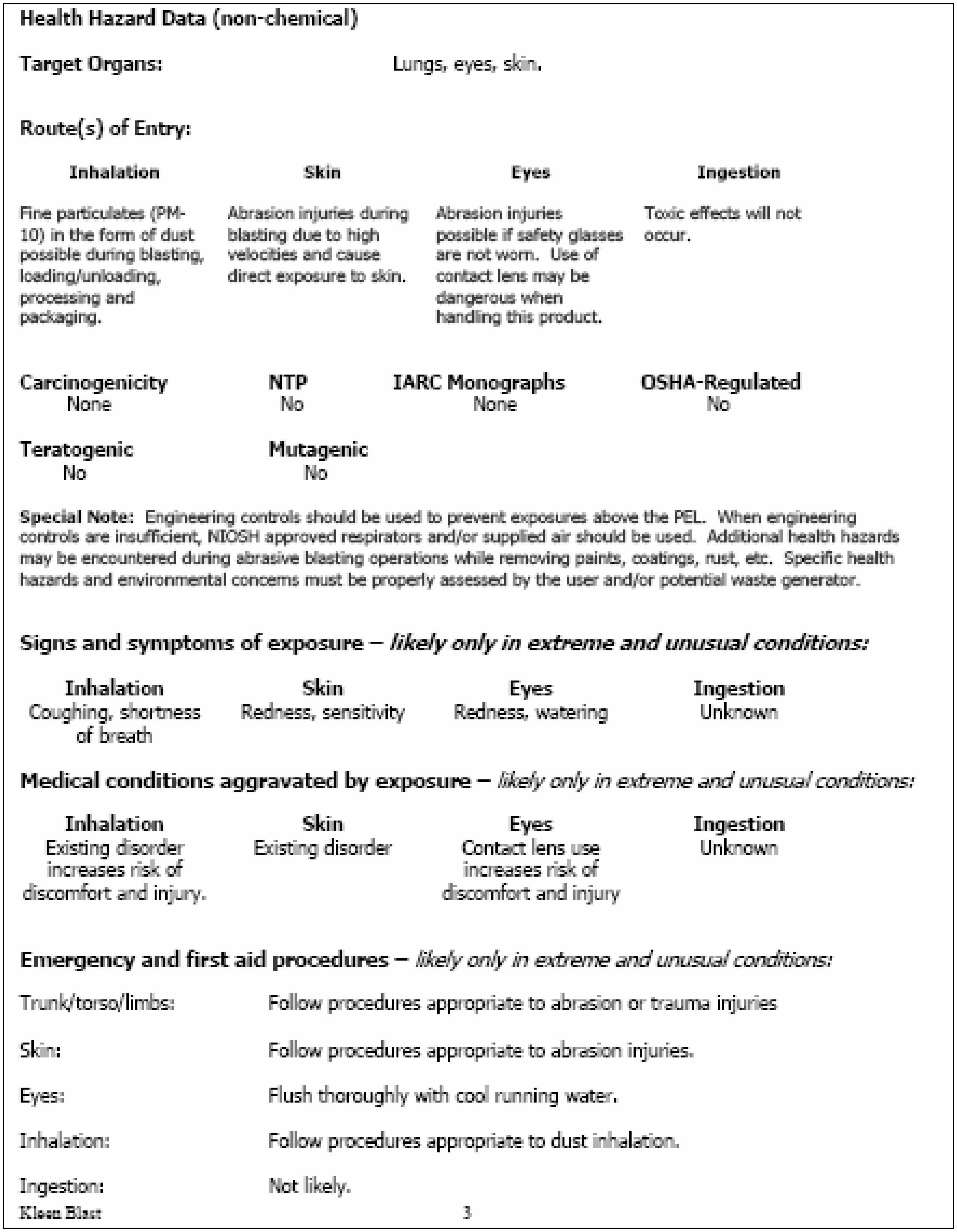
### Physical/Chemical Characteristics

| | | | |
|---|---|---|---|
| Boiling Point | NA | Specific Gravity (H20=1) | 2.8 |
| Vapor Pressure (mm Hg) | NA | Melting Point | 2400 F |
| Vapor Density (Air=1) | NA | Evaporation Rate | None |
| Solubility in Water | None | (Butyl Acetate=1) | None |

## Section 4: First Aid Measures

**Specialized medical treatment required:** No

**Toxicity Data:** Not toxic to mammals or aquatic environments. Not persistent in the environment. Freshwater and saltwater bioassays performed according to protocols described by the States of California and Washington are available on request.



## Health Hazard Data (non-chemical)

**Target Organs:** Lungs, eyes, skin.

**Route(s) of Entry:**

| Inhalation | Skin | Eyes | Ingestion |
|---|---|---|---|
| Fine particulates (PM-10) in the form of dust possible during blasting, loading/unloading, processing and packaging. | Abrasion injuries during blasting due to high velocities and cause direct exposure to skin. | Abrasion injuries possible if safety glasses are not worn. Use of contact lens may be dangerous when handling this product. | Toxic effects will not occur. |

| Carcinogenicity | NTP | IARC Monographs | OSHA-Regulated |
|---|---|---|---|
| None | No | None | No |

| Teratogenic | Mutagenic |
|---|---|
| No | No |

**Special Note:** Engineering controls should be used to prevent exposures above the PEL. When engineering controls are insufficient, NIOSH approved respirators and/or supplied air should be used. Additional health hazards may be encountered during abrasive blasting operations while removing paints, coatings, rust, etc. Specific health hazards and environmental concerns must be properly assessed by the user and/or potential waste generator.

**Signs and symptoms of exposure – *likely only in extreme and unusual conditions:***

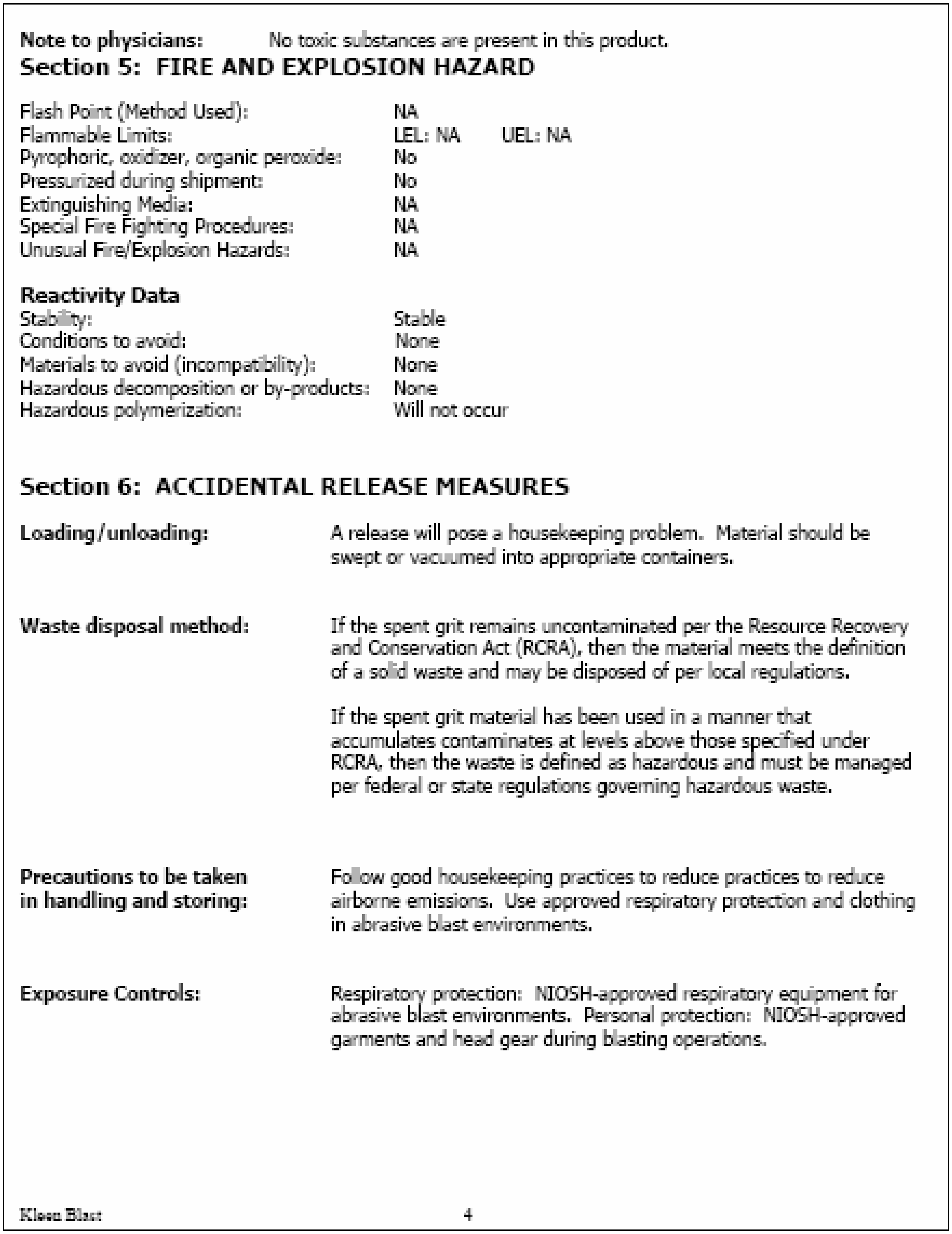
| Inhalation | Skin | Eyes | Ingestion |
|---|---|---|---|
| Coughing, shortness of breath | Redness, sensitivity | Redness, watering | Unknown |

**Medical conditions aggravated by exposure – *likely only in extreme and unusual conditions:***

| Inhalation | Skin | Eyes | Ingestion |
|---|---|---|---|
| Existing disorder increases risk of discomfort and injury. | Existing disorder | Contact lens use increases risk of discomfort and injury | Unknown |

**Emergency and first aid procedures – *likely only in extreme and unusual conditions:***

| | |
|---|---|
| Trunk/torso/limbs: | Follow procedures appropriate to abrasion or trauma injuries |
| Skin: | Follow procedures appropriate to abrasion injuries. |
| Eyes: | Flush thoroughly with cool running water. |
| Inhalation: | Follow procedures appropriate to dust inhalation. |
| Ingestion: | Not likely. |



**Note to physicians:** No toxic substances are present in this product.

## Section 5: FIRE AND EXPLOSION HAZARD

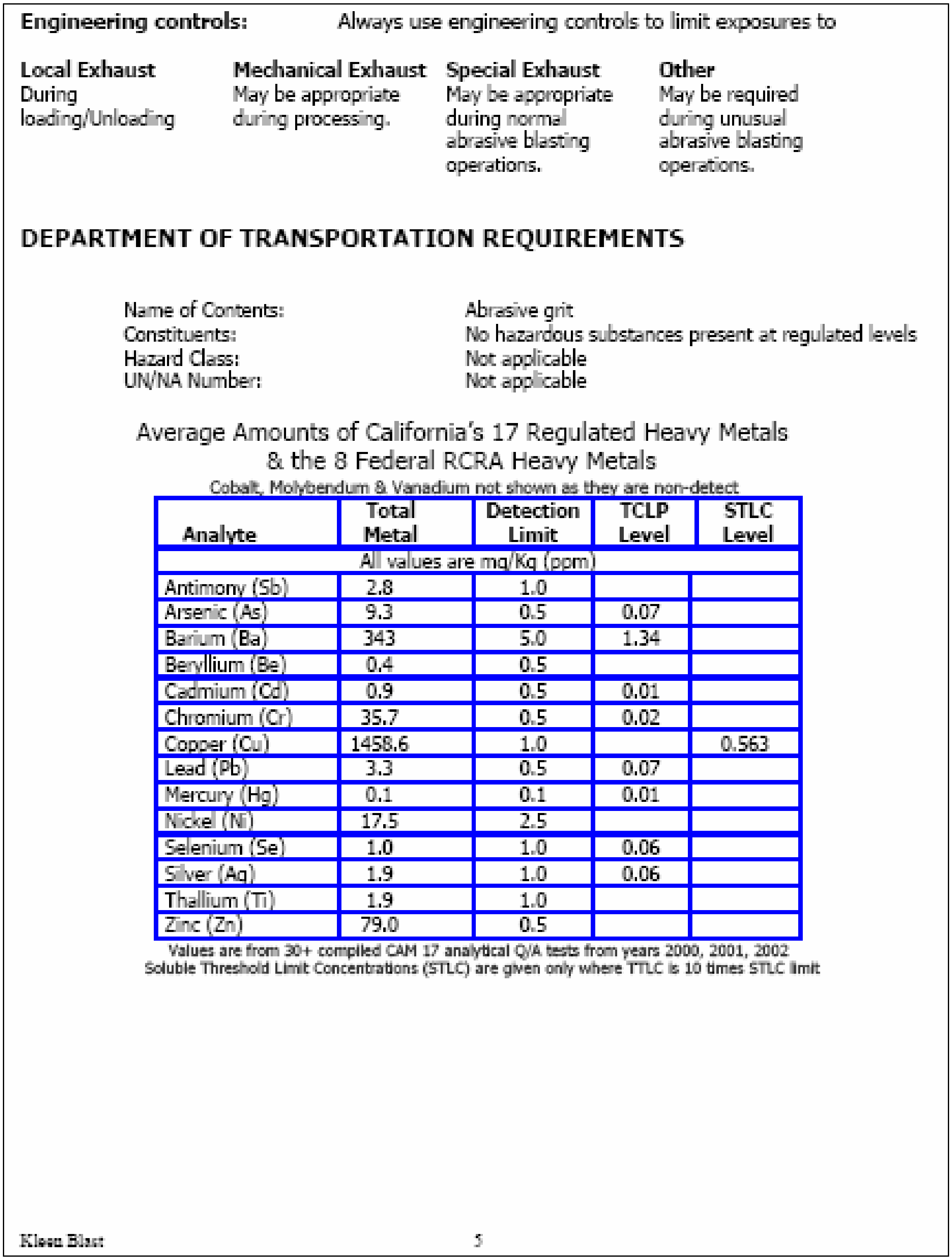
| | |
|---|---|
| Flash Point (Method Used): | NA |
| Flammable Limits: | LEL: NA UEL: NA |
| Pyrophoric, oxidizer, organic peroxide: | No |
| Pressurized during shipment: | No |
| Extinguishing Media: | NA |
| Special Fire Fighting Procedures: | NA |
| Unusual Fire/Explosion Hazards: | NA |

### Reactivity Data

| | |
|---|---|
| Stability: | Stable |
| Conditions to avoid: | None |
| Materials to avoid (incompatibility): | None |
| Hazardous decomposition or by-products: | None |
| Hazardous polymerization: | Will not occur |

## Section 6: ACCIDENTAL RELEASE MEASURES

| | |
|---|---|
| **Loading/unloading:** | A release will pose a housekeeping problem. Material should be swept or vacuumed into appropriate containers. |
| **Waste disposal method:** | If the spent grit remains uncontaminated per the Resource Recovery and Conservation Act (RCRA), then the material meets the definition of a solid waste and may be disposed of per local regulations.<br>If the spent grit material has been used in a manner that accumulates contaminates at levels above those specified under RCRA, then the waste is defined as hazardous and must be managed per federal or state regulations governing hazardous waste. |
| **Precautions to be taken in handling and storing:** | Follow good housekeeping practices to reduce practices to reduce airborne emissions. Use approved respiratory protection and clothing in abrasive blast environments. |
| **Exposure Controls:** | Respiratory protection: NIOSH-approved respiratory equipment for abrasive blast environments. Personal protection: NIOSH-approved garments and head gear during blasting operations. |



**Engineering controls:** Always use engineering controls to limit exposures to

| Local Exhaust | Mechanical Exhaust | Special Exhaust | Other |
|---|---|---|---|
| During loading/Unloading | May be appropriate during processing. | May be appropriate during normal abrasive blasting operations. | May be required during unusual abrasive blasting operations. |

## DEPARTMENT OF TRANSPORTATION REQUIREMENTS

| | |
|---|---|
| Name of Contents: | Abrasive grit |
| Constituents: | No hazardous substances present at regulated levels |
| Hazard Class: | Not applicable |
| UN/NA Number: | Not applicable |

### Average Amounts of California's 17 Regulated Heavy Metals & the 8 Federal RCRA Heavy Metals

Cobalt, Molybendum & Vanadium not shown as they are non-detect

| Analyte | Total Metal | Detection Limit | TCLP Level | STLC Level |
|---|---|---|---|---|
| All values are mg/Kg (ppm) | | | | |
| Antimony (Sb) | 2.8 | 1.0 | | |
| Arsenic (As) | 9.3 | 0.5 | 0.07 | |
| Barium (Ba) | 343 | 5.0 | 1.34 | |
| Beryllium (Be) | 0.4 | 0.5 | | |
| Cadmium (Cd) | 0.9 | 0.5 | 0.01 | |
| Chromium (Cr) | 35.7 | 0.5 | 0.02 | |
| Copper (Cu) | 1458.6 | 1.0 | | 0.563 |
| Lead (Pb) | 3.3 | 0.5 | 0.07 | |
| Mercury (Hg) | 0.1 | 0.1 | 0.01 | |
| Nickel (Ni) | 17.5 | 2.5 | | |
| Selenium (Se) | 1.0 | 1.0 | 0.06 | |
| Silver (Ag) | 1.9 | 1.0 | 0.06 | |
| Thallium (Ti) | 1.9 | 1.0 | | |
| Zinc (Zn) | 79.0 | 0.5 | | |

Values are from 30+ compiled CAM 17 analytical Q/A tests from years 2000, 2001, 2002
Soluble Threshold Limit Concentrations (STLC) are given only where TTLC is 10 times STLC limit

# MSDS for Specialty Sand

## 1. PRODUCT/COMPANY IDENTIFICATION

Manufacturer's Name & Address:

Titan America LLC

1151 Azalea Garden Rd.

Norfolk, VA 23502

Telephone Number for Information:

1.800.468.7622

Emergency Telephone:

1.757.858.6500

## 2. COMPOSTION INFORMATION

Chemical Name CAS Registry Number % (approx.)

Natural Sand* NA 100

*May contain crystallline silica 14808-60-7 >1

## 3. PHYSICAL/CHEMICAL CHARACTERISTICS

Boiling Point N/A

Specific Gravity (H2O = 1) 2.55-2.80

Vapor Pressure (mm Hg) N/A

Melting Point N/A

Vapor Density (AIR-1) N/A

Evaporation Rate N/A

Solubility in Water Not soluble

Appearance & Odor Fine grains, yellow to white in color; no odor.

## 4. FIRE AND EXPLOSION HAZARD DATA

Flash Point N/A

Extinguishing Media N/A

Special Fire Fighting Procedures None

Unusual Fire & Explosion Hazards None

Flammable Limits N/A

LEL N/A

UEL N/A

Trade Name:

Sand

Chemical Name and Synonyms

Natural Sand*, Construction Aggregate

Department of Transportation Identification No.:

None

*Composition varies naturally, typically contains crystalline silica

## 5. REACTIVITY DATA

Stability: Stable. Avoid contact with incompatible materials.

Incompatibility: Contact with powerful oxidizing agents such as fluorine, boron trifluoride, chlorine trifluoride,

manganese trifluoride, and oxygen difluoride may cause fire and/or explosions. Silica dissolves in hydrofluoric acid producing a corrosive gas-silicon tetrafluoride.

Hazardous Decomposition or Byproducts: Respirable dust particles may be generated when sand is moved or ground.

Hazardous Polymerization: Will not occur. No conditions to avoid.

## 6. HEALTH HAZARD DATA AND FIRST AID

EXPOSURE LIMITS:

Unless specified otherwise, limits are expressed as a time-weighted average (TWA) concentration for an 8-hour work shift of a 40-hour workweek. Limits for cristobalite and tridymite (other forms of crystalline silica) are equal to one-half the limits for quartz.

ABBREVIATIONS:

ACGIH TLV: Threshold limit value of the American Conference of Governmental Industrial Hygienists (ACGIH).

mg/m3: Milligrams of substance per cubic meter of air.

NIOSH REL: Recommended exposure limit of the National Institute for Occupational Safety and Health (NIOSH), expressed as a TWA

concentration for up to a 10-hour work-day during a 40-hour workweek.

OSHA PEL: Permissible exposure limit of the federal Occupational Safety and Health Administration (OSHA).

Crystalline Silica SiO2: OSHA PELs (respirable fraction) [10 mg/m3 ÷ (% SiO2+2)], (total dust) [30 mg/m3 ÷ (% SiO2+2)]; ACGIH TLV (respirable

fraction) 0.05 mg/m3, NIOSH REL (respirable fraction) 0.05 mg/m3.

Other Particulates: OSHA PEL (total particulate, not otherwise regulated) 15 mg/m3, (respirable particulate, not otherwise regulated) 5 mg/m3,

ACGIH TLV (nuisance particulates) 10 mg/m3 (inhalable), 5 mg/m3 (respirable).

HEALTH HAZARDS:

Primary Route(s) of Entry:

Inhalation: Yes

Skin: No

Ingestion: No

Acute:

Eye Contact: Minor irritation to the eyes or nose.

Inhalation: Dusts may irritate the nose, throat, and respiratory tract by mechanical abrasion. Coughing, sneezing, and shortness of breath may occur following exposures in excess of appropriate exposure limits.

Skin Contact: Direct contact may cause irritation by mechanical abrasion.

Ingestion: Expected to be practically non-toxic. Ingestion of large amounts may cause gastrointestinal irritation and blockage.

Chronic:

Inhalation: Chronic exposure to respirable dust in excess of appropriate exposure limits may cause lung disease. Silicosis may result from excessive exposure to respirable silica dust for prolonged periods. Not all individuals with silicosis will exhibit symptoms. Silicosis is progressive and symptoms can appear at any time, even after exposure has ceased. Symptoms may include shortness of breath, coughing, or right heart enlargement and/or failure. Persons with silicosis have an increased risk of pulmonary tuberculosis infection. Tobacco smoking may increase the risk of developing lung disorders, including emphysema and lung cancer.

Carcinogenicity: Crystalline silica is classified by the International Agency for Research on Cancer (IARC) as a carcinogenic to humans (Group 1). The National Toxicology

Program (NTP) has characterized respirable silica as “known to be a human carcinogen”. Prolonged and repeated breathing of silica may cause lung cancer.

Signs & Symptoms of Exposure: Dust irritation of eyes and/or respiratory system.

Medical Conditions Generally Aggravated by Exposure: Inhaling respirable dust may aggravate existing respiratory system disease(s) and/or dysfunctions such as emphysema or asthma. Exposure may aggravate existing eye conditions.

EMERGENCY & FIRST AID PROCEDURES:

Eyes: Immediately flush eye(s) with plenty of clean water for at least 15 minutes, while holding the eyelid(s) open. Beyond flushing, do not attempt to remove material from the eye(s). Contact a physician if irritation persists or later develops.

Inhalation: Remove to fresh air. Dust in throat and nasal passages should clear spontaneously. Contact a physician if irritation persists or later develops.

Skin: Wash with soap and water. Contact a physician if irritation persists or later develops.

Ingestion: If person is conscious, give large quantity of water and induce vomiting; however, never attempt to make an unconscious person drink or vomit. Get immediate medical attention.

## 7. PERSONAL PROTECTION AND CONTROL MEASURES

Ventilation: Local exhaust or general ventilation adequate to maintain exposures below appropriate exposure limits.

Other: Respirable dust and silica levels should be monitored regularly. Dust and silica levels in excess of appropriate exposure limits should be reduced by all feasible engineering controls, including (but not limited to) wet suppression, ventilation, process enclosure, and enclosed employee work stations.

Respiratory Protection: When dust or silica levels exceed or are likely to exceed appropriate exposure limits, follow MSHA or OSHA regulations, as appropriate, for use of NIOSH-approved respiratory protection equipment.

Skin Protection: Protective gloves should be worn to prevent mechanical injury.

Eye Protection: Safety glasses with side shields should be worn as minimum protection. Dust goggles should be worn when excessive (visible) dust conditions are present or anticipated. Contact lenses should not be worn when working with this product.

Hygiene: Ordinary personal hygiene.

## 8. STORAGE AND HANDLING PRECAUTIONS

Respirable silica and dust may be generated during processing, handling, and storage. The personal protection and controls identified in Section VII of the MSDS should be applied as appropriate.

## 9. SPILL, LEAK AND DISPOSAL PRACTICES

The personal protection and controls identified in Section VII of the MSDS should be applied as appropriate.

Steps to Be Taken if Material Is Released or Spilled: Spilled materials, where dust can be generated, may overexpose cleanup personnel to respirable silica and dust. Wetting of spilled material and/or use of respiratory protective equipment may be necessary. Do not dry sweep spilled material.

Waste Disposal Method: Dispose of waste materials only in accordance with applicable federal, state, and local laws and regulations.

NOTICE: Based on research of available data, Titan America LLC believes that the information contained in this Material Safety Data Sheet is accurate. The suggested procedures are based on data and experience as of the date of preparation of the MSDS. The suggestions should not be confused with nor followed in violation of applicable laws, regulations, rules or insurance requirements. Titan America LLC’s voluntary preparation of this MSDS should not be construed, in any way, as an agreement to be subject to OSHA jurisdiction.

# APPENDIX D: Example for Calculation of Blasting Costs

Blasting costs include abrasive material cost, labor cost, equipment cost, emission control cost, cleanup cost, waste disposal cost, emission fees, and other costs. Productivity and consumption are two important parameters in calculating the blasting costs. Emission factors help in determining the emission quantities and thus compliance costs and emission fees. The regression equations developed in this research will help in determining productivity, consumption, and emission factors at a given blast pressure and feed rate condition for three abrasives: coal slag, copper slag, and specialty sand. These values may then be used to calculate the blasting costs in order to select a better abrasive material that will result in minimum costs. . Abrasive cost, labor cost, equipment cost, clean up cost, and other were obtained from various sources and average of these values were used in the calculations. The following table shows unit costs used in the calculations.

**Table: Unit Costs**

| **Item** | **Units** | **Avg., $** | **Remarks** |
|---|---|---|---|
| Coal Slag | 1000 kg | 55 | |
| Copper Slag | 1000 kg | 70 | |
| Specialty Sand | 1000 kg | 40 | |
| Labor | hr | 25 | Labor cost includes, hourly pay rates and benefits |
| Power | kWh | 0.1 | Typical energy costs paid by industries in the US |
| Equipment Depreciation | hr | 1.66 | A total of $ 10,000 assumed towards blast pot, hoses, secondary air supply unit, and other peripherals; Life of equipment assumed: 4000 hours 6000 hours |
| Shrouds | $m^2$ | 15 | Includes scaffolding, screens, installation labor, and dismantling labor; 2 sqft screen required for 1 sqft cleaned; $ 0.75/ sqft for screens or $1.50/sqft area cleaned; higher side cost of $1.70/sqft; highly subjective based on work setting. |
| Cleanup costs | 1000 kg | 16 | |
| Disposal costs | 1000 kg | 40 | |
| Emission Fee | 1000 kg | 8000 | |

First, emission factors, productivity, and consumption are calculated for the three materials using equations 2, 4, and 5 and their coefficients respectively. These values and unit costs were then used to determine blasting costs per 1000 $m^2$ area cleaned. The following table shows the calculation methods and blasting costs. From this example, it evident that copper slag results in minimum costs. Material cost, labor cost, emission costs etc. vary from one supplier to another and one state to another. Using the actual costs and including addition costs incurred by the industries, more accurate costs can be estimated. This will greatly help industries in material selection and process optimization.

## Table: Calculation of Blasting Costs

| Variable | Units | Avg. Unit Cost, $ | Remarks | Coal Slag | Copper Slag | Specialty Sand |
|---|---|---|---|---|---|---|
| Productivity | $m^2$/hr | NA | From Equation 4 and Table 11 | 14.04 | 13.99 | 15.08 |
| Abrasive Consumption | kg/$m^2$ | NA | From Equation 5 and Table 12 | 33.57 | 31.75 | 23.71 |
| PM Emissions | kg/$m^2$ | NA | From Equation 2 and Table 9 | 1.89 | 1.40 | 2.97 |
| | | | | | | |
| Abrasive Purchase Cost | $/1000 $m^2$ | From Unit Costs Table | (Abrasive Cost/1000) *Consumption * 1000 | 1846.35 | 1746.25 | 1304.00 |
| Power Consumption | $/1000 $m^2$ | $ 0.11/ kWh | ((Power Rating * Unit Power Cost) / Productivity) *1000 | 783.48 | 786.42 | 729.44 |
| Labor | $/1000 $m^2$ | $30/ hr | (Unit Labor Cost / Productivity) *1000 | 2136.75 | 2144.77 | 1989.39 |
| Equipment Capital Cost | $/1000 $m^2$ | $2.08/ hr | (Unit Equipment Cost / Productivity) *1000 | 148.15 | 148.70 | 137.93 |
| Shrouds Cost | $/1000 $m^2$ | $15/ $m^2$ | Unit Shroud Cost * 1000 | 15000.00 | 15000.00 | 15000.00 |
| Used Abrasive Cleanup Costs | $/1000 $m^2$ | $16/ 1000 kg | (Unit Cleanup Cost/1000) *Consumption * 1000 | 537.12 | 508.00 | 379.34 |
| Used Abrasive Disposal Costs | $/1000 $m^2$ | $40/ 1000 kg | (Unit Disposal Cost/1000) *Consumption * 1000 | 1342.80 | 1270.00 | 948.36 |
| Emissions Fee | $/1000 $m^2$ | $8000/ 1000 kg | (Emission Factor * Unit Emission Fee /1000) *1000 | 15136.00 | 11200.00 | 23760.00 |
| | | | | | | |
| **Total Cost** | **$/1000 $m^2$** | | | **36,931** | **32,804** | **44,248** |

# VITA

Kalpalatha Kambham was born in Piler, India in 1978. She graduated with a Bachelor of Engineering in Civil Engineering from Sri Venkateswara University College of Engineering, India in 1999 and a Master of Science in Civil Engineering from University of New Orleans in 2002. Her areas of interest are air pollution control, air quality modeling, waste management, industrial hygiene, risk assessment, and development of Expert Management Systems.