UTILIZATION OF INDUSTRIAL WASTES OF TURKEY AS ABRASIVE IN SURFACE PREPARATION TECHNOLOGIES

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ABSTRACT

UTILIZATION OF INDUSTRIAL WASTES OF TURKEY AS ABRASIVE IN SURFACE PREPARATION TECHNOLOGIES

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Surface preparation is the key factor in determining the success of a protective coating system and its ultimate objective is to create proper adhesion of a coating over an underlying substrate.

Abrasive blast cleaning involves mechanical cleaning by the continuous impact of abrasive particles at high velocities on to the substrate in a jet stream of compressed air. Industries that use abrasive blasting include the shipbuilding industry, automotive industry, and other industries that involve surface preparation and painting.

Materials from different origins can be used as a blasting media including coal slag, smelter slag, mineral abrasives, metallic abrasives, and synthetic abrasives.

Purpose of this thesis is to investigate the usability of industrial wastes (coal slag, smelter slags, etc.) of Turkey as abrasives in surface preparation technologies.

Four different slag samples of three sources, namely coal furnace slag sample from Çayırhan thermal power plant, ferrochrome slag sample from Eti Krom A.Ş., granulated blast furnace and converter slag sample from Ereğli Iron and Steel Works were studied within the scope of this thesis work. The samples were prepared by crushing and screening. The chemical composition and physical characteristics of the samples were determined. All the samples were tested in industrial scale.

Test results showed that the converter slag meet all the specifications for abrasives and it can be used in blast cleaning operations. However, coal furnace slag, granulated blast furnace slag and ferrochrome slag are not suitable to be used as abrasive in surface preparation technologies.

Keywords: Abrasive, Industrial waste, Slag, Blast cleaning, Surface preparation.

ÖZ

TÜRKİYE'DEKİ ENDÜSTRİYEL ATIKLARIN YÜZEY HAZIRLAMA TEKNOLOJİLERİNDE AŞINDIRICI OLARAK KULLANILMASI

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Yüzey hazırlama, koruyucu kaplama sistemlerinin başarısını belirlemede anahtar etkendir ve nihai hedefi kaplamanın alt tabaka üzerine tam bir yapışma meydana getirmesidir.

Aşındırıcı püskürtme, aşındırıcı parçacıklarının basınçlı hava ile bir jet akım içinde, yüksek hızla, yüzey üzerine sürekli çarptırılarak yapılan mekanik bir temizlemedir. Aşındırıcı püskürtme yapılan sanayiler, gemi inşa sanayisi, otomotiv sanayisi ve yüzey hazırlama ve boyama gerektiren diğer sanayilerdir.

Kömür cürufu, izabe cürufları, mineral aşındırıcılar, metalik aşındırıcılar ve sentetik aşındırıcılar gibi değişik kökenli malzemeler püskürtme işleminde aşındırıcı olarak kullanılmaktadır.

Bu tez çalışmasının amacı Türkiye'deki endüstriyel atıkların (kömür cürufu, izabe cürufları, vs.) yüzey hazırlama teknolojilerinde aşındırıcı olarak kullanılabilirliğini araştırmaktır.

Bu çalışmada, Çayırhan termik santralı kazanaltı cürufu, Eti Krom A.Ş.'den ferrokrom cürufu, ve Ereğli Demir ve Çelik Fabrikaları'ndan granüle yüksek fırın cürufu ve çelikhane cürufu olmak üzere üç kaynaktan dört farklı cüruf numunesi incelenmiştir. Kırma ve eleme işlemleriyle hazırlanan numunelerin kimyasal kompozisyonu ve fiziksel karakterleri belirlenmiştir. Tüm numuneler endüstriyel ölçekte denenmiştir.

Yapılan çalışmalar, çelikhane cürufunun, aşındırıcı olarak bütün spesifikasyonları sağladığını ve aşındırıcı püskürtme işleri için uygun olduğunu göstermiştir. Bununla birlikte, termik santral kazanaltı cürufu, granüle yüksek fırın cürufu ve ferrokrom cürufunun yüzey teknolojilerinde aşındırıcı olarak kullanılmasının uygun olmadığı saptanmıştır.

Anahtar Kelimeler: Aşındırıcı, Endüstriyel atık, Cürüf, Aşındırıcı püskürtme, Yüzey hazırlama

To My Mother
Firdevs Ataman

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CHAPTER I

INTRODUCTION

1.1 General Remarks

Corrosion is an electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties. Corrosion occurs when metals react with nonmetallic elements of their environment. Since the industrial revolution, and particularly in recent decades, advancing technology has required the use of ever greater quantities of iron and of other metals and alloys under increasingly severe conditions. The need for corrosion control to insure the most efficient use of metallic resources has increased accordingly. Control of corrosion is based on preventing the reaction between a metallic surface and its environment. The general approaches to this objective are through control of the environment, of the nature of the metal or of the surface between the two [1].

If one envisages the corrosion process in terms of a simple electro-chemical cell, in which an anode and cathode are joined by an electronic conductor, a range of means of protecting the anode can be proposed [2]. In general, the approach to control most corrosion is to understand the corrosion mechanism involved and remove one or more of the elements of the corrosion cell. Putting a barrier between a corrosive environment and the material to be protected is a fundamental method of corrosion control. There are many organic and metallic coating systems to choose from, and they are available in various combinations.

In addition to proper coating selection and application methods, substrate preparation is critical to the success of the coating. It is now well established, and increasingly well appreciated, that good surface preparation is the key to good protection by surface coatings. The majority of coating failures are caused either completely or partially by faulty surface preparation, such as leaving contaminants on the surface or having an inappropriate surface morphology [3]. Therefore, surface preparation is the essential first stage treatment of a substrate before the application of any coatings.

Today the technical-scientific area of surface treatments covers a vast scope. The main surface treatments of industrial interest include thermal treatments, diffusion treatments, ion bombardment, mechanical treatments, and physical-chemical treatments. However, among those treatments the last two groups are of greatest interest for industrial application [4].

For reasons fundamentally of an economic nature, steel continues to be the main metal used in construction despite its poor corrosion resistance. The economic reasons behind this are related to its ease of manufacture and its availability in a great variety of shapes and dimensions. Thus, in industrial reality, the vast majority of surface treatment and coating applications are destined to protect and/or improve the properties of ferrous surfaces [4].

1.2 Statement of the Problem

The shipbuilding and maintenance industry builds and repairs ships, barges, and other large vessels. Typical maintenance and repair operations include surface preparation and repainting the ship’s hull, freeboard, superstructure, and interior tanks and work areas. Dry abrasive blasting is one of the most common types of blasting in the shipbuilding and maintenance industry for paint removal and surface preparation. Copper slag, coal slag, steel grit, and steel shot are common blasting abrasives. Traditionally sand was used, but metallic grit and slag abrasives have replaced it due to the adverse health and environmental effects of silica dust associated with sand.

Shipbuilding and maintenance industry of Turkey has grown during the last decade and it keeps growing with an increasing trend. This results in a large demand for blasting abrasives. Unfortunately, Turkey's production of blasting abrasives is negligible and most of the demand is supplied by imports, mainly slag abrasives from Greece and garnet from India. This means that Turkey pays money for the industrial wastes of other countries. Considering the fact that automotive industry and other industries that involve surface preparation and painting also demands for blasting abrasive, active work should be carried out on the research of domestic blasting abrasives.

1.3 Objectives of the Thesis

The objective of this research is to produce blasting abrasives from domestic industrial wastes (coal slag, smelter slags, etc.) and investigate the usability of produced abrasives in surface preparation technologies. In this thesis work, the aim is both to find a new usage area for industrial wastes of Turkey and to reduce the amount of imported abrasives giving a surplus to Turkish economy.

1.4 Methodology of the Study

In order to evaluate the industrial wastes of Turkey as blasting abrasives a method consisting of three stages was followed. In the first stage characteristics of wastes from different sources were investigated in accordance with the tests and assessments given in Turkish standard TS EN ISO 11127. In the second stage test samples were prepared according to market requirements and specifications stated by Turkish standard TS EN ISO 11126. In the last stage the produced abrasives were tested in industry and they were evaluated from performance and quality points of view.

1.5 Thesis Outline

Following the introduction in Chapter I, a literature survey covering very broad concepts about history of abrasives and abrasive blasting, surface preparation methods, standards, blast cleaning techniques, and abrasive media in blast cleaning is carried out in Chapter II. Chapter III covers materials and methods employed for the investigation of domestic industrial wastes as abrasive. Materials and the experimental procedure are described in this section. The results of the laboratory studies and industrial application are stated in Chapter IV. Brief analyses of the results are given in this section. Characteristics of the materials were examined by comparing the same type of materials used in industry and performance of the produced abrasive was evaluated. Finally, Chapter V provides conclusions and recommendations pertinent to this study.

CHAPTER II

LITERATURE REVIEW

2.1 Historical Notes on Abrasives and Abrasive Blasting

It is difficult to say when abrasive technology had a beginning. Abrasives were used by man many thousands of years before he learned to write. Primitive man used abrasives for the sharpening of tools of wood, bone or flint. The beginning of the science of abrasives, however, may be taken as that time when man began to select certain rocks for their peculiar properties, and to fashion these into tools for grinding [5]. For example, the Chinese used corncob skins for polishing. Humans also harvested the most common and abundant minerals in the Earth's crust, namely, the quartz family of minerals. The ancient Greeks called quartz “crystal” and this quartz took the form of sandstone, loose sand, and flint. This crystal material was used in the abrading of stone, wood, metal and grinding grains, and limestone. Additionally, the ancient Greeks developed the use of corundum (naturally occurring aluminum oxide) and garnet, which were superior to quartz [6]. Evidence collected in Egypt indicates that stones were being sawed by some crude sort of grinding machine as early as 4000 B.C. The earliest record of the use of abrasives for the grinding of metal also comes to us from Egypt. A steel dagger was found there along with a sharpening stone, which has been dated at about 1500 B.C. From these early beginnings the modern abrasive industry gradually evolved [5]. Other abrasive materials known were hematite, now known as Jeweler's rouge, in 325 BC by Theophratus. Diamond as a polishing material was referenced in India in 800 BC and its exceptional hardness was referred to in ancient Hindu proverbs and in the Bible [6].

The natural abrasives mentioned above served all purposes for two thousand years or more, until the discovery of the synthetic products. The first of these to reach commercial importance was silicon carbide, first produced by *Dr. Acheson* in 1901 and made today by essentially the same process. Shortly after, in the same year, abrasive grade aluminum oxide was being produced by *C. B. Jacobs* from bauxite by fusion in an electric furnace. In 1934 boron carbide was first produced commercially by *R. R. Ridgeway* of the Norton Company. The first synthesis of boron carbide had been accomplished many years earlier by *Moissan*. The remaining advances of the non-diamond abrasives up to the present were the use of sintered aluminous abrasives, made directly from bauxite without fusion, and the use of fused mixtures of aluminum and zirconium oxides. In 1960 synthetic diamond was produced by the General Electric Company and was soon after available in commercial quantities [5].

Cleaning metallic surfaces always has been a major problem. Alfred Guttman's *Uber Sandstrahlgeblase* has set forth the earliest history of blast cleaning (abrasive blasting) as follows [7]:

"In the early sixties a farmer on the prairies of the United States called in an engineer for advice because the windows of his house became opaque. These were exposed to the strong winds which were carrying sand. The expert recommended that a fine mesh wire screen be put in front of the window panes immediately after reglazing in order to hold back the sand. This was done and resulted in a true sketch pattern on the window panes, because the fine orifices had let the sand pass, which in turn shaded the glass on the exposed spots. Although the engineer regretted his inability to explain the phenomenon to the colonist (settler), a new field was opened to the practical use of this phenomenon, by an artificial means-a new idea was born. Industry did not have to wait long."

In 1870, the American Gen. Benjamin Chew Tilghman, for the first time flung fine quartz sand against glass panes and objects in order to shade or etch them. He used stencils in order to effect ornaments and as he saw the possibilities of the wide application of the sand jet, formulated his patent claim as follows: “To etch or shade glass, stone, metals and other hard materials by means of a sand jet which in turn is propelled by Compressed air of varying density.” The Tilghman patent is the broad base upon which rests today's improved pressure blasting equipment, whether used with rooms, tables, cabinets, or barrels, and including abrasive propelled by air or by centrifugal force [7].

It appears that the standard method of abrasive blasting is still followed with little variation in principle than the method developed during 19th century, though with some improvements in mechanical features and abrasive media.

2.2 Surface Preparation

An essential preliminary to any coating operation is proper surface preparation. It is believed that of the cost of a coating job, as mush as two-thirds goes for surface preparation and labor [8]. When the coating is applied over a poorly prepared surface, at some future time the coating is going to fail prematurely [9].

A surface treatment is considered to be that which leads to a modification of the surface, either by modifying the material to a small depth or by modifying the surface itself. Surface preparation is simply the removal of contamination or unwanted matter from a surface. The preparation of a metal surface consists in removing scales, oxides, grease and other impurities from it [10].

Methods that may work to remove one contaminant may not be appropriate for removal of another type of contaminant on the same item. The type of surface preparation required will depend on the condition of the surface and the performance of the coating in its particular environment [9].

The four principal reasons for surface preparation are as follows [11]:

1. To ensure a uniform substrate that is as close as possible to the theoretical model consieved by the specifiying design engineer.

2. To ensure adhesion of paint system to the steel by removing all loose and tightly adherent contamination and foreign matter from the steel surface, and freeing up reactive sites on the metal surface.
3. To improve adhesion by increasing the real surface area per apparent surface area.
4. To ensure that the mechanism by which the paint system protects the steel is neither hindered nor prohibited by the presence of such soluble moieties as chloride and sulphate ions on the steel surface.

The selection of appropriate cleaning and surface preparation techniques is primarily dependent on the nature of the surface and the intended coating or surface treatment technique. The size and shape of the largest predicted work-piece is generally used to establish the cleaning procedure, equipment sizes, and handling techniques involved [12]. In selecting a metal cleaning process, many factors must be considered, including [12]:

a) The identification and characterization of the soil to be removed;
b) Identification of the substrate to be cleaned and the importance of the condition of the surface or structure to the ultimate use of the part;
c) Degree of cleanliness required;
d) Capabilities of the available facilities;
e) Impact of the process on the environment;
f) Overall cost of the process;
g) Subsequent operations to be applied, such as phosphating, plating, and painting.

There are two general steps in the preparation of a metal surface for coating. These have as objectives first the removal of organic substances such as oil and grease and, secondly, inorganic materials such as scale, corrosion products, and mineral matter. In short, these steps consist of processes for degreasing and descaling and are designed to bring about a clean surface suitable for the application of coatings [1].

In the scope of this thesis work, brief explanation of surface preparation techniques and cleaning methods of metal surfaces before the application of surface coatings is given in this section, mainly concentrating on ferrous surfaces and steel.

2.2.1 Degreasing Processes

During the working of metal it is often necessary to apply oils or greases to the surfaces to assist the processes, and these have to be removed as part of the process of surface preparation for subsequent coating. This operation is known as 'degreasing' [13]. There are numerous types of degreasing process applied in surface preparation. This section provides information on a variety of conventional technologies typically used for cleaning and degreasing metal parts prior to coating

2.2.1.1 Solvent Cleaning

Solvent cleaning, as the name implies, is the dissolution of the contaminant by a liquid, such as organic solvents and chlorinated hydrocarbons. Solvent cleaning is limited to removing the common oils or greases from metal parts-soil that accumulates as a result of normal manufacturing operations. It will not remove rust or scale and is of limited value in removing buffing, lapping, and drawing compounds [14]. Temperature elevation accelerates the activity. One major drawback to solvent cleaning is the possibility of leaving some residues on the surface, often requiring additional cleaning [12]. The two principal types of solvent cleaning are vapor degreasing and cold-solvent cleaning.

Vapor degreasing is particularly well adapted for cleaning oil-impregnated parts, such as bearings, and for removing solvent-soluble soils from the interiors of storage tanks [12] by using a variety of halogenated solvents [15].

Cold-solvent cleaning method uses traditional solvents in their liquid form rather than their vapor form to clean the workpiece [14].

2.2.1.2 Steam Cleaning

Steam degreasing is carried out by means of steam containing small amounts of some cleaning agent and which under high pressure is blown against the surface to be cleaned. It removes oil and grease by liquefying and diluting them [16]. It is often used for cleaning particularly large objects, railway cars and the like [17].

2.2.1.3 Alkaline Cleaning

Alkaline cleaning is the oldest method of degreasing based upon the use of alkalies [1]. Alkali cleaners such as tri-sodium phosphate, caustic sodas, and silicated alkalis are considered more efficient, and less likely to be harmful than solvents [16]. To meet the requirements of an efficient alkali cleaner for the removal of the variety of oily liguids and solids and other foreign materials, it is customary to use mixtures of varying proportions of several different alkaline compounds [1]. This method requires high temperatures (up to 100°C). As the temperature increases the operation becomes more efficient.

2.2.1.4 Electrolytic Cleaning

Electrolytic cleaning is a modification of alkaline cleaning in which an electrical current is imposed on the part to produce vigorous gassing on the surface to promote the release of soils. Electrocleaning can be either anodic or cathodic cleaning [12]. During cathodic cleaning, the film of electrolyte in contact with the surface of the articles being treated is enriched in hydroxyl ions (OH^-), which react with animal and vegetable fats, converting them into soap. Anodic degreasing is less efficient than cathodic degreasing owing to the fact that OH^- ions are discharged at the surface of the articles, i.e. oxygen is evolved. The pH of the film of electrolyte in contact with the anode decreases, and the rate of saponification of grease falls [10].

2.2.1.5 Ultrasonic Cleaning

Ultrasonic energy is used in combination with conventional metal cleaning procedures to meet rigid cleaning standards [14]. In this process high frequency sound is focused by means of a ceramic transducer on the surface of the metal to be cleaned while immersed in an organic solvent or a detergent solution [1]. The process is applicable to all types of soil, except those that are a part of a metallic surface such as rust, scale, and tarnish [14].

2.2.2 Descaling Processes

Oxide scale is removed from iron and ferrous alloys by pickling in acids, immersion in fused salts, thermal energy, and mechanical abrasion. The thickness, composition, and character of scale depend upon the composition of the metal and particularly upon its heat history [1].

2.2.2.1 Acid Pickling

Acid pickling is sometimes called as chemical pickling. It is defined as the removal of oxides in the form of scale or corrosion products from metallic surfaces, usually by means of an acid solution. Acids have the ability to dissolve oxides, which are usually insoluble in other solutions [14]. Straight mineral acids, such as hydrochloric, sulfuric, and nitric acids, are used for most acid cleaning, but organic acids, such as citric, oxalic, acetic, tartaric, and gluconic acids, occupy an important place in acid cleaning because of their chelating capability [12].

2.2.2.2 Electrolytic Pickling

Surfaces which can be submerged in water, such as tanks, can be cleaned by making them the cathode in an electrical circuit. The electrical current reaching the surface of the cathode either produces hydrogen or reduces surface rust to a lower valence hydrated oxide, softens, partially dislodges and takes with it scale contamination from the surface [8]. Electrochemical pickling can either be anodic or cathodic. Anodic pickling consists in the mechanical removal of oxides and scales from the surface of the components as the result of dissolution of the metal underneath these oxides or scales.

2.2.2.3 Molten Salt Descaling

This process is sometimes called as salt bath descaling and is an effective means of removing or conditioning scale on stainless steel, titanium and copper alloys and nickel alloys [12]. Typical is the sodium hydride process using a bath liquid comprising a mixture of caustic soda, sodium metal and ammonia operating at a temperature of about 700°F (375°C). The mixture reacts with the metallic oxides and reduces them to powdered metals, without gassing and without attacking the metal surfaces. After immersion for suitable periods they are removed and quenched in cold water, the steam thus produced giving a final cleaning effect to remove any adhering loose scale [13].

2.2.2.4 Thermal Cleaning

This type of cleaning process utilizes termal energy in descaling metallic surfaces and includes flame cleaning and induction cleaning processes.

Flame cleaning consists in applying an intensely hot flame over surfaces to be descaled. Cleaning is attained via passage of an oxy-acetylene flame over the surface [1]. Induction cleaning process consists of removing mill scale from steel by inductive heating.

2.2.2.5 Mechanical Cleaning

In the field of industrial applications involving the use of a hot-rolled steel sheet (ship- building, bridge building, etc.) mechanical treatments are preferred for the descaling of surfaces [4]. Mechanical descaling to remove oxides, millscale, and other corrosion products can be achieved by the use of hand and power tools, by grinding, polishing, and blast cleaning.

Among the mechanical cleaning methods hand tools is the most common but the least satisfactory methods of surface preparation [8]. It removes loose paint, rust and scale. It will not remove surface contaminants and soluble salts [9].

Power tool cleaning is generally more effective and less laborious than hand tool cleaning for the removal of loosely adhering millscale, paint and rust. However, power tool cleaning will not remove tightly adhering rust and millscale. The main disadvantage of power tools is that they usually will produce a polished surface. In some cases, the profile of such surfaces is such that good adhesion of synthetic coatings cannot be obtained [8].

The grinding and polishing technique consists in abrading the surfaces of the components until they become relatively smooth. The abrasive material is applied to felt, felted or cotton wheels, or else wheels made entirely of the appropriate grinding materials are used [10].

Blast cleaning is the most important mechanical cleaning method whose details are given in section 2.3.

2.3 Blast Cleaning

By far the most significant and important method used for the thorough cleaning of mill-scaled and rusted surfaces is blast cleaning. Blast cleaning is a comparatively new name for the process formerly called sandblasting. This method involves mechanical cleaning by the continuous impact of abrasive particles at high velocities on to the steel surface either in a jet stream of compressed air or by centrifugal impellers [18]. When sand was the abrading medium, the name, sandblast, was justified. With the advent of steel abrasives, grit and shot, the term, sandblasting, became a misnomer and has therefore been substituted by the term, *blast cleaning* [19].

Hydroblasting is a special type of blast cleaning technique for cleaning surfaces, which relies entirely on the energy of water striking a surface to achieve its cleaning effect. Abrasives are not used in hydroblasting systems [20].

Centrifugal blasting is a mechanical method by which abrasive is propelled by centrifugal force from a rotating wheel [14].

Pneumatic blasting is sometimes called as airblast system. These systems simply use compressed air to propel the abrasive to the surface being cleaned [21]. Two main types of pneumatic blasting are wet abrasive blasting and dry abrasive blasting, later being the most popular.

2.3.1 Wet Abrasive Blasting

Wet abrasive blasting uses a slurry of water and abrasive rather than dry abrasive alone. This has the advantage that the hazards of dust and associated health problems are largely overcome [20]. The slurry, pumped and continually agitated to prevent settling, is forced by compressed air through one or more nozzles, which are directed at the work [12]. A further important advantage is that when wet blasting old, well rusted surfaces, many of the soluble corrosion products in the pits of the steel will be washed out, which will greatly improve the performance of the applied coating system. However, a disadvantage of this technique is that the cleaned steel begins to rust rapidly after blasting [20].

2.3.2 Dry Abrasive Blasting

This is the most widely used method of surface preparation for painted steelwork. Dry abrasive blasting is the process of propelling abrasive particles from a blast machine, using the power of compressed air [22]. Therefore, it is sometimes called as air blasting or pressure blasting. The fundamental principle of dry abrasive blasting is very elementary. Compressed air propels abrasive particles at high velocities to impact and clean a substrate [23].

Abrasive blasting is primarily based on conversion of this impact energy to abrasion energy resulting in a cleaning action and giving the work surface a certain profile. Since each particle has a certain mass, causing this particle to move at a high speed gives it energy. When a particle impacts the substrate only a small portion of the surface of the particle contacts the substrate. During abrasion, the particle deforms and bounces and then either shatters or returns to its original shape. On the other hand, the portion of the substrate contacted by the particle also deforms. If the forces involved are large enough substrate stays permanently deformed [24]. Schematic representation of dry abrasive blasting is shown in Figure 1.

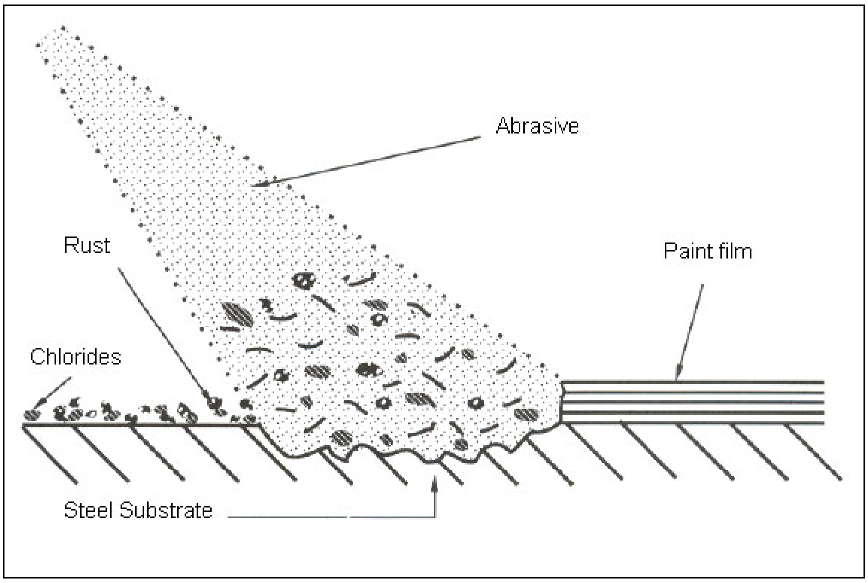

Figure 1: Dry Abrasive Blasting [11]

Air blasting has been the most common method of surface preparation since its inception in the 1930s. Many different abrasives may be used with this blasting procedure and it may be used for blasting ships, industrial structural steel, concrete, and many other different surfaces [25].

Industries that use abrasive blasting include the shipbuilding industry, automotive industry, and other industries that involve surface preparation and painting. Typical uses for dry abrasive cleaning include [14]:

1. removal of contaminated surface layers;
2. removal of oxides, corrosion products, and mill scale;

3. production of a hammered or matte finish;
4. conditioning the surface for better bonding of paint;
5. removal of burrs, scratches, and surface irregularities;
6. removal of paint and dry surface dirt.

Hansel [22] classify abrasive blasting applications into three broad categories as surface preparation, surface cleaning and finishing, and shot peening and explains briefly in following paragraphs.

Surface preparation removes unwanted material and leaves a surface ready for coating or bonding. The impact of angular abrasive roughens a surface to produce a profile or etch. Most paint manufacturers specify surface profiles that will ensure their products perform as intended. Contractors blast masonry so it will accept sealers or paints. Beyond steel and masonry, blast cleaning can strip layers of paint from wood. On fiberglass boats, blasting removes the top layer of gelcoat and exposes air bubbles.

Surface cleaning and finishing differ from surface preparation in that the desired result is to improve a product's appearance and usefulness rather than condition it for coating or bonding. Surface cleaning includes removing production contaminants and heat scale. Surface finishing includes deflashing and deburring molded parts and enhancing visual features. Metal foundries blast cast parts to remove small burrs for functional and aesthetic purposes. Blast finishing heat-treated parts removes the discoloration and the scale that sometimes forms. Abrasive blasting can improve a product's appearance by removing stains, manufacturing compound residue, corrosion, and tool marks. Some blast media can blend surface variations, such as scratches and tooling marks, into an overall uniform appearance.

Shot peening increases the strength and durability of high-stress components by bombarding the surface with high-velocity, spherical media such as steel shot, ceramic shot, and glass beads. To make a metal product or component, manufacturers must cast, cut, bend, stamp, roll, or weld metal stock to produce the desired shape. Sometimes these processes leave residual stresses in the metal that can cause parts to fail when stressed. The bombardment of metals by small particles creates a uniformly compressed surface, diffusing the stress forces over a larger area and leaving the surface less likely to crack. The automotive and aircraft industries use peening extensively. Gear manufacturers peen to eliminate burrs and sharp edges, and to strengthen gear teeth. Spring manufacturers peen their products to combat stress.

The dry abrasive blasting is divided into two basic systems: suction and direct pressure system.

2.3.2.1 Suction System

In suction systems, two rubber hoses are connected to a blasting gun. One hose is connected to the compressed-air supply and the other is connected to the bottom of the abrasive supply tank or “pot”. The gun consists of an air nozzle that discharges into a larger nozzle. The high velocity air jet (expanding into the larger nozzle) creates a partial vacuum in the chamber. This vacuum draws the abrasive into the outer nozzle and expels it through the discharge opening. Figure 2 shows a typical suction type blasting machine [21].

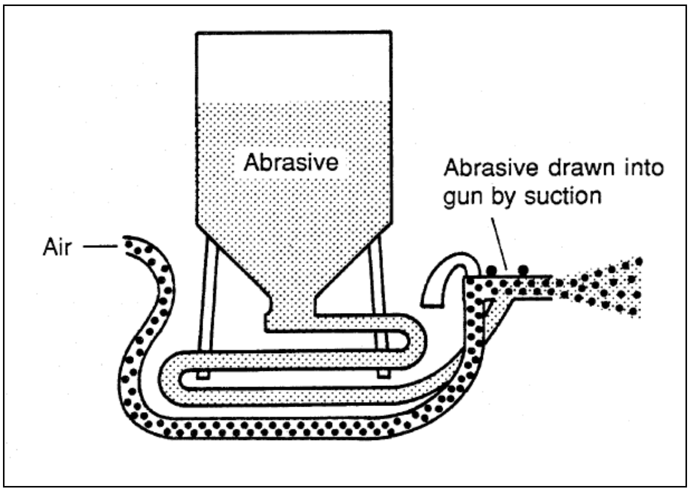

Figure 2: Suction-type Blasting Machine [21]

During this type of blasting application a wider spray pattern results, and the abrasive has less force than the direct-pressure type. Less media is used, however, and the lower speed results in less abrasive breakdown so that a larger percentage can be reused. Suction blast cleaning equipment is generally used for less severe cleaning applications, such as removing light scale or rust and other contaminants from castings, structurals, and various other parts, light-to-medium production requirements, limited space, and moderate budgets. These systems can blast continuously without stopping for abrasive changes and refills [21, 14].

2.3.2.2 Direct Pressure System

The direct pressure system consists of a pressure tank in which the abrasive is contained. In this system, the abrasive in a pressurized tank is fed directly into the blast-cleaning equipment hose and discharged through a nozzle. The use of a pressure tank forces abrasive through the blast hose rather than siphoning it [21], [14]. A typical pressure type blasting machine is shown in Figure 3.

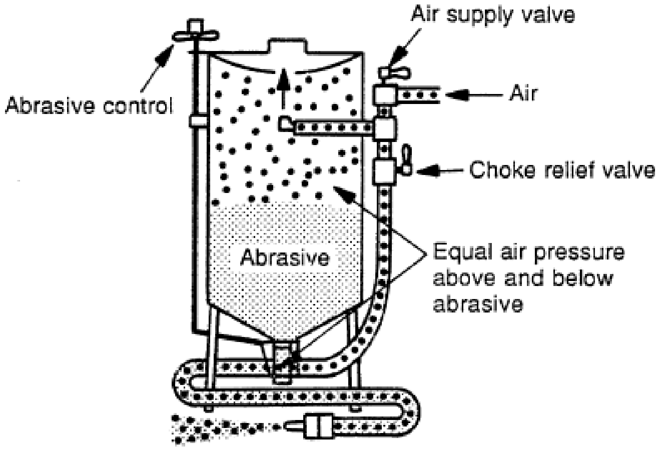

Figure 3: Pressure-type Blasting Machine [21]

All types of abrasive are used in this system and the selection is dependent upon the material to be cleaned and the degree of cleaning necessary. Direct pressure method is generally used for exceptionally heavy cleaning, such as removing scale from castings and forgings. The abrasive is ejected at higher speeds and with greater concentration than in the gravity method. Nozzles and lines are subjected to greater wear, and more abrasive is consumed [14]. Pressure blast systems generally give a faster, more uniform finish than suction blast systems. They also produce high abrasive velocities with less air consumption than suction systems [21].

2.3.3 Factors Affecting Dry Abrasive Blasting

Three basic components are found in most abrasive blasting operations: the personnel, the equipment, and the abrasive. Careful attention to these three basic components is the key to the success or failure of the entire operation [23].

The skill of the workman in keeping the blast stream at the proper distance from and angle to the work and his conscientiousness in being sure that all areas are properly cleaned are prerequisite to a good job. He must have the right kind of equipment, including the proper size and type of nozzle for the job being done, the correct size and lengths of hose, proper air pressure and abrasive of the right quality and size to produce the desired surface [8].

The type and amount of work done on the surface is controlled by characteristics of abrasive used and operating parameters. The most important of these are:

(1) Type of particles (i.e., size, shape, density, etc.),
(2) Blasting pressure,
(3) Blasting standoff distance,
(4) Determination of blast nozzle size,
(5) Angle of impact,
(6) Substrate material characteristics,
(7) Number of particles impacting each unit area of substrate in a unit of time.

2.3.4 Advantages and Disadvantages of Dry Abrasive Blasting

It is the most versatile type of surface preparation and undoubtedly involves the lowest cost of any surface preparation method. It is also the most effective method of surface preparation, particularly for coatings that are to be used in highly corrosive areas [25].

Dry abrasive blasting provides more production in less time which means fast cleaning. Exposure of up to four hundred square feet of white metal per hour is possible when blasting heavy scale and rust, and the ability to remove surface contaminants and heavy corrosion [24].

The primary advantage of dry abrasive blasting is that the blasted surface is dry. Unless there is considerable humidity in the area, the surface will remain dry until the coating is applied, which is usually done on the same day [25].

Another advantage of dry abrasive blasting is that the residue that may be left on the surface is simply dust and with vacuum recovery and air wash system it is easily removed. Giving a good profile and cleanliness dry abrasive blasting provides a good surface over which a coating is applied.

The disadvantage of dry blasting is primarily the dust which forms because of the breakup of the particles of sand or grit. The dust not only is objectionable to environmental protection agencies, but it is a contaminating influence to areas where blasting takes place. The dust is also harmful to the individual who may breathe it. This is particularly true of silicate dust. While silica is the most damaging because of silicosis, other dusts from nonsiliceous sources do not carry this threat [25].

2.4 Surface Preparation Specifications

Paint manufacturers have long recognized the importance of surface preparation to the success of their coatings. Improperly cleaning a steel surface will cause premature coating failure; consequently, coating manufacturers specify surface preparation [22].

Steel surface preparation standards measure two critical specifications: surface profile and degree of cleanliness.

2.4.1 Degree of Cleanliness

In order to assess the steel surface prior to surface preparation, the International Organization for Standardization - ISO 8501-1 “Visual assessment of surface cleanliness” is used. This part of ISO 8501 identifies four levels (designated as “rust grades”) of mill scale and rust that are commonly found on surfaces of uncoated erected steel and steel held in stock. The four rust grades, designated A, B, C and D, respectively, are defined by written descriptions together with representative photographic examples [26].

- Rust grade A: Steel surface largely covered with adherent mill scale but little, if any, rust.
- Rust grade B: Steel surface which has begun to rust and from which the mill scale has begun to flake.
- Rust grade C: Steel surface on which the mill scale has rusted away or from which it can be scraped, but with slight pitting visible under normal vision.
- Rust grade D: Steel surface on which the mill scale has rusted away and on which general pitting is visible under normal vision.

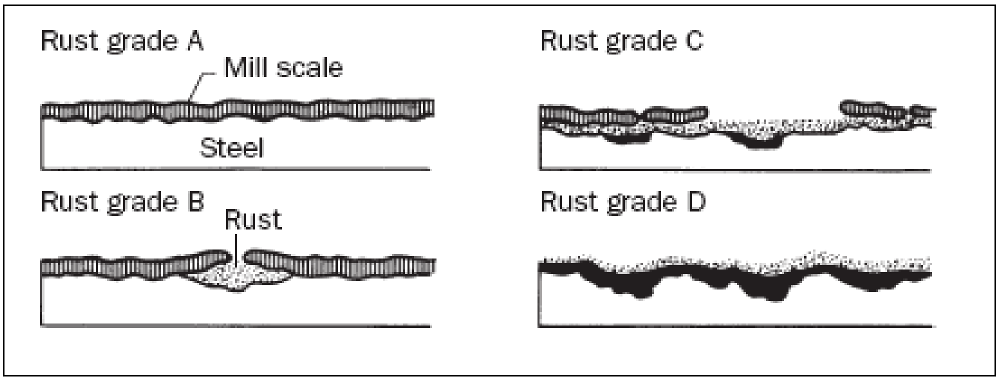

Figure 4: Rust Grades [26]

In addition to the four pictures of the rust grades A, B, C and D, the standard also contains pictures showing the visual cleanliness after preparation of the steel. The standard grades of cleanliness for abrasive blast cleaning are:

- **Sa 1** **Light blast cleaning**
- **Sa 2** **Thorough blast cleaning**
- **Sa 2 ½** **Very thorough blast cleaning**
- **Sa 3** **Blast cleaning to visually clean steel**

Cleaned surfaces should be compared with the appropriate reference photograph in the standard according to the treatment specification [18].

2.4.2 Surface Profile

Blast cleaning produces a clean surface as well as an anchor pattern for the paint, but it also increases the surface area of the steel [26]. Abrasive particles cut into the steel to form tiny peaks and valleys. The depth of this profile is controlled by the size, type, and hardness of the abrasive; by the air pressure; and by the distance and angle of the nozzle to the surface. Deviations in air pressure or in the distance or angle of the nozzle to the surface also affect profile. Reduced air pressure or increased nozzle distance causes smaller profiles. Severe nozzle angles produce a skimmed blast pattern rather than definite peaks and valleys. For blasting structural steel, nozzles should be held at 80 to 90° to the surface [22].

The maximum height of the profile is called R_y. This is the distance between the top line and the bottom line of the profile within a reference length (see Figure 5). Sometimes one may encounter R_{y5} or R_z. R_{y5} is the average of R_y on 5 adjoining reference lengths. R_z is the ten-point height of profile irregularities and the mean value of the heights of the five highest peaks and depths of the deepest valleys within one reference length. Previously, roughness was usually indicated as R_a, which is the arithmetic mean deviation of the profile [26].

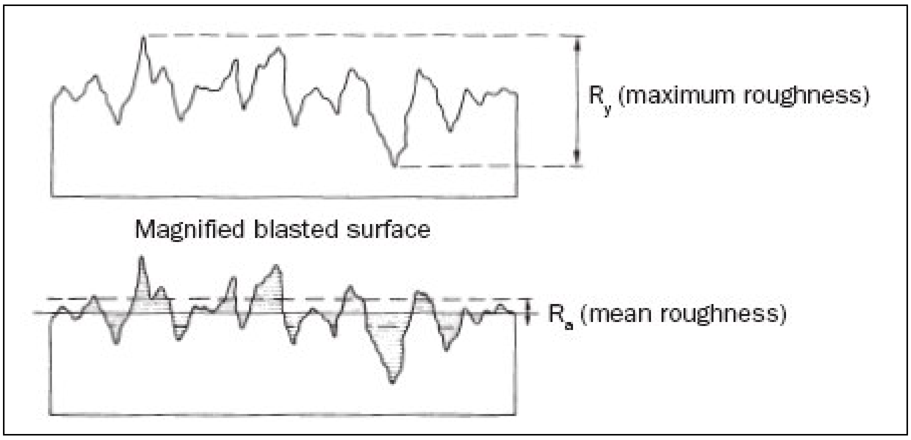

Figure 5: Roughness given as R_a and R_y [26]

Several methods have been developed to measure or assess the distance between the peaks and troughs of blast cleaned surfaces [18]. These have included comparator panels, special dial gauges, replica tapes, and stylus instruments. But the comparators are the most common tools.

Comparators made of stainless steel have been used for a number of years. Previously, within the shipping and offshore industries, the comparator Rugotest No. 3 was used in many European countries, while in the USA comparators from Clemtex and Keane-Tator were used. Even though comparators used in Europe and in the USA look different, they are used more or less in the same way. The comparators consist of small areas or segments which have been blast cleaned using an abrasive. This produces two types of comparators, one for grit and one for shot, with increasing roughnesses [26].

In 1988 the international standard ISO 8503 for determining surface roughness was adopted. This method uses a square panel with a central hole surrounded by four segments with different grades of roughness (see Figure 6). There is one comparator for grit blasted surfaces and one for shot blasted surfaces. The appropriate comparator is placed against the substrate then visual and tactile comparisons are made [18].

ISO 8503-1 assesses the average maximum profile height, R_{y5}, while Rugotest No.3 assesses the arithmetic mean deviation of the profile, R_a. The average maximum roughness, R_{y5}, is usually four-eight times higher than R_a [26].

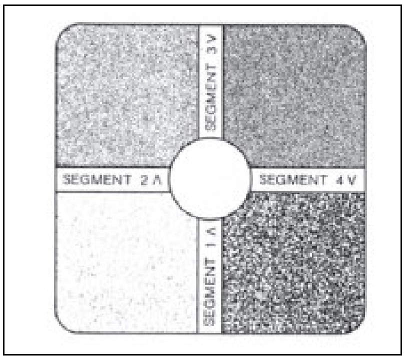

Figure 6: ISO 8503 Comparator Samples [26].

2.4.3 Other Standards

While ISO standards have been adopted over the national standards of all EU countries, the USA has a complete set of surface preparation standards of its own in the form of a suite of joint Steel Structures Painting Council (SSPC)/NACE standards as well as individual SSPC standards [9].

The Society for Protective Coatings (SSPC) has established four degrees of cleanliness for blasting, ranging from removal of all contaminants to removal of loose materials only. The four degrees are White Metal Blast, Near-White Metal Blast, Commercial Blast, and Brush-Off Blast.

Some of the other standards of surface preparation of steel are briefly described below.

1. Steel Structures Painting Council (SSPC), Pittsburg, PA, USA - Surface Preparation Specification.
2. National Association of Corrosion Engineers (NACE), - Joint Surface Preparation Standard, Houston, TX
3. Swedish Standards Institution - SIS 05 59 00 (1967) - Pictorial Surface Preparation Standards for Painting Steel Surfaces.
4. Shipbuilding Research Association of Japan - Standard for the preparation of steel surface prior to painting ("JSRA" Standard).
5. Australian Standards AS 1627 (1997) – Metal finishing – Preparation and pretreatment of surfaces.

The equivalence of some of the Standards is summarized in the following table:

Table 1: Equivalence of Surface Preparation Standards

	ISO 8501-1 (1988)	Swedish Standard SIS055900 (1967)	SSPC (1982)	NACE
White Metal	Sa 3	Sa 3	SP5	1
Near White Metal	Sa 2½	Sa 2½	SP10	2
Commercial Blast	Sa 2	Sa 2	SP6	3
Brush-Off Blast	Sa 1	Sa 1	SP7	4

2.5 Blasting Equipments

For abrasive blasting, as with any discipline, efficiency and productivity are directly affected by the appropriateness of the tools that are used [23].

A typical rig for efficient pressure blasting is shown in Figure 7. This illustrates a standard commercial set up. Also, equipment in which the abrasives are stored in a small container fastened beneath the blasting gun may be used for small areas or inside shops for work on small pieces [11].

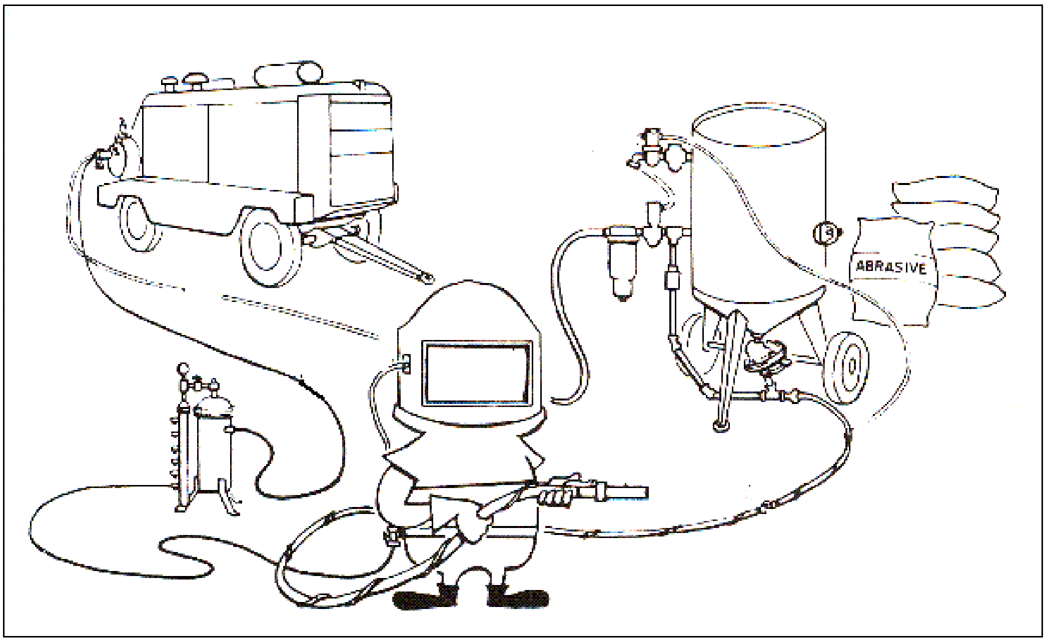

Figure 7: Air Blasting Methodology [11]

Three fundamental components constitute a blast equipment setup: air compressor, blast machine, and abrasive. The exact equipment used depends to a large extent on the specific application and type(s) of abrasive [21]. The compressor must produce sufficient air pressure and volume to convey abrasive from the blast machine to the surface being blasted. A blast machine's role is to smoothly meter abrasive into the passing air stream. The third major component in the blasting system is the abrasive. It produces the finish on the surface. Match the abrasive material and size to the surface being blasted to ensure the best possible finish, cleaning speed, and cost efficiency [22].

2.6 Abrasive Media in Blast Cleaning

An abrasive is a substance used to abrade, smooth, or polish an object [27]. The term ‘abrasive’ in blasting refers to a wide range of materials used to establish a profile on clean steel and remove unwanted coatings or contaminants from the surface of steel or other substrates [28].

Following section includes selection criteria and types of abrasives commonly used in abrasive blasting.

2.6.1 Factors Affecting Abrasive Selection

Generally speaking, abrasive selection is determined by the scope of the job, the job location, and the desired surface finish, which may be determined by the coating manufacturer or the owner of the equipment or structure that is being cleaned [23]. During blasting, there are numerous considerations, mostly physical, in the selection of suitable media. When choosing an abrasive, one must consider its specific characteristics which include hardness, grain shape, particle size, specific gravity, and other features such as economical factors, chemical cleanliness, environmental concerns and health considerations.

The performance of an abrasive and economics of blasting operation are affected by physical properties of the abrasive, which are hardness, grain shape, particle size, and specific gravity.

When selecting an abrasive for a specific job, only physical properties may not be sufficient. There are some additional considerations including chemical cleanliness, economical factors, environmental and health concerns. These will be discussed under the heading of “other features”.

2.6.1.1 Hardness

Hardness is a relative measure of the media’s resistance to abrasion by other materials. Hardness determines whether an abrasive particle can etch or provide an anchor pattern on a particular substrate. One way to determine the hardness of an abrasive is to use the Mohs' hardness scale. This scale classifies minerals based on relative hardness of the unknown to a standard set of 10 minerals, with 1 being the softest (talc) and 10 being the hardest (diamond). Most abrasives that effectively achieve an anchor pattern on a surface have a Mohs' hardness of at least 6.0 [29]. The hardness of metallic abrasives is usually measured on the Rockwell system and steel grit generally has a Rockwell C value of 45 to 55, roughly equal to 6.0 to 6.5 on the Mohs scale [28].

Hardness dictates the friability or breakdown rate of most abrasives; hard abrasives fracture or pulverize easily upon impact. Hard abrasives are used on surfaces where the material to be removed is tenacious or where a deep profile is required [23].

2.6.1.2 Grain Shape

Abrasive shape will determine the surface etch or surface profile. The shape of an abrasive may be angular, blocky, semi-round or spherical. Grain shape is important as rounded and angular grains behave differently when they impact a substrate such as steel [28]. Angular, sharp particles produce the greatest cutting action and the deepest profile. Round or semi-round particles will cut much more slowly and will produce a more shallow profile.

2.6.1.3 Particle Size

Size is a very critical aspect of any abrasive selection process. Properly sized abrasive has a major effect on coating coverage and coating adhesion. Cleaning rate and anchor pattern produced is mainly affected by particle size. Achieving the specified profile depends upon selecting the right size range of abrasive. A coarse particle will produce a deep profile, while a finer particle will produce a more shallow profile [23].

Particle size is determined by U.S. sieve analysis, which distributes the particles in mesh sizes. Abrasives are generally available from 4 to 325 mesh. Abrasives should be graded to a uniform size. This allows for precise flow rates through a metering valve on a blast machine. Hard abrasives must be uniformly graded to provide a consistent anchor profile on the substrate [29]. Excessively deep or shallow profiles can cause major coating problems and failures. When a profile is too deep for the applied coating, peaks will protrude through the coating surface allowing premature coatings failure. Shallow profiles do not provide a sufficient roughness for bonding [23].

2.6.1.4 Specific Gravity

The density or specific gravity of an abrasive affects the cleaning rate and anchor profile achieved on the surface. The cleaning action is the result of energy transfer, which is transferred from the abrasive to the substrate. As the kinetic energy is proportional to the mass of the grain and the square of its velocity, a small, heavy grain moving at high speed will have more effect on a substrate than a larger, lighter grain [28]. When blasted at the same pressure, a heavy abrasive achieves a deeper anchor pattern than that from a lighter one. Abrasives with a high specific gravity tend to be less dusty. Those with a low specific gravity impact the substrate with less force and are used for light cleaning, polishing and deburring [29].

2.6.1.5 Other Features

2.6.1.5.1 Chemical Cleanliness

One of the prerequisite for abrasive is chemical cleanliness. Chemical composition must be considered to assure compatibility of the substrate with the abrasive. Abrasives should be washed and screened to remove any contaminants, dust, or fines. When blasting a substrate, particles may be embedded or leave a residue, which could damage the protective coating. Dust and fines reduce cleaning rates and can interfere with surface profiles. In addition, contaminants, such as soluble salts, can ultimately cause premature coating failure [23]. In cases where an iron abrasive is used to blast a stainless steel substrate, the embedded particles will form corrosion cells on the substrate [29].

2.6.1.5.2 Economical Factors

Any project aims to achieve the fastest cleaning at minimum cost. The cost of the abrasive is a critical part of any job. Often, the cost of freight to transport the abrasive from manufacturer to job site can determine the choise [29]. A cheaper abrasive does not always mean that it could provide more economical operations. On the contrary, studies show that improvements in the quality of abrasives result in more economical results. High-priced material is always superior to cheap grades, which are usually made of inferior materials [7]. A good abrasive should provide a high cleaning rate, low consumption rate, and low breakdown rate, if it is recyclable.

Another important factor is availability in choosing an abrasive. It is important to ensure that the abrasive selected for a project can be easily obtained in sufficient quantities to finish the job. To obtain optimum results, it is best not to change abrasives in the middle of a project. Many abrasives are naturally occurring minerals or by-products from other industries. Therefore, they may not be available for immediate delivery in all geographical regions [29]

2.6.1.5.3 Environmental and Health Concerns

The final consideration is environmental and health concerns. Followings are expected from a good abrasive [28]:

- Low levels of dusting under normal usage conditions.
- Low health risk, including low levels of dangerous contaminants, such as asbestos (in olivine) and arsenic (in copper slag).

- Low environmental impact during storage, use and disposal.
- Durability of the media to allow collection, reclamation and reuse.

The abrasive's respiratory effects on the blaster and other workers in the area are the most remarkable concern. Employees must be provided with approved respiratory equipment and monitored throughout the job. Besides, the toxicity of junk being removed sometimes makes disposal of the abrasive/junk mix difficult. The effect of spent abrasive on the soil must also be considered. In confined areas, the toxicity of the abrasive may require the use of additional safety and engineering controls [29].

2.6.2 Abrasive Types

Abrasives can be naturally occurring minerals, man-made materials or by-products of another process. In the very broadest sense, there are two basic types of blasting abrasives: expendable and re-usable. Sand and slag are two examples of expendable abrasives normally used outdoors. Steel grit and aluminum oxide are two reusable abrasives normally used in a blast room or blast cabinet where there is some type of reclaim system [23]. However, blasting abrasives are classified as mineral abrasives, manufactured abrasives, mineral slags and miscellaneous media in context of this study and properties of most common blasting abrasives is given in following sections.

2.6.2.1 Mineral Abrasives

Silica Sand

Common quartz sand is among the most abundant minerals in the earth’s surface. For many years, silica sand was the favored material for blast cleaning throughout the world. The entire industry was founded on its use and the term ‘sandblasting’ was the common term for this type of operation. The material is readily available and of low-cost [28]. However, silica sand commonly contains high concentrations of crystalline silica (quartz). Respirable silica quartz causes the disease, silicosis after repeated exposure [30, 31]. Despite strict health and safety controls in most developed countries, silica sand is still a widely used blasting media. It is not considered a recyclable material [31].

Garnet

Garnet is a hard silicate mineral quarried in several parts of the world, including Australia, India, the USA and South Africa. There are some eight different forms of garnet but the one most commonly used for abrasive blasting is almandite garnet which is an iron-based material [32]. It is very heavy, very hard and durable. Specific gravity and durability are critical factors affecting both blasting and recycling performance. Because of these properties, garnet is capable of very high performance when used as a single pass (disposable) or a recycled abrasive [32]. Garnet is used on both ferrous and non-ferrous metal substrates and has several benefits, including the following: Fast cutting, low dusting (compared to coal slag or silica sand), recyclable, low risk to health, with no detectable amounts of heavy metals and low free-silica [33].

Olivine

Olivine is a naturally occurring magnesium iron silicate, which is pale green in color and contains no free silica or toxic metals [34]. However, it is reported that olivine is a mineral of which concern has been expressed over asbestos impurities [28]. The major use for olivine is a safer replacement for silica sand in the cleaning of buildings but it also finds application in the blast cleaning of steel, particularly stainless steels, for which slag abrasives are often not permitted because of ferrous contamination which leads to rust spotting [34]. Olivine is very hard but tends to fracture on impact, creating much light-colored dust [35].

Staurolite

Staurolite is a dark colored mineral that is a silicate of aluminum and iron. It has some free silica but much less than silica sand [35]. The material, which tends to be used in niche applications, is relatively high priced but offers benefits such as low dusting (due to high hardness), low embedment and is considered environmentally friendly [30]. Staurolite poses virtually no environmental hazard. In spite of the material's high hardness, the rounded shape of the grains ensures that virtually no particulate embedment takes place [28].

The above minerals are the main types commonly used in industrial blasting applications, although as might be expected there are a number of other materials which have been used (e.g. specular hematite).

2.6.2.2 Manufactured Abrasives

Metallic Grit and Shot

Grit consists of angular metallic particles with high cutting power. Grit is usually made of crushed, hardened cast iron shot. Generally, the screen distribution and velocity of the grit impacting on the substrate surface control the finish [28]. Applications for grit include removal of heavy forging and heat treat scale, removal of rust and controlled profiling of materials before adhesive bonding [36].

Shot is normally made of the same materials as grit and is usually in the form of spherical particles. Shot removes scale and other contaminants by impact. Steel shot is the most widely used metallic abrasive medium and is the least destructive to the components of the abrasive blast system [37].

Because of their durability, steel abrasives can be recycled many times in most cleaning operations without loss of efficiency [31]. One major disadvantage with steel abrasives is that they must not be allowed to become wet. It cannot lie on the ground or be used to clean wet surfaces. When steel grit is wet, it forms lumps that can clog equipment and harm the substrate [38].

Metallic abrasives can contaminate impacted surfaces with pieces or streaks of the media itself and such contamination can lead to corrosion of the blasted surface and subsequent coating failure [30].

Glass Beads and Grits

Manufactured abrasives such as soda lime glass beads are good abrasive materials for specific operations. The particles are heat treated in a round ball to equalize stress and resist fracture. They are reasonably free of sharp angular particles and are manufactured in a wide range of sizes. They are generally used in blast cabinets that provide recycling. They do not contain crystalline silica as they are manufactured from soda lime glass [39, 40]. Glass beads work by imparting a hammering or peening action at the point of contact. Unlike steel shot which is the most widely used of the spherical blasting media, glass beads contain no free iron to cause corrosion on non-ferrous surfaces; they can therefore be used on all types of metals [39].

Processed recycled glass is used as an industrial abrasive and is manufactured from waste container glass, mainly collected from public recycling schemes. Other waste glass streams can also be used for this application such as tempered automotive glass and recovered commercial glass that provides a safer method of cleaning than using silica sand [40]. The waste container glass is initially coarse crushed and then screened to remove bottle tops, lids, caps, corks, labels and other contaminants. After drying the glass is finely crushed, and then screened to produce the desired particle size distribution. Cleaning trials have been undertaken using recycled glass grit as an abrasive media and it has found to perform very well in cleaning operations before painting and also in the removal of hard coatings such as epoxy and enamels [41]. The crushed glass is a true low silica material that behaves somewhat like slag. Because of the low specific gravity of the crushed glass the impact per particle is reduced and it is suggested that coarser gradings are often necessary [31].

Aluminum Oxide (Alumina)

Aluminum oxide is usually used in its brown form when it is manufactured by fusing bauxite; coke and iron in an electric furnace at very high temperatures. Refined grades of white and pink alumina are also available that contain very low levels of free iron. This abrasive is available in a number of grades and the main use is as a recyclable abrasive in cabinets [35]. Because of its low iron content, alumina is often specified in high-tech applicators (e.g. the aerospace industry), particularly on non-ferrous metals. It is also commonly specified for use on stainless steel which is going to be used in sea water applications, this because it will not contaminate the steel and set up an electrolytic corrosion cell which, should it happen, would cause attack to the metal [35].

2.6.2.3 Mineral Slags

Slags are the glassy waste products of industrial smelting and combustion. Although formed in differing environments, all share common traits. Chemically, they are aluminosilicate glasses, usually enriched in iron and one or more alkaline metals [31]. Like all glassy solids, slags are highly stable under most environmental conditions and like other glasses; they tend toward brittle fracture on impact and may therefore, be dusty when used as an abrasive. Because of their nature as waste products formed during smelting or industrial combustion, slags may contain small quantities of heavy metals or radioactive elements [40, 30, 31]. The slag abrasives are classified as metal slags (copper, nickel, etc.) and coal slags. They are usually very hard (Mohs scale 7) and sharp edged.

Copper Slag (Sulphide Ores)

Slags from the reduction of sulphide ores are found throughout the world. Since slags are almost always associated with copper mines, the general term ‘copper slag’ has come to be used even for slags that might be more accurately be called ‘lead slags’, ‘zinc slags’ or even ‘arsenic slags’ [28]. Copper slags carry small amounts of the metals that were present in the original ores and smelter concentrates [31]. The purpose of the slag was to act as a collection mechanism of these undesirable contaminates during the recovery of the metal of interest i.e. copper [31].

Nickel Slag

A unique, non-sulphide metal slag is formed during the smelting of certain nickel ores. The material is used regionally as a replacement for both silica sand and copper slag [31]. The nickel slag does not contain the usual heavy metals associated with copper slag but does contain small quantities of chromium and nickel, both of which may require monitoring for airborne dust exposures [28].

Coal Slag

Coal slag is a mixture of ferro aluminum silicates, calcium silicate and silica and is formed as a by-product of burning coal in electric power generation plants. Inevitably, the composition will vary according to the source. Coal slag used for abrasive blasting is primarily used for etching. A secondary application is cleaning [28].

Blast Furnace Slag

Blast furnace slag is formed when iron ore or iron pellets, coke and a flux (either limestone or dolomite) are melted together in a blast furnace [42]. Different forms of slag product are produced depending on the method used to cool the molten slag. The most important products include air-cooled blast furnace slag and granulated blast furnace slag.

The molten products are tapped separately and the slag is either allowed to air cool to form crystalline slag called as air-cooled blast furnace slag, or it is passed through a trough of high pressure, high volume water sprays, where the heat energy contained in the molten slag causes it to explode and instantly form slag which is in granules, typically 2-3mm in size, called as granulated blast furnace slag [43]. While air-cooled blast furnace slag is used primarily as a construction aggregate, granulated blast furnace slag is used mostly in cement industry and as a blasting media. It is particularly suitable on soft metals such as aluminum where a light etch is required [44]. The chloride content of ground granulated blast furnace slag is variable and depends on the water used in the quenching process. The chloride content can be significantly high if salt water is used, adversely affecting the coatings system.

2.6.2.4 Miscellaneous Media

Plastic Media

Plastic media blasting comes under the heading of soft media blasting in comparison to blasting using conventional blasting media such as mineral sand, alumina, slags and steels/irons which are very hard in comparison. Such soft media will not damage the substrate surface being treated [28]. Plastic media is durable and recyclable. Blasting with plastic media is normally performed with high air volume but low blast pressure (e.g. 10-50 psi). The low pressure eliminates warpage of the substrate. Plastic media can be recycled about 5-20 times [45]. The resilient plastic particles used in Plastic media blasting operations are harder than walnut shells but softer than mineral abrasives. A variety of granulated plastics are available, including soft polyester, medium acrylic (polymethyl methacrylate) and urea and harder melamine formulations [28].

Sodium Bicarbonate (Baking Soda)

Sodium bicarbonate is a soft, white, crystalline powder that readily dissolves in water to form an alkaline solution. As a blast cleaning material, sodium bicarbonate is available in different particle sizes and incorporates flow agents and other additives to give enhanced performance. It has been used for cleaning sensitive components such as those found in the aerospace industry [28]. However, its alkalinity has been known to cause corrosion of aluminum alloys if it is not properly removed from the substrate surface after blasting [35]. Whilst too light to effectively create a profile in steel, this material fills a different niche in the market.

Dry Ice

Dry ice is the solid form of carbon dioxide. The blasting media can vary in size from that of rice grains to about 3mm. The media is very cold (-79ºC) and requires blasting equipment specific to this substrate [28]. The technology of blasting with solid carbon dioxide utilizes two distinct techniques. Thermal shock occurs when the solid pellets blast the surface and surface cracks develop. Differential thermal contraction results in failure of the bond interface. The pellets thus actually penetrate the cracked surface layer of contamination and once between this and the substrate, the pellets sublime (change from a solid to a gas without going through a liquid phase) and the expanded carbon dioxide gas blasts the surface layer away from the substrate [28].

Organic Abrasives

Organic products, many being derived from vegetables, including materials such as corncobs, starch, nut shells (e.g. walnuts), rice hulls and fruit pits, have long been used as abrasives in areas where loose dirt and grease are to be removed without attendant damage to the underlying coating system or to the substrate [31].

Organic abrasives have low hardness and low bulk density and will not etch most industrial substrates, including wood [45]. They are mainly used for removing dirt or other deposits on paint films, for cleaning valves or turbine rotor blades and for removing grease from motors [45]. Vegetable abrasives are a one-time use material and materials such as corncob grit [46] and starch [47] are environmentally benign because the media is non-toxic and biodegradable.

CHAPTER III

EXPERIMENTAL MATERIALS AND METHOD

3.1 Materials

Four different slag samples of three generic types were studied and tested. A coal furnace slag sample from Çayırhan thermal power plant, a ferrochrome slag sample from Eti Krom, a blast furnace and a converter slag sample from Ereğli Iron and Steel Works were investigated within the scope of this thesis work. Properties of samples are given in following sections.

3.1.1 Coal Furnace Slag

Coal furnace slag sample was obtained from Çayırhan Thermal Power Plant, which is a subsidiary of Park Termik Elektrik San. Tic. A.Ş. located in Çayırhan district, 120 km away from Ankara.

The sample is a coarse, granular, gray colored waste-product that is collected from the bottom of the furnace that burn coal for the generation of steam. It contains white and brownish particles and porous granules of 1.5 cm maximum size (see Figure 8). Chemical analysis of coal furnace slag sample was determined by X-ray Fluorescence Spectroscopy and carried out in General Directorate of Mineral Research and Exploration. Its chemical composition is given in Table 2.

Figure 8: Coal Furnace Slag Sample

Table 2: Chemical Analysis of Coal Furnace Slag Sample

Components	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	Other*	LOI
CFS (%)	48.1	10.5	13.7	7.4	6.2	1.6	1.6	0.9	9.6

* Total of P_2O_5 + TiO_2 + MnO

3.1.2 Granulated Blast Furnace Slag

Granulated blast furnace slag sample was obtained from Ereğli Iron and Steel Works Co., which is a subsidiary of Erdemir Group, located in Ereğli district of Zonguldak.

Granulated blast furnace slag sample is water-quenched, glassy, yellowish, sand-like granules with a top size of about 5-6 mm (see Figure 9). Chemical analysis of sample was determined by X-ray Fluorescence Spectroscopy and performed in Ereğli Iron and Steel Works. The results are given in Table 3.

Figure 9: Granulated Blast Furnace Slag Sample

Table 3: Chemical Analysis of Granulated Blast Furnace Slag

Components	FeO	SiO_2	MnO	Al_2O_3	CaO	MgO	S	Other*
GBFS	0.09	36.82	0.56	15.38	40.80	4.91	1.20	0.15

* Total of Na_2O + K_2O + TiO_2

3.1.3 Converter Slag

Converter slag sample was obtained from Ereğli Iron and Steel Works Co., which is a subsidiary of Erdemir Group, located in Ereğli district of Zonguldak.

Converter slag is the air-cooled steel furnace slag and the sample contains brownish grey vesicular lumps with a top size of about 15-20 cm (see Figure 10). Chemical analysis of converter slag sample was determined by X-ray Fluorescence Spectroscopy and carried out in Ereğli Iron and Steel Works. Its chemical composition is given in Table 4.

Figure 10: Converter Slag Sample

Table 4: Chemical Analysis of Converter Slag Sample

Components	Total Fe	FeO	SiO_2	MnO	Al_2O_3	CaO	MgO	P_2O_5	Other*
Weight (%)	21.87	9.36	9.62	4.66	0.89	49.48	2.39	1.43	0.46

* Total of S + Na_2O + K_2O + TiO_2

3.1.4 Ferrochrome Slag

Ferrochrome slag sample was obtained from Eti Krom A.Ş., which is a subsidiary of Eti Holding, located at Kovancılar district of Elazığ.

Ferrochrome slag is a by-product from the production of ferrochrome, an essential component in stainless steel. The sample is composed of grey or brownish grey and white grains with a top size of about 8 cm (see Figure 11). Chemical analysis of ferrochrome slag sample was determined by X-ray Fluorescence Spectroscopy and carried out in General Directorate of Mineral Research and Exploration. The results are given in Table 5.

Figure 11: Ferrochrome Slag Sample

Table 5: Chemical Analysis of Ferrochrome Slag Sample

Components	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	TiO_2	Cr_2O_3	Other*
FS	1.75	25.2	23.6	1.4	41.8	0.3	5.3	0.6

* Total of $P_2O_5 + NaO_2 + MnO + K_2O$

3.2 Method

In order to evaluate the industrial wastes of Turkey in surface preparation of steelworks as abrasive, quality and performance of the materials should be determined. Therefore, the characterization studies were carried out followed by preparation of samples for industrial application. The details are given in following sections.

3.2.1 Material Characterization

A mineral slag to be utilized in blast cleaning in Turkey should satisfy some requirements stated by Turkish standard TS EN ISO 11126 “Preparation of steel substrates before application of paints and related products - Specification for non - metallic blast cleaning abrasives”. This standard evaluates the materials from the aspects of physical properties such as size distribution, apparent density, hardness and moisture content; and chemical cleanliness like existence of water soluble compounds.

The assessments of materials whether they meet the specifications stated by TS EN ISO 11126 is performed in accordance with Turkish standard TS EN ISO 11127 “Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives”.

The characteristics of materials investigated in this thesis work were determined by following methods based on mentioned standards above.

3.2.1.1 Particle Size Distribution

Particle size distribution of samples was determined by dry sieve analysis. A quantity of the sample was put in the top of a set of Tyler series laboratory sieves stacked vertically in descending order of decreasing aperture size with a collector pan at the base, and it was sieved for 30 minutes using a sieve shaker.

Specification in TS EN ISO 11126 states that abrasive particles should not be coarser than 3.15 mm and amount of particles finer than 0.2 mm should not be higher than 5 %. Therefore, coarser samples were first crushed successively to top size of 3 mm in a jaw and a roll crusher before the sieve analysis and the sizes of the sieves were selected as within the range of 0.074 mm and 3.36 mm.

3.2.1.2 Determination of Apparent Density

Apparent density of samples was determined using a Gay-Lussac type pycnometer according to Turkish standard TS EN ISO 11127-3 “Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives - Part 3 : Determination of apparent density”.

Oven-dried sample is cooled down to room temperature in a desiccator. First, empty dry pycnometer is weighed. Next, a quantity of sample is placed into the pycnometer and weighed again. Then, the pycnometer containing the sample is filled with distilled water and weighed. Later, emptied pycnometer is refilled with distilled water alone and weighed again. Finally, the apparent density of samples is calculated by using formula (1):

$$\rho_A = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \rho_W \times 10^3 \qquad (1)$$

where

ρ_A : apparent density of sample, kg/dm^3
m_1 : weight of pycnometer, g
m_2 : weight of pycnometer + sample, g
m_3 : weight of pycnometer + sample + water, g
m_4 : weight of pycnometer + water, g
ρ_W : density of water at experiment temperature, kg/m^3

3.2.1.3 Assessment of Hardness by Glass Slide Test

Hardness of samples was assessed according to Turkish standard TS EN ISO 11127-4 “Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives - Part 4: Assessment of hardness by a glass slide test”.

The samples are examined under a microscope. Then, some of the different sized and colored particles are picked and placed between two glass microscope slides. The two slides are moved in opposite directions under pressure during 10 seconds. Then, the surfaces of the glass slides are examined. If slides are scratched by the particles, the hardness of the sample is accepted as minimum 6 in Mohs scale.

3.2.1.4 Determination of Moisture Content

Moisture content of samples was determined according to Turkish standard TS EN ISO 11127-5 “Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives - Part 5 : Determination of moisture”.

A container is dried at 110 ± 5°C for 15 minutes in an oven and cooled down to room temperature in a desiccator. Then, the container is weighted and a quantity of sample (approximately 100 g) is placed into the container. Next, the container and the sample are placed into a preheated oven and dried for minimum 1 hour. Later, the container is transferred to the desiccator to cool down to room temperature and the weight of the dry sample is determined after weighing the sample and container. Finally, moisture content of sample is calculated by using formula (2):

$$M = \frac{m_0 - m_1}{m_0} \times 100 \qquad (2)$$

where

M : water content of sample, %

m_0 : weight of sample before drying, g

m_1 : weight of sample after drying, g

3.2.1.5 Water Soluble Contaminants

Water soluble contaminants were determined by conductivity measurement in accordance with Turkish standard TS EN ISO 11127-6 “Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives - Part 6 : Determination of water – soluble contaminants by conductivity measurement”.

100 g of sample is placed into a 250 ml-flask and 100 ml of distilled water is added. It is stirred for 5 minutes and waited for 1 hour. Then, it is stirred for 5 minutes again and allowed to settle down. If solution is not clear it is filtered and

sufficient amount of solute is transferred into the cell of the conductivity bridge. Finally, conductivity of the sample is measured at 20°C and calculated by using formula (3):

$$\gamma_s = \gamma_m \times K_{20} \tag{3}$$

where

γ_m : conductivity of sample at 20°C, miliSiemens/m

K_{20} : cell constant of conductivity cell at 20°C

Conductivity measurements were carried out in General Directorate of Research and Exploration laboratories.

3.2.1.6 Water Soluble Chlorides

Water soluble chlorides were determined in accordance with Turkish standard TS EN ISO 11127-7 "Preparation of steel substrates before application of paints and related products - Test methods for non-metallic blast cleaning abrasives - Part 7 : Determination of water – soluble chlorides".

100 g of sample is placed into a 250 ml-flask and 100 ml of distilled water is added. It is stirred for 5 minutes and waited for 1 hour. Then, it is stirred for 5 minutes again and allowed to settle down. If solution is not clear it is filtered. 25 ml of solution is taken and 0.1 ml of concentrated sulfuric acid (H_2SO_4) is added. Then, it is diluted to 75 ml with distilled water. Finally, the sample was titrated with silver nitrate solution ($AgNO_3$) using an amperometric titration device. The amount of water soluble chlorides is calculated as weight percent by using formula (4):

$$w(Cl) = \frac{V \times 0.000355 \times 4}{m_0} \tag{4}$$

where

w : Amount of water soluble chlorides, %

m_0 : weight of sample, g

V : volume of silver nitrate solution consumed during titration, ml

0.000355 : conversion factor of silver nitrate solution (0.01 M) to Cl in grams.

Titrations were performed in General Directorate of Research and Exploration laboratories.

3.2.2 Sample Preparation

The second part of method followed during this thesis work is preparation of test samples for industrial application. The samples were prepared according to specifications requested by Hempel Coatings Co. Turkey, which is a subsidiary of an international company performing paint and coating works in shipbuilding and maintenance industry in İstanbul. The company uses specifications in Turkish standards, except for particle size distribution. Since the company use its own particle size distribution in general purpose applications, which is in the range of 1.7 mm and 0.3 mm.

Since original samples have different physical characteristics, pretreatments of test samples before sieving were performed in different ways. Converter and ferrochrome slag samples were first crushed in a jaw crusher to below 3 mm because of their lumpy nature. On the other hand, coal furnace slag and granulated blast furnace slag samples were air-dried before sieving due to their high moisture content. Oversize materials were crushed and then all samples were sieved for specified sizes. Undersize materials were rejected.

Besides the sample preparation method mentioned above a coal furnace slag sample was also prepared by wet screening and a granulated blast furnace slag sample was prepared within two different size ranges, which were 1.7 mm – 1.2 mm and 1.2 mm – 0.3 mm. Finally all test samples were packed and sent to Tuzla (İstanbul) for industrial application.

3.2.3 Industrial Application

The last but the most significant part of the method is the industrial application. Prepared samples were tested in Sedef Shipyard from the performance and quality aspects under surveillance of experts from Hempel Coating Co.

Suitable painted and partly rusted steel surfaces were first selected from the body plates and panels of a ship to be maintanenced. The photos of test surfaces were taken before abrasive utilization. Sufficient amount of test samples were placed into the cabinet of blasting machine and the test surfaces were blasted until all of the samples were consumed. Finally, photos of blasted surfaces were taken again and the surfaces were evaluated. The experts assisted in evaluation of the blasted surfaces from the surface cleanliness and profile pattern point of views. Details are given in following headings.

3.2.3.1 Visual assessment of surface cleanliness

In order to assess the surface cleanliness, Turkish standard TS EN ISO 8501-1 “Preparation of steel substrates before application of paints and related products- Visual assessment of surface cleanliness Part 1: Rust grades and preparation grades of uncoated steel substrates after overall removal of previous coatings” was used.

The standard contains a total of 24 pictures showing the visual cleanliness after preparation of the steel. Blasted surface was visually evaluated by comparing with the pictures. Each preparation grade is designated by the appropriate letters, “Sa”, “St” or “Fl” to indicate the type of cleaning method used. The number following, if any, indicates the degree of cleaning from mill scale, rust and previous coatings.

The standard includes three preparation grades:

- Blast cleaning, Sa
- Hand and power tool cleaning, St
- Flame cleaning, Fl

Four levels of cleanliness are defined in blast cleaning, which have the following designations: Sa 1, Sa 2, Sa 2½ and Sa 3. Only very light blast cleaning is required to achieve a cleanliness of Sa 1 or Sa 2. In order to achieve a cleanliness of Sa 2½ and Sa 3 very thorough blast cleaning is required.

Sa 1: ***Light blast cleaning***

When viewed without magnification, the surface shall be free from visible oil, grease and dirt, and from poorly adhering mill scale, rust, paint coatings and foreign matter.

Sa 2***: Thorough blast cleaning***

When viewed without magnification, the surface shall be free from visible oil, grease and dirt, and from most of the mill scale, rust, paint coatings and foreign matter. Any residual contamination shall be firmly adhering.

Sa 2½: ***Very thorough blast cleaning***

When viewed without magnification, the surface shall be free from visible oil, grease and dirt, and from mill scale, rust, paint coatings and foreign matter. Any remaining traces of contamination shall show only as slight stains in the form of spots or stripes.

Sa 3: ***Blast cleaning to visually clean steel***

When viewed without magnification, the surface shall be free from visible oil, grease and dirt, and shall be free from mill scale, rust, paint coatings and foreign matter. It shall have a uniform metallic color.

3.2.3.2 Assessment of Surface Profile

Surface profile pattern of blasted surfaces were evaluated using Rugotest No:3 surface profile comparator. The comparator has a rectangular shape and the blasted specimens are grouped vertically according to the shape of the abrasives with which they have been blasted. The specimens on the left side, denoted A, are shot blasted, while those on the right side, denoted B, are grit blasted [26].

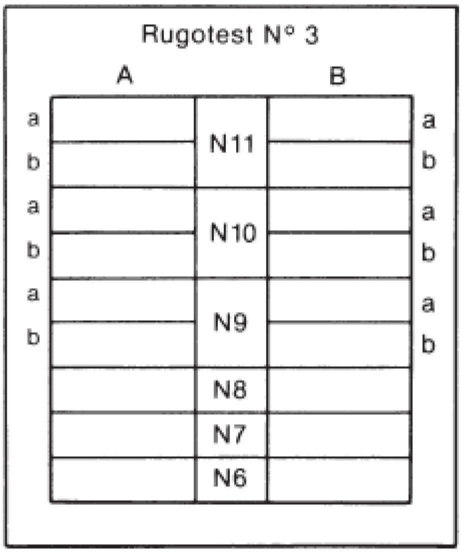

Figure 12: Rugotest no.3 Comparator [26]

Each half is divided into six roughness areas, from N 6 to N 11. N 11 indicates the highest and N 6 the lowest roughness. The average roughness Ra ranges from 0.8 µm to 25 µm on the specimens from N 6 to N 11 on Rugotest no. 3. Some of the specimens, N 6-N 11, have been subdivided into two specimens. These specimens are designated “a” or “b”. The letter “a” indicates that blasting has been carried out with coarse abrasive grains, b with fine abrasive grains. In the offshore industry a roughness within the range B N9a-B N10a is usually required [26].

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Evaluation of Material Characteristics as Abrasive

Assessment of material characteristics as abrasive was based on Turkish standard TS EN ISO 11126 “Preparation of steel substrates before application of paints and related products - Specification for non - metallic blast cleaning abrasives”. Coal furnace slag (CFS) and granulated blast furnace slag (GBFS) are included within the scope of this standard in part 4 and part 6, respectively. But, converter slag (CS) and ferrochrome slag (FS) are not covered. However, during the evaluation of these materials common specifications of mentioned standard are also applied to these materials.

4.1.1 Chemical Composition

Although related Turkish standard does not contain any specification about chemical composition of the materials except for water soluble compounds, chemical analysis of the materials were performed since chemical composition is strongly related with the physical properties of a material, and hence affects the quality of an abrasive. It also gives a tool in comparing the samples with the same type of materials used in industry.

Although the elements exist as their silicates and other complex compounds, in their chemical analyses they are given in their oxides forms.

Coal slag is mainly an aluminum silicate material. Chemical analysis of the coal furnace slag sample and a blast cleaning grit made of coal slag from Eurogrit BV, an international company producing abrasives, is given in Table 6.

Table 6: Chemical Analysis of CFS Sample and Eurogrit Coal Slag Abrasive

Components	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	Other	LOI
Eurogrit* (%)	45-52	24-31	3-8	7-11	2-3	0-1	2-5	traces	-
CFS (%)	48.1	10.5	13.7	7.4	6.2	1.6	1.6	0.9**	9.6

* source: http://www.eurogrit.nl/temp/uk_us/index.html

** Total of P_2O_5 + TiO_2 + MnO

Chemical compositions of two coal slags showed that SiO_2 percentages are similar. However, Al_2O_3 content of CFS is lower than the half of that of coal slag abrasive used in industry. On the other hand, CFS differs from the Eurogrit coal slag abrasive with high CaO and MgO content. Those differences are possibly due to the petrographical and mineralogical compositions of coal and its associated mineral matter. Chemical analysis of CFS also reveals that there is almost 10 % loss of ignition, which possibly indicates that the slag sample contains unburned coal. Those differences in chemical composition of the sample are expected to cause variations from expected physical properties such as apparent density, hardness, etc. Those are discussed in following headings.

Results of the chemical analysis of granulated blast furnace slag sample and typical slag composition obtained from National Slag Association (USA) is given in Table 7. Apart from the little variations, GBFS seems to be a typical calcium silicate slag.

Table 7: Chemical Analysis of Granulated Blast Furnace Slags

Components	FeO	SiO_2	MnO	Al_2O_3	CaO	MgO	S	Other
NSA	0.2-1.6	27-38	0.15-0.76	7-12	34-43	7-15	1.0-1.9	-
GBFS	0.09	36.82	0.56	15.38	40.80	4.91	1.20	0.15*

* Total of Na_2O + K_2O + TiO_2

Table 8 shows the chemical analysis of converter slag.

Table 8: Chemical Analysis of Converter Slag Sample

Components	Total Fe	FeO	SiO_2	MnO	Al_2O_3	CaO	MgO	P_2O_5	Other*
Weight (%)	21.87	9.36	9.62	4.66	0.89	49.48	2.39	1.43	0.46

* Total of S + Na_2O + K_2O + TiO_2

High iron, MnO and CaO content of converter slag draw attention (see Table 8) when the chemical analysis of converter slag sample is compared with the other type of slags investigated.

The reason may be originated from the source of slag. Converter slag is produced during steel production in a furnace. Hot iron and scrap metal are the primary metals to make steel in process. Lime is injected to act a fluxing agent. The lime combines with the silicates, aluminum oxides, magnesium oxides, manganese oxides and ferrites to form converter slag which is also known as steel furnace slag.

Chemical analysis of ferrochrome slag sample and a Chrome Grit from Gritblasting Co. (South Africa) is given in Table 9.

Table 9: Chemical Analysis of Ferrochrome Slag Sample and Chrome Grit

Components	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	TiO_2	Cr_2O_3	Other
Chrome Grit*	8	32	26	2	20	1	12	-
FS	1.75	25.2	23.6	1.4	41.8	0.3	5.3	0.6**

* Source: http://www.gritblasting.co.za

** Total of $P_2O_5 + NaO_2 + MnO + K_2O$

As it is seen from Table 9, ferrochrome slag sample has lower Fe_2O_3, SiO_2 and Cr_2O_3 content, comparing to chrome grit. On the other hand, Its MgO content is twice that of the ferrochrome slag abrasive used in industry. Those differences might be originated from source materials and fluxing agent used in ferrochrome production and efficiency of operation during production.

4.1.2 Particle Size Distribution

Sieve analyses of original coal furnace slag and granulated blast furnace slag samples are shown in Figure 13 and Figure 14, respectively.

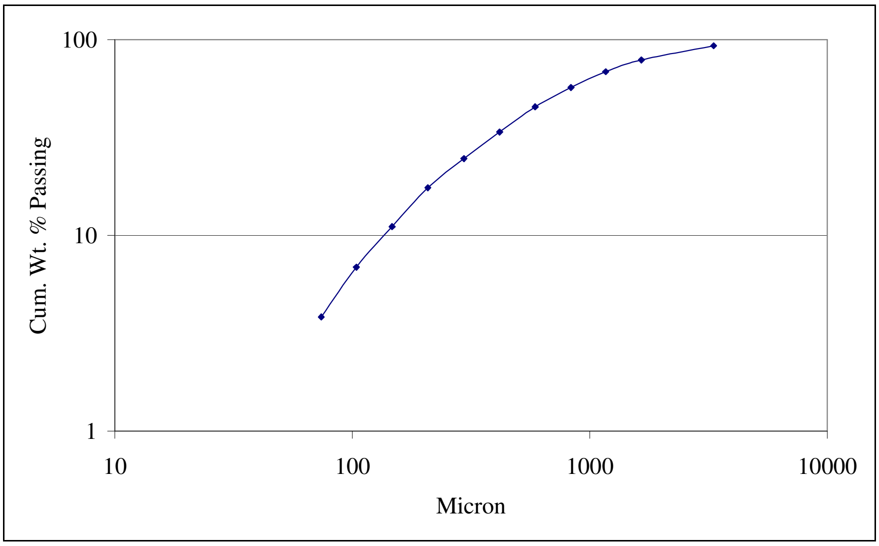

Figure 13: Sieve Analysis of Coal Furnace Slag

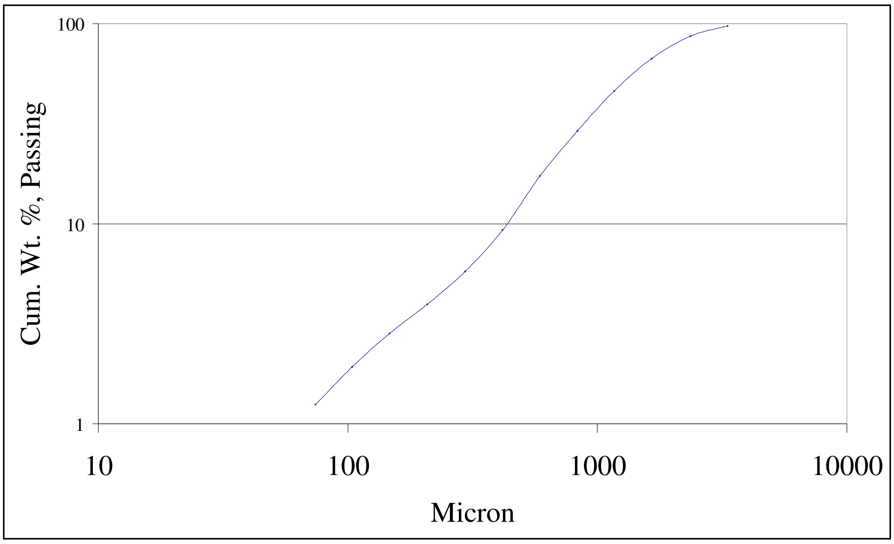

Figure 14: Sieve Analysis of Granulated Blast Furnace Slag

According to related standard abrasive particles should not be coarser than 3.15 mm and amount of particles finer than 0.2 mm and coarser than 2.8 mm should not be higher than 5 %.

Particle size distributions of coal furnace slag and granulated blast furnace slag samples showed that original materials can not be used as an abrasive in blast cleaning without sizing. However, more than 70 % of original coal furnace slag and almost 90 % of original granulated blast furnace slag can be utilized as abrasive after only a proper sizing if they meet the other specifications requested by the blast cleaning industry. On the other hand, lumpy nature of converter slag and ferrochrome slag necessitated a crushing stage before sizing. Figure 15 and Figure 16 show the sieve analyses of converter slag and ferrochrome slag samples after successively crushing to below 3 mm size. It is seen from the figures that more than 90 % of converter slag and ferrochrome slag can be used in blast cleaning operations from the point of size distribution. However, they should meet the other requirement in order to be utilized in industry.

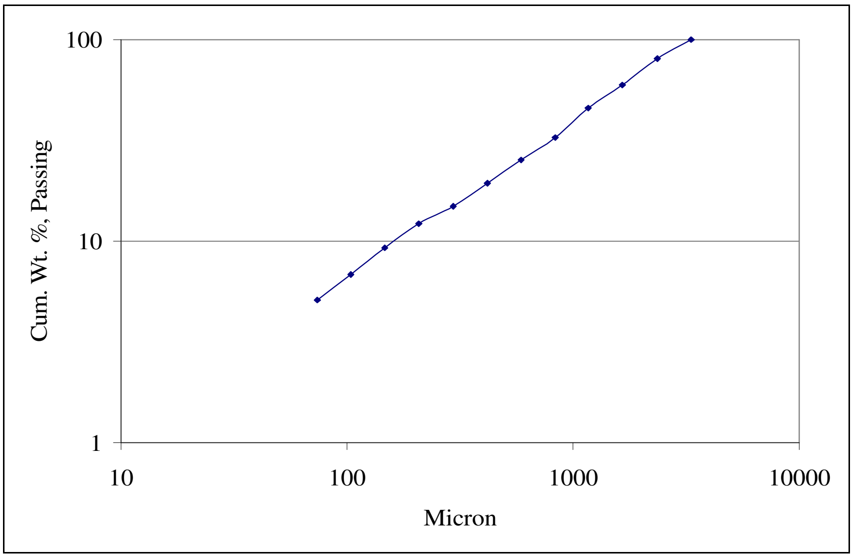

Figure 15: Sieve Analysis of Converter Slag

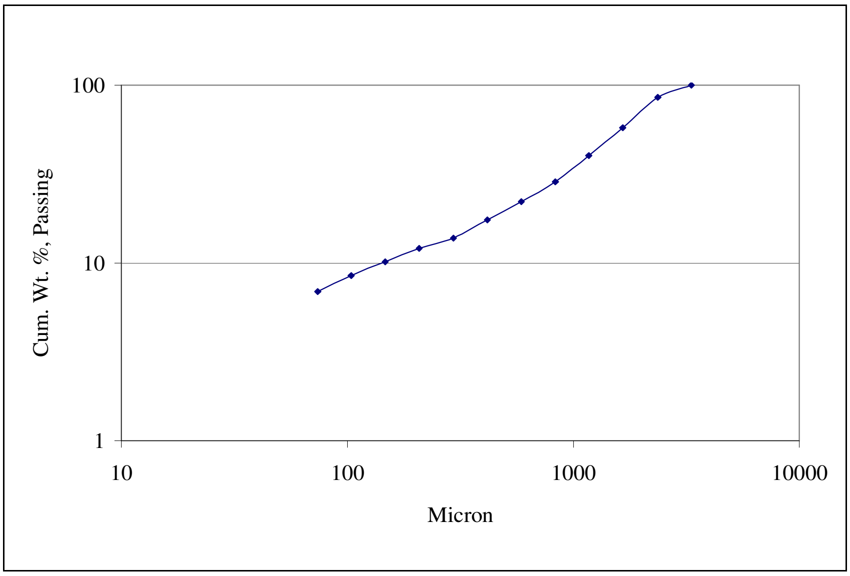

Figure 16: Sieve Analysis of Ferrochrome Slag

4.1.3 Apparent Density

Measured apparent densities of investigated materials and specifications stated by related standard are given in Table 10.

Table 10: Apparent Densities of Materials

Material	CFS	GBFS	CS	FS
TS EN ISO 11126 (kg/dm^3)	2.4-2.6	3.0-3.3	-	3.47*
Sample (kg/dm^3)	2.1	2.4	3.8	3.4

*Chrome Grit, http://www.gritblasting.co.za/msds.htm

As it is seen from the Table 10 coal furnace slag and granulated blast furnace slag samples do not meet the specifications. Both of them are below the required values. Lower apparent density of coal furnace slag is attributed to its chemical composition. Low Al_2O_3 content and unburned coal possibly reduces its apparent density. As to granulated blast furnace slag, its apparent density is much lower than specified values. This might point out a porous structure possibly due to cooling regime. Converter slag has the highest apparent density among studied materials. It might be due to high iron content in the slag and possibly occur with scrap metal additions during steel production. Compared to ferrochrome slag abrasive used in industry, Turkish ferrochrome slag seems to be suitable to be utilized in blast cleaning from the density point of view.

4.1.4 Hardness

Hardness values of materials determined by glass slide test and specifications of related standards are given in Table 11.

Table 11: Hardness Values of Materials

Material	CFS	GBFS	CS	FS
TS EN ISO 11126 (Mohs)	min. 6	min. 6	-	-
Sample (Mohs)	6 (?)	> 6	> 6	> 6

Results showed that all of the investigated materials are suitable to be utilized as abrasives in blast cleaning operations. Hardness of granulated blast furnace slag, converter slag and ferrochrome slag samples are obviously greater than 6 in mohs scale. On the other hand, different particles of coal furnace slag sample scratches the glass slide in different levels, but the others do not. Therefore the exact hardness value of CFS is doubtful and it is considered to be low to be used in blast cleaning since hardness of Black Beauty® coal slag abrasive from Reed Minerals (USA) is reported to be up to 7 mohs. Low hardness of CFS is attributed to its chemical composition and applied cooling regime. CFS is cooled by water quenching. On the other hand, it is known that coal slags used as abrasive are generally rapidly cooled by water-jetting.

4.1.5 Moisture Content

The moisture content requirement of TS for abrasives is below 0.2 %. Original coal furnace slag and granulated blast furnace slag samples contain 12 % and 7 % moisture, respectively. However, original coal furnace slag and ferrochrome slag samples are dry. CFS and GBFS samples were air-dried to meet the TS specifications. Moisture contents of the materials are given in Table 12.

Table 12: Moisture Content of Materials

Material	CFS	GBFS	CS	FS
TS EN ISO 11126 (%)	0. 2	0. 2	-	-
Sample (%)	0.03	0.02	0.03	0.04

4.1.6 Water Soluble Contaminants

Water soluble contaminants of studied materials were determined by conductivity measurement. The related specifications and the results of conductivity tests are given in Table 13.

Table 13: Water Soluble Contaminant Levels of Materials

Material	CFS	GBFS	CS	FS
TS EN ISO 11126 (mSiemens/m)	max.25	max.25	-	-
Sample (mSiemens/m)	-	15.7	811	14.3
Washed Sample (mSiemens/m)	-	26.5	440	24.0

As it is seen from the Table 13, granulated blast furnace slag and ferrochrome slag samples meet the specifications of related standards. Whereas converter slag sample contains relatively high amount of water soluble contaminants, which may cause corrosion and premature failure of applied paints or coatings. High amount of lime addition during steel production is taught to be the reason of this problem. It is also known via private communication with an expert from Erdemir Iron and Steel Works [48] that converter slag is dumped in open atmosphere and it is probably contaminated from its environment and this situation possibly results in formation of water soluble compounds. In order to reduce the high level of water soluble contaminants the converter slag sample were washed with tap water. Washing also removed the adhering dust. This treatment reduced soluble contaminants to 440 mS/m level, which is still higher than the specified value. This problem is possibly solved with thorough washing with river water. Erdemir uses river water supplied from their dam to quench the blast furnace slag. However, converter slag is allowed to cool in open air. The same water can be used to wash their converter slag. It is also seen from Table 13 that soluble contaminant levels of GBFS and FS are unexpectedly increased after washing with tap water. This result is attributed to high water hardness, and chlorinated nature of tap water used in METU. Water soluble contaminants of coal furnace slag sample was not determined because it did not provide sufficient cleaning performance during industrial application.

4.1.7 Water Soluble Chlorides

Water soluble chloride content of investigated materials was determined by titration with silver nitrate solution. That of coal furnace slag sample was not determined since it failed during industrial application. Soluble chloride content of other materials and specifications in related standards are given in Table 14.

Table 14: Water Soluble Chloride Content of Materials

Material	CFS	GBFS	CS	FS
TS EN ISO 11126 (%, m/m)	max.0.0025	max.0.0025	-	-
Sample (%, m/m)	-	0.0004	0.0013	0.0001
Cl^- Amount in Water Soluble Extract (%)	-	3.50	9.10	3.05

Table 14 reveals that the water soluble chloride content of measured materials are much lower than the maximum allowable value of 0.0025 % specified by the related standards. Cl^- amount in water soluble extract was determined by an argentometric method described in Appendix and carried out in General Directorate of Mineral Research and Exploration. It is seen from the table that water soluble chloride content is only 9.1 % of soluble compounds of the slags. This supports the fact that water soluble contaminants of converter slag are mainly originated from other sources. However, converter slag contains higher amount of water soluble chlorides relative to that of granulated blast furnace slag and ferrochrome slag. This is attributed to its cooling conditions. The converter slag is allowed to cool down in open air at the dump site and it is possibly contaminated from its environment.

4.2 Industrial Application

Within the scope of this thesis work, two industrial applications were performed at Sedef Shipyard with the guidance of experts from Hempel Coatings Turkey. The first application was held on 16th October, 2004 and coal furnace slag, granulated blast furnace slag and converter slag samples were tested. Particle size and quantity of materials are given in Table 15.

Table 15: Particle Size and Quantity of Materials Tested in the First Application

Material	Particle Size (mm)	Quantity (kg)
CFS	0.3 – 1.2	23.7
CFS (washed)	0.3 – 1.2	17.2
GBFS (coarse)	1.2 – 1.7	13.0
GBFS (fine)	0.3 – 1.2	13.3
CS	0.3 – 1.7	9.2

The second application was performed at the same place on 8th April, 2005. During this application ferrochrome slag and converter slag samples were tested. Table 16 gives the particle size and quantity of tested materials during second application.

Table 16: Particle Size and Quantity of Materials Tested in the Second Application

Material	Particle Size (mm)	Quantity (kg)
FS	0.3 – 1.2	29.6
CS	0.3 – 1.2	29.2

Results of the industrial applications and their evaluation are given in following headings.

4.2.1 Converter Slag

Converter slag samples were tested both in the first and the second industrial applications. During the first application, a steel test plate was first selected from the body plates of a ship in maintenance (see Figure 17). The test sample was placed into the cabinet of blasting machine and the test plate was blasted until all of the samples were consumed (see Figure 18).

Figure 17: First Steel Plate before Blasting

Figure 18: Blasting Operation Using CS

Figure 19: Steel Plate Blasted with CS

First industrial application of converter slag showed that the tested sample cleaned the work surface from most of the mill scale, rust, paint coatings and foreign matter (see Figure 19). With the surveillance of the experts from Hempel Coatings it was decided that the converter slag sample provided Sa 2 degree of cleanliness according to Turkish standard TS EN ISO 8501-1 “Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness Part 1: Rust grades and preparation grades of uncoated steel substrates after overall removal of previous coatings”. Converter slag sample also provided surface roughness of B N9a on Rugotest No.3, which is sufficient for general purpose blast cleaning operations. Therefore, the tested sample was accepted to have a sufficient cleaning performance by meeting the requirements of the industry.

It was observed that tested sample did not leave residues on the work surface. Therefore it did not cause any contamination. It was also noticed that converter slag sample was a low dusting material during blast cleaning operations. Laboratory studies showed that dusting level of converter slag could be further reduced by thorough washing. Washing could also reduce the water soluble contaminant level of converter slag below the maximum allowable limit.

After the first application the experts from Hempel Coatings advised to retest the converter slag with a higher quantity in order to be sure about the results. Converter slag sample was tested again in the second industrial application. The test panel selected from the body panels of a ship at maintenance work (see Figure 20) was blasted in the same way as mentioned above. The photograph of blasted test panel is shown in Figure 21.

Figure 20: Steel Panel before Blasting

Figure 21: Steel Panel Blasted with CS

The second application supported to previous trial and it was decided that converter slag from Erdemir Iron and Steel Works can be utilized as an abrasive in blast cleaning operations. The experts agreed with the fact that the abrasive made from that converter slag can be used in surface preparation operation before the general purpose application of epoxy paints.

4.2.2 Granulated Blast Furnace Slag

Two granulated blast furnace slag samples with different size ranges were tested in the first industrial application in order to investigate possible effects of particle size on blast cleaning. During the application, a new surface was selected from the body plates of the ship (see Figure 22 & 23) and the test plate was blasted with fine size (0.3 mm – 1.2 mm) and coarse size (1.2 mm – 1.7 mm) samples.

Figure 22: Second Steel Plate before Blast Cleaning

Figure 23: Blasting Operation with Fine GBFS

After the industrial application of the fine sample it was observed that the GBFS sample cleaned the work surface from all of the foreign matter (see Figure 24). It is decided that the granulated blast furnace slag sample provides "Sa 2 ½" degree of cleanliness according to Turkish standard TS EN ISO 8501-1 with the assistance of the experts from Hempel Coatings.

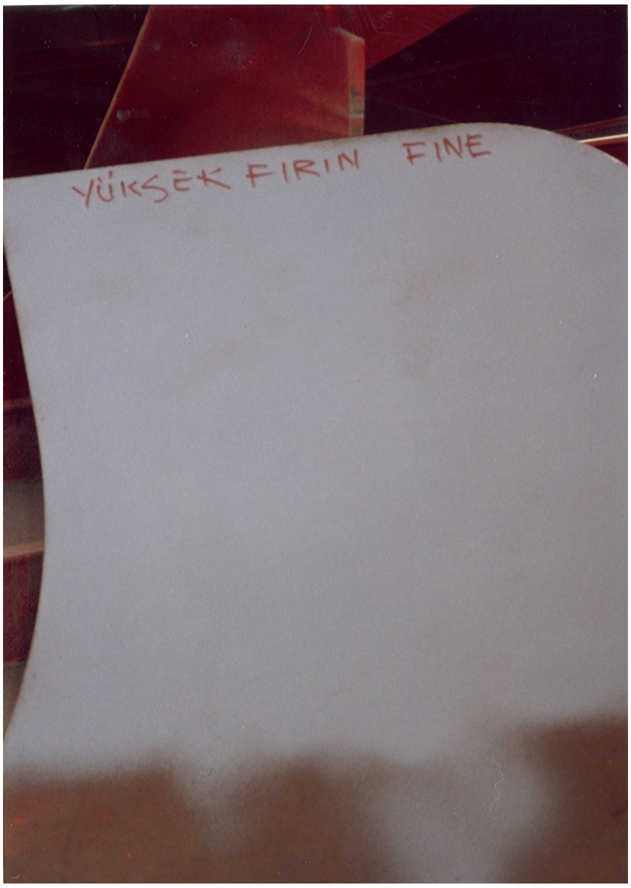

Figure 24: Second Plate Blasted with GBFS

After comparison of the worked surface with the surface profile comparator it was decided that fine sample provides surface roughness between the mid point of B N9 and B N10 on Rugotest No.3, which is suitable for all purpose blast cleaning operations. In addition, low dusting property provided a superior feature to that sample. These results showed that the fine size GBFS sample has a good cleaning performance and enables a good working condition.

When the worked surface was viewed with magnification, it was realized that the sample leaved local traces of contamination in the form of white spots, which was the unique drawback of the tested sample. The occurrence of these spots may be related with the physical structure of the particles forming the sample. As it is seen from the Table 10 the apparent density of the granulated blast furnace slag is lower than the expected values. This indicates that slag particles might have a porous structure, probably micro pores, giving them a relatively lower toughness than the abrasives used in industry. Besides, it is known via private communication with an expert from Erdemir [48] that granulated blast furnace slag particles contain some micro cracks, which further reduce the toughness of the sample.

The coarse sample was tested on a new surface. The application shows that the tested sample cleaned the work surface from all of the foreign matters (Figure 25). It is decided that the granulated blast furnace slag sample also provides “Sa 2 ½” degree of cleanliness according to Turkish standard TS EN ISO 8501-1.

Figure 25: Second Plate Blasted with Coarse GBFS

The result of the surface profile comparator test revealed that coarse sample provided surface roughness of B N10 on Rugotest No.3, which means that coarse sample more roughens the surface than the fine sample. These results also showed that the tested sample has a good cleaning performance. In addition, coarse sample did not create much dust either, which is favorable in blast cleaning operations However, the main disadvantage of granulated blast furnace slag is still valid for the coarse sample. It also leaved white spots on the surface which is objectionable in the industry.

As a result, although granulated blast furnace slag from Erdemir Iron and Steel Works has a good cleaning performance it can not be utilized as an abrasive due to their contaminations of the treated surfaces by white spots.

4.2.3 Coal Furnace Slag

During the industrial application of coal furnace slag, the second test plate was used again (see Figure26) in order to easily compare the results with the other application. A new surface was blasted again until all of the samples were consumed (see Figure 27 & 28).

Figure 26: Second Steel Plate before Blast Cleaning

Figure 27: Steel Plate Blasted with CFS

Figure 28: Steel Plate Blasted with CFS (lower) and GBFS (upper)

The test sample was not able to clean the surface from mill scale, rust and paint coatings. Visual assessment of surface cleanliness showed that the tested coal furnace slag sample is not applicable in blast cleaning operations. It did not fulfill the requirements of the "Sa 1" degree of cleanliness in Turkish standard, which is the lowest degree in blast cleaning. In addition, although the sample created some roughness locally it was not able to provide the lowest degree of roughness, which is B N6 on Rugotest No.3. Hence it does not meet the surface profile requirement by the industry, which is commonly in the range of B N9a-B N10a in industry.

The properties of the sample showed that it does not have sufficient hardness and toughness to do required work. Hardness test results shown in Table 11 indicated that some of the particles have hardness value lower than 6 mohs. Those particles probably can not scratch the surface properly to remove the unwanted matters and other particles with high hardness possibly are not sufficient in quantity to do the required work. Besides, the test sample created high amount of dust during the operation. It was observed that dust generation did not arise from abrasion of particles, but it was due to explosion of particles when they impact the surface of the plate. Excessive dusting of sample is attributable to its low toughness, which may probably related with ash fusion temperature and combustion technology applied in power generation plant as well as the chemical composition of gangue minerals associated with the coal. After the failure of dry sample as abrasive, washed sample was not tested.

All showed that coal furnace slag from Çayırhan thermal power plant can not be utilized as an abrasive in blast cleaning operations.

4.2.4 Ferrochrome Slag

During industrial application of ferrochrome sample another steel panel was selected from the body panels of the ship (see Figure 29) and the test panel was blasted in the same way as converter slag sample case. The blasted test panel is shown in Figure 30.

Figure 29: Second Steel Panel before Blasting

Figure 30: Steel Panel Blasted with FS

The application of the ferrochrome slag on the work surface showed that the FS cleaned the surface from most of the mill scale, rust, paint coatings and foreign matter (see Figure 30). At the first look, ferrochrome slag sample seemed to provide “Sa 2½” degree of cleanliness according to TS EN ISO 8501-1 and created brighter, near to white, surface than converter slag sample (see Figure 31).

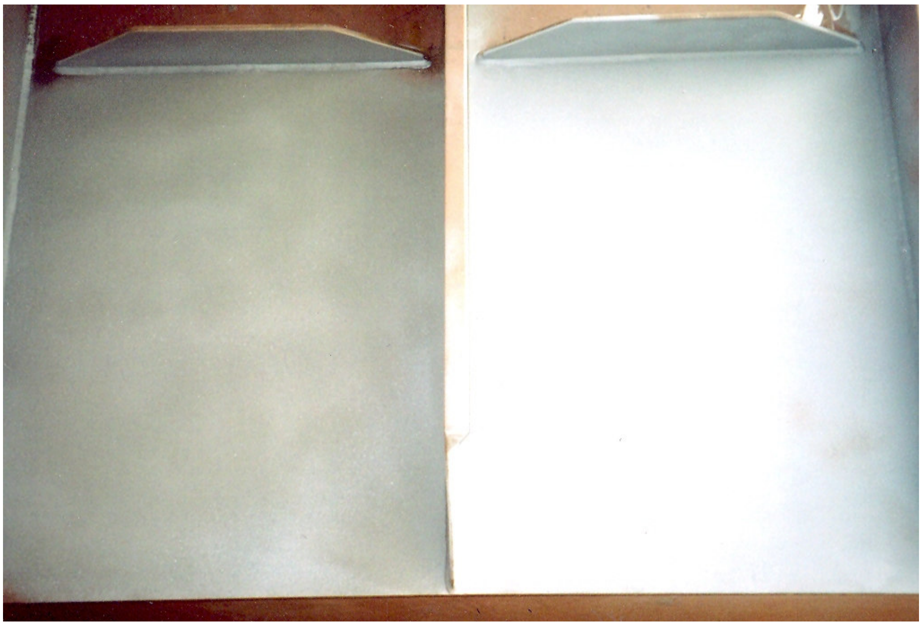

Figure 31: Steel Panels Blasted with CS (left side) and FS (right side)

However the appearance of blasted surface was possibly misleading. Because the FS sample created high amount of dust during the operation due to explosion of particles when they impact the work surface and leaved local contamination in the form of white spots similar to granulated blast furnace slag. The spots were much larger and greater in number. They seem to smear the surface and gave an extra brightness and white look to the surface.

Excessive dusting and smearing action of the sample was attributed to its different chemical composition than the same type of abrasive used in industry (see Table 9). Lower silica and Cr_2O_3 content, and higher MgO content possibly lower the toughness of the sample.

Surface profile test also supported the possible low toughness of the sample. Ferrochrome slag sample provided surface roughness of B N9b on Rugotest No.3, which does not meet the specifications of general purpose blast cleaning operations. As a result, ferrochrome slag sample from Eti Krom is not suitable to be utilized as an abrasive in surface preparation of steel surfaces.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this thesis:

1. Although the standards do not contain any specifications about chemical composition of the abrasives except for water soluble compounds. It appears that chemical composition affects the quality and performance of an abrasive.

2. Sieve analysis of investigated materials shows that none of the materials can be used directly as an abrasive in blast cleaning operations. They should be prepared for industrial application by drying, crushing and screening treatments.

3. Toughness, hardness and apparent density are appeared to be the dominating parameter in performance of an abrasive. Among the investigated materials, the converter slag has the highest toughness and apparent density while the granulated blast furnace slag has the highest hardness value.

4. Washing of the slags with fresh water improves the quality, since washing removes the water soluble contaminants and also prevent dusting generated by adhering fines.

5. Any material that meets the specifications stated in related standards may not necessarily be utilized as an abrasive. Industrial application determines the final decision.

6. The converter slag from Erdemir Iron and Steel Works provides “Sa 2” degree of cleanliness (TS EN ISO 8501-1) and surface roughness of B N9a on Rugotest No.3. It can be utilized as an abrasive in surface preparation operations before the general purpose application of epoxy paints.

7. Although the granulated blast furnace slag from Ereğli Iron and Steel Works has a good cleaning performance it can not be utilized as an abrasive in preparation of the steel since it leaves local traces of contamination in the form of white spots on the worked surface.

8. A coarse abrasive roughen the work surface deeper than the fine one creating a higher surface profile.

9. The coal furnace slag from Çayırhan thermal power plant can not provide the minimum cleaning performance and creates excessive dusting therefore it can not be utilized as an abrasive in blast cleaning operations.

10. The ferrochrome slag from Eti Krom A.Ş. can not provide required surface roughness for general purpose blast cleaning operations. It leaves white spots and smears the work surface giving it an extra brightness and white look. Therefore ferrochrome slag can not be utilized as an abrasive in surface preparation of steel substrates.

The followings are recommended for further investigations:

1. Effect of cooling regime on the physical properties of slag abrasives should be investigated.

2. Slag samples from other sources should be investigated.

REFERENCES

[1] Burns, R. M. and Bradley, W. W., *Protective Coatings for Metal*, 3rd ed, Reinhold, New York, 1967.

[2] Gabe, D. R., *Principles of metal surface treatment and protection*, 2nd ed, Pergamon Press, New York, 1978.

[3] Jacobson, G. A., *Corrosion – A natural but Controllable Process*, Material Ease, The AMPTIAC Quarterly, 7 (4), 39-45, 2003.

[4] Almeida, E., *Ind. Eng. Chem. Res.*, 2001, 40, 3-14

[5] Coes, L., *Abrasives*, Springer-Verlag, New York, 1971.

[6] Bange, G. and Gary, R., *Abrasives*, Kirk-Othmer Encyclopedia of Chemical Technology, 5th ed, V1, 1-35, John Wiley & Sons, 2002.

[7] Reams, C. A., *Modern Blast Cleaning and Ventilation*, 1st ed, Penton publishing, Clevaland, 1939.

[8] NACE International Basic Corrosion Course Handbook, Houston, chp 14, 7-14, 2000.

[9] Robinson, J., *What Lies Beneath - Surface Preparation, The Key To Coating Performance*, Corrosion Management, May 2003.

[10] Bakhvalov, G.T. and Turkovskaya, A.V., Isserlis G. (editor), *Corrosion and Protection of Metals*, Pergamon Press, New York, 1965.

[11] Hare, C. H., *Painting of Steel Bridges and Other Structures*, Van Nostrand Reinhold, New York, 1990.

[12] ASM Metals Handbook, *Selection of Cleaning Process*, 9th ed., vol. 5 (Surface Cleaning, Finishing, and Coating), pp 3-21, 1989.

[13] Wilson, C. L. and Oates, J. A., *Corrosion and the Maintenance Engineer*, Hart Pub, New York, 1968.

[14] Murphy, A., *Surface Preparation and Finishes for Metals*, McGraw-Hill, New York, 1971.

[15] Division of Pollution Prevention and Environmental Assistance (DPPEA), Metal Painting and Coating Operations, *Surface Preparation*, http://www.p2pays.org/ref/01/00777/surface.htm, retrieved 16 October, 2005.

[16] Banov, A., *Paints & Coatings Handbook for Contractors Architects Builders and Engineers*, Structures Pub., Farmington, 1973.

[17] Wranglén, G., *An Introduction to Corrosion and Protection of Metals*, Institut för Metallskydd, Stockholm, 1972.

[18] National Physical Laboratory, *Guides to Good Practice in Corrosion Control - Surface Preparation for Coating,* http://www.npl.co.uk/ncs/docs/surface_coating.pdf, retrieved 15 October, 2005.

[19] Rosenberger, W. A., *Impact Cleaning*, The Penton Publishing Co., Cleveland, 1939.

[20] International Protective Coatings, *Surface Preparation*, http://www.international-pc.com/pc/pds/pre_uk.pdf, retrieved 15 October, 2005.

[21] U. S. Environmental Protection Agency, , *Abrasive Blasting,* Emission Factor Documentation for AP-42, Section 13.2.6, Final Report, September 1997, http://www.epa.gov/ttn/chief/ap42/ch13/bgdocs/b13s02-6.pdf, retrieved 15 October, 2005.

[22] Hansel D., *Abrasive Blasting Systems*, Metal Finishing, V98 (7), July 2000.

[23] Chemco Industries, *Achieving Productivity from Abrasive Blast Cleaning Systems*, Journal of Protective Coatings and Linings, vol. 9, no. 9, pp 31-36, Sept, 1989.

[24] Potters Industries Inc., *Outline of Impact Blasting*, http://www.pottersbeads.com/Literature/ImpactBlasting.pdf, retrieved 08 October, 2005.

[25] Munger, C. G. and Vincent, L. D., *Corrosion Protection by Protective Coating*, 2nd ed., 221-232, Advanced Material Research Institude, 1999.

[26] Hempel Coatings, *Corrosion Protection - Inspector's Book of Reference*, chap. 13, Inspection Methods and Equipment, FROSIO, 2003.

[27] Rue, C. V., *Abrasives*, Kirk-Othmer Encyclopedia of Chemical Technology, 4th ed. V1, 17-37, John Wiley & Sons, New York, 1999.

[28] Gould, R. and Wilson, B., *Literature Review: Abrasive Blast Media*, Draft Report by Pera Knowledge, The Waste and Resources Action Programme**,** www.wrap.org.uk/document.rm?id=436, retrieved 01 November, 2005.

[29] Reade Advanced Materials, *Mohs' Hardness of Abrasives*, http://www.reade.com/Particle_Briefings/mohs_hardness_abrasive_grit.html, retrieved 05 October, 2005.

[30] Skillen, A.D., *Abrasive blast cleaning: evolution or revolution?*, Ind.Miner. No..317, 1994, p.25-39.

[31] Hansink J. D., *An Introduction to Abrasives for Protective Coating Removal Operations*, Journal of Protective Coatings and Linings, vol. 17, no. 4, pp 66-73, Apr 2000.

[32] Schuster, A. J., *Recycling garnet in the shop and field*, Protect. Coat. Europe 2002, vol. 7, no. 7, 7 (4 pp) 2002.

[33] Pereira, J., *Which abrasive: sand, slag or garnet?*, Protect. Coat. Europe 1998, vol. 3,no. 5, 26-7, 1998.

[34] Briggs, M., *Review of expendable abrasives*, Anti-Corros., vol. 34, no. 5, 10-2, 1987.

[35] Paddison, R. D., *What type of abrasive to use?*, Protect. Coat. Europe 2000, vol. 5, no. 4, 10(8 pp), 2000.

[36] Adley, D. and Trimber, K., *Evaluation of substitute materials for silica sand in abrasive blasting*, J. Protect. Coat. Linings, vol. 16, no. 8, 49 (18 pp), 1999.

[37] ASM Metals Handbook, *Abrasive Blast Cleaning*, 9th ed, vol. 5 (Surface Cleaning), pp 83-96, 1989.

[38] Rex, J., *Review of recent developments in surface preparation methods*, Jour. Protect. Coat. Linings, vol. 7, no. 10, 50-5, 1990.

[39] Dyer, D., *Glass beads: a unique cleaning medium*, Surface World, 1997, vol. 4, no. 9, 14-5, 1997.

[40] Bennett, P. J., *Non-metallic abrasives for surface preparation*, Jour. Protect. Coat. Linings, vol. 3, no. 4, 32-9, 1986.

[41] McCoach, H. and McLeod, J., *Recycled glass as an industrial abrasive*, Surface World 2000, vol. 7, no. 9, 32-3, 2000.

[42] National Slag Association, Slag Information, *Slag Types*, http://www.nationalslagassoc.org/Slag_Information.html#Types%20of%20Slag, retrieved 6 September, 2005.

[43] Ellicott, G., *Don't slag off slag*, Rio Tinto Review, number 75, September, 2005, http://www.riotinto.com/library/reviewmagazine/75/article2-1.aspx, retrieved 12 November, 2005.

[44] Australasian (iron & steel) Slag Association Inc., *slag products*, http://www.asa-inc.org.au/home.html, retrieved 6 September, 2005.

[45] *Soft media blasting: an introduction*, Journal of Protective Coatings & Linings (USA), vol.19, no. 1, pp. 23-29, Jan. 2002.

[46] Foley, K. M. and Weaver, T., *An Update on Soft Grit Blast Cleaning With Corncob Grit*, Abrasive Engineering Society, pp 107-116, 1981.

[47] Spelt, J. K., Tangestanian, P., Papini, M., *Starch media blast cleaning of artifically aged paint films*, University of Toronto; Ryerson Polytechnic University Wear (Switzerland), vol. 248, no. 1-2, pp. 128-139, Mar. 2001.

[48] Karakaş, Y. (private communication), Chief of Re-De Department, Erdemir Iron and Steel Works, December 2005.

APPENDIX

Details of the argentometric method used in determination of Cl^- amount in water soluble extract are given below.

Argentometric Method

1. Principle

In a neutral or slightly alkaline solution, potassium chromate can indicate the end point of the silver nitrate titration of chloride. Silver chloride is precipitated quantitatively before red silver chromate is formed.

2. Reagents

a. Potassium chromate indicator solution

Dissolve 50 g K_2CrO_4 in a little distilled water. Add $AgNO_3$ solution until a definite red precipitate is formed. Let, stand 12 hr, filter, and dilute to 1 L with distilled water.

b. Standard silver nitrate titrant, 0.0141N

Dissolve 2.395 g $AgNO_3$ in distilled water and dilute to 1,000 mL. Standardize against 0.0141N NaCI by the procedure described in 3*b* below; 1.00 mL = 500 µg Cl. Store in a brown bottle.

c. Standard sodium chloride, 0.014IN:

Dissolve 824.0 mg NaCI (dried at 140 °C) in distilled water and dilute to 1,000 mL; 1.00 mL = 500 µg Cl.

3. Procedure

a. Sample preparation:

Use a 100-mL sample or a suitable portion diluted to 100 mL. If the sample is highly colored, add 3mL $Al(OH)_3$ suspension, mix, let settle, and filter.

b. Titration

Directly titrate samples in the pH range 7 to 10. Adjust sample pH to 7 to 10 with H_2SO_4 or NaOH if it is not in this range. Add 1.0 mL K_2CrO_4 indicator solution. Titrate with standard $AgNO_3$ titrant to a pinkish yellow end point. Be consistent in end-point recognition.

Standardize $AgNO_3$ titrant and establish reagent blank value by the titration method outlined above. A blank of 0.2 to 0.3 mL is usual

4. Calculation

$$\text{mg Cl/L} = \frac{(A-B)\times N\times 35{,}450}{\text{mL sample}}$$

where:

A = mL titration for sample,

B = mL titration for blank, and

N = normality of AgNOa.

mg NaCl / L = (mg Cl / L) x 1.65