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Reuse and Recycling Drill Cuttings in Concrete Applications

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REUSE AND RECYCLING OF DRILL CUTTINGS IN CONCRETE APPLICATION

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ABSTRACT

Drill cutting (DC) is a major waste produced during petroleum extraction, which could present a major source of contamination to soil and groundwater, if not disposed properly. The objective of this study aims to test the hypothesis that drill cuttings can be incorporated as an aggregate in the production of concrete, and is suitable for use in controlled, low-strength material (CLSM) for non-structural applications. To achieve this objective, the physical and consensus properties of drill cuttings were characterized. Concrete mixtures were designed for CLSM applications with and without drill cuttings sampled from two sources. Prepared concrete mixes were then evaluated in terms of strength for use in non-structural concrete applications. Results showed that well-graded drill cuttings performed better than poorly-graded samples. Furthermore, when compared to the control samples, no significant compressive strength reduction was observed for concrete mixes prepared with drilled cuttings at high strength targets (2800, 1200 and 300 psi). Yet, a significant reduction was observed at low strength targets (80 and 200 psi). This may be due that the higher content of cement in high strength concrete mixtures compensates for the lack of strength as a result of drill cuttings. At high strength targets, it is feasible to replace the fine aggregates up to 20% without reducing the target compressive strength significantly.

Keywords: Drill cuttings, controlled low strength material (CLSM), concrete applications, recycled materials.

CHAPTER 1. INTRODUCTION

Concretes represent the most common construction material in the United States, given the safety, flexibility in design, load bearing capacity, and fire resistance (McGregor, 1997). Approximately 70% of the total volume of concrete consists of fine and coarse aggregates. Therefore, the concrete industry consumes more than 12 million tons of natural aggregates annually. Aggregate characteristics can influence the properties of fresh and hardened concrete, such as workability, density, shrinkage, and compressive strength (Devi & Gnanavel, 2014; Al-Jabri, Hisada, Al-Oraimi, & Al-Saidy, 2009). The other important component of concrete material is cement. Cement production consumes much energy and causes environmental impacts such as the release of high amounts of CO_2 (Naik, 2005). The shortage of natural resources brings a realization that utilization of waste material can produce more environmentally friendly material. In addition to saving natural resources, waste recycling in concrete application can reduce waste accumulation (Dash, Patro, & Rath, 2016).

Oil and gas exploration have increased during previous decades, due to increasing requests for energy. Drill cutting is a waste material generated by crushing the rock formation during drilling activities (Barabadi & Markeset, 2011). Oil and gas companies are using innovative techniques and modern technologies to reduce the generated amount of drill cuttings. However, the huge amounts of drilling waste must be managed with minimum environmental impacts. Environmental organizations passed many restrictions to limit the disposal of drill cuttings in seawaters. Therefore, a recycling and reuse of drill cuttings has drawn much interest among researchers. Several studies use the drill cuttings as an alternative aggregate. Many researchers utilized the drill cuttings as a substituent of natural aggregates. Mostavi, Asadi, and Ugochukwu (2015), as well as Okoh (2015) investigated the effects of a partial replacement of cement with

drill cuttings. The next step following the application of drill cuttings is to evaluate the performance of the cuttings by checking the mechanical and physical properties of the fresh, hardened concrete.

Aggregates carry an undeniable influence on the mechanical and physical properties of fresh and hardened concrete. The physical and chemical characteristics of the aggregates, such as particle size distribution, stiffness, shape, nominal size, and chemical composition can vary the properties of the concrete, such as durability, density, workability, compressive and flexural strengths, and elasticity modulus (Rangaraju & Kizhakommudom, 2013). For instance, well-graded sands can provide a better interlocking of aggregates that in turn results in a denser structure and a higher compressive strength. On the other hand as a consequence, angular and irregular aggregates can reduce the desired workability and the compressive strength (Rangaraju & Kizhakommudom, 2013). Overall the properties of the concrete, when produced by waste material such as drill cuttings, should be investigated to determine the feasibility of incorporation and the optimum amount that can be used.

1.1 Problem Statement

Drill cutting (DC) is a major waste produced during petroleum extraction; drill cuttings can be a major source of contamination to soil and groundwater if not disposed properly (Chaillan, Chaineau, Point, Saliot, & Oudot, 2006). Drill cuttings consist of excavated soil mixed with drilling fluid, which may include a fuel oil cut; drill cuttings can be separated from drilling fluid by using shale shakers, centrifuges, or other methods (Chaillan et al., 2006). Drill cuttings have usually been considered a waste, which requires proper disposal in landfills or pits. Yet, leaching of DC becomes a major concern in order to avoid soil and groundwater contamination. Also, EPA restricted drill cutting disposal based on the type and level of contamination (Malachosky,

Shannon, Jackson, & Aubert, 1993). Hence, potential reuse applications have been suggested in recent years for drill cuttings, which may offer the possibility of reclassifying it as a recyclable product instead of a waste. Potential markets for drill cuttings include land farming, land treatment, and road base applications (Gonzales, Crawley, & Patton, 2007). With an inventory of over 400,000 yd3 in South Texas, there is a strong potential to recycle DC as road construction materials; however, DC must be dried, treated, and screened to produce a material with consistent physical and mechanistic properties. Scant research, however, has explored the possibilities of incorporating drill cuttings as a replacement of the aggregate component in concrete mixtures.

1.2 Objectives

The objective of this study aimed to test the hypothesis that drill cuttings may be incorporated as a natural fine aggregate in the production of concrete, suitable for use in controlled low strength material (CLSM) and similar non-structural applications. To achieve this objective, three main tasks were conducted: (1) Characterize the physical, mechanical and mineralogical properties of drill cuttings; (2) Define the optimum mix proportion to attain specific levels of compressive strength; and (3) Measure the effects of drill cuttings on the mechanical properties of the hardened mixtures.

1.3 Scope of the Study

The focus of this study is on the evaluation of the performance of drill cuttings as an alternative material in drill cutting. Therefore, the physical characteristics of the cuttings such as initial moisture content, particle size distribution, specific gravity, absorption capacity will be determined through the ASTM experiments. Also, the chemical composition of the drilling wastes will be identified by using the secondary electron microscopy (SEM) and X-ray

Diffraction (XRD). Five targeting compressive strength (80, 200, 300, 1200, 2800 psi) is considered. In each compressive strength level 5 and 20% of natural sand will replace with the drill cuttings. Then, the mechanical properties of the hardened concrete, such as compressive strength and modulus of elasticity will be determined after 28 days. The conclusion will be drawn based on the mechanical properties of the concrete mixtures produced by incorporation of drill cuttings.

1.4 Research Approach

To achieve the objective of this study, the following research tasks will be conducted:

1.4.1 Task 1: Characterize the Physical and Chemical Properties of Drill Cuttings

The objective of this task is to characterize the physical and mechanical properties of drill cuttings. To achieve this objective, a minimum of two drill cuttings sources will be sampled from Texas and Louisiana. Physical properties will be tested in the laboratory including particle size distribution, specific gravity, and Atterberg limits. The absorption capacity and initial moisture content of drill cuttings will be measured so that the total water content of concrete can be controlled. The presence of organic impurities and other substances that may interfere with the normal hydration of cement will be evaluated using applicable ASTM standards. The elemental compositions of drill cuttings will also be investigated using Environmental Scanning Electron Microscopy (E-SEM) coupled with Energy dispersive x-ray (EDX) and X-Ray Diffraction (XRD).

1.4.2 Task 2: Prepare Concrete Mixtures and CLSM Incorporating Drill Cuttings

The objective of this task is to prepare concrete test specimens with and without drill cuttings. Concrete mixtures and CLSMs will be designed to meet available state specifications in terms of strength and modulus of elasticity. CLSM has gained wide interest for use as a structural fill or

backfill and in areas when placing and compacting a regular concrete can be challenging. Prepared mixes will be evaluated in terms of strength, workability, density, and durability for use in non-structural concrete applications.

1.4.3 Task 3: Measure the Mechanical Properties of Concrete Mixes

The objective of this task is to evaluate the mechanical behavior of concrete specimens prepared with and without drill cuttings. Of particular interest, the concrete compressive strength at 28 days will be measured in the laboratory and will be evaluated for different contents of drill cuttings ranging from zero (i.e., control) to 20% of the aggregate by weight. Also, the variation of elasticity modulus will be evaluated based on the effects of drill cuttings.

1.5 References

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CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Increasing waste production has become a worldwide problem during previous decades. Therefore, the investigators used different strategies to manage huge amounts of wastes. At the same time, public concerns were raised regarding the environmental and health issues related to these waste management activities. Therefore, the recycling and reuse of waste material absorbed much attention in numerous industries. Many researchers attempted to incorporate different types of waste in pavement and construction industries. Using waste material as a substituent of conventional material proved to be beneficial in asphalt, concrete, pavement structure, and building constructions. Indeed, waste recycling not only mitigates waste accumulation and solves relative environmental impact concerns, but also saves our natural resources and reduces energy consumption. As a result of these findings, drill cutting is viewed as a major waste of drilling activities which must be managed properly.

Drill cuttings are considered to be a hazardous waste, due to contamination by different toxic chemicals. As a result, environmental organizations passed several restrictions on drill cutting disposals during previous decades. At present, huge amounts of waste must be either treated or recycled. The investigators utilized drill cuttings as alternative aggregates or additives for different purposes, such as concrete production, asphalt manufacturing, sandcrete making, surface stabilization, and restoring coastal wetland, etc. One of the most important considerations is to investigate the chemical composition of cutting ingredients before recycling drill cuttings.

Drilling companies use various additives to improve the efficiency of drilling activities. These additives include weighting materials, viscosifiers, thinners, alkalinity (additives to control PH), bactericides, filtrates reducers, flocculants, foaming agents, lost circulation materials, and pipe

freeing agents. One of the most abundant chemical elements in drill cuttings is barite ($BaSO_4$). Barite is a high-density weighting agent that is usually found blended with a variety of minerals such as silica, dolomite, limestone, and iron oxide, as well as some metal sulfides. According to the level of high density, using barite can prevent a possible blow up in the formation. Furthermore, mud thinners such as chrome lignosulfonates are used to prevent infiltration of drilling mud into the formation. Chromate use is coupled with chrome lignosulfonates in high temperature drillings; these dual chemicals are considered to be the highest toxic chemicals used in drill cuttings. Therefore, the presence of any toxic chemicals should be investigated before using the cuttings as recycling aggregates.

Concrete is one of the most popular materials in construction industry, consisting of aggregates, cement, water, and additives. In the construction industry, the increased demand for using concrete has resulted in much energy and natural resource consumption. Therefore, the use of alternative material gained more interest. Many researchers replaced the conventional components of concrete with various waste materials, such as waste foundry sand (WFS), steel slag, granulated furnace blast (GFB) slag, drill cuttings, recycled glass, and recycled aggregates, etc. The researchers compared the mechanical properties of waste-based concrete to the original concrete, in order to find the optimum amount of waste material that should be used. The following chapter reviews various studies regarding concrete production with different waste materials.

2.2 Waste Material Management and Consequences

The amount of waste generation, having increased during past decades, is especially found in developed countries with high rates of gross domestic product (GPD) (World Bank, 1992; OECD, 2003). According to the Environmental Protection Agency (EPA), waste material may be

sorted in several categories, such as municipal solid waste (MSW), bio-solids, clinical, construction and demolition, e-wastes, expanded polystyrene, glass, lead acid batteries, mineral oil, organic, quarantine, radioactive, timber, tires, and virgin excavated natural material (EPA, 2105). , As a result, a variety of techniques must be applied to protect environmental quality in order to reach future sustainable goals (UNEP, 2005). Therefore, sustainable waste management strategies and technologies must be developed.

Huge public concerns exist regarding the health issues and environmental impacts associated with waste management practices. Wrong applications of waste management practices, such as landfilling, incineration, composting, sewage treatment, and landspreading, as well as radioactive waste management, has forced many governments to pass new regulations related to erroneous applications of waste management (Giusti, 2009).

In European countries, landfilling dominates as a waste management method. According to DHV CR, Western Europe countries deposited 57% of municipal solid waste (MSW) in landfills in 1999. This amount is significantly higher in Eastern Europe, where landfill is composed of 83.7% of MSW as well (DHV CR, 2001). Furthermore, the United States incinerated 14% of solid waste, landfilled 54%, and of the remainder, some 32% was either recovered or composted (EPA, 2008). Overall, the data indicates most developed countries are in the midst of transitioning to more sustainable approaches.

2.3 Health issues related to Waste Management Practices

2.3.1 Landfilling

Regardless of environmental and health issues, one of the most economic methods to handle the solid waste is landfilling (Rushbrook, 1983; Carra and Cossu, 1990). Hence, the landfilling of solid wastes could remain as the most attractive and available alternative for decision makers at

the preliminary stages. A report by EPA in 2011avers that more than 134 million out of 250 million tons of MSW produced in the US was placed in a landfill. This number is significantly higher than most western European countries, such as Belgium, Denmark, Austria, Sweden, Germany, Netherlands, etc. Figure 2.1 illustrates the quantity of landfills in different regions of the United States (Castaldi, 2014).

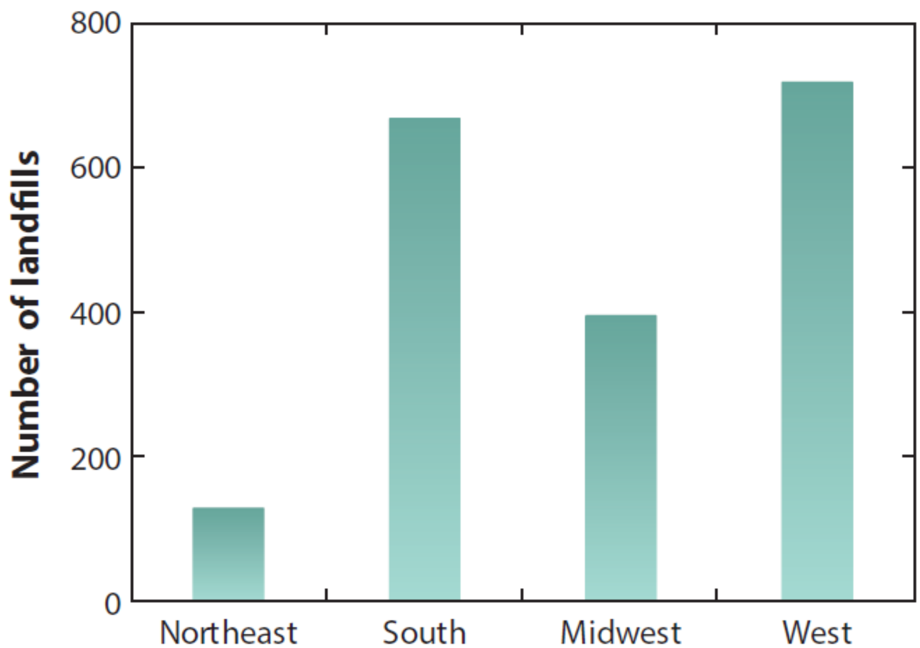


Figure 2. 1. Number of landfills in different regions of the United States (Castaldi, 2014)

Different studies produced conflicting results regarding the harmful effects of exposure to landfill sites. Scientific research found that a link exists between health issues and exposure to landfills. For instance, risks of birth defects and cancer may be increased by living in close proximity to landfills (Sever, 1997; Johnson, 1997). According to the workshop findings of the World Health Organization, however, there is no sufficient or convincing evidence to prove that waste landfills cause severe health issues, such as cancer and birth defects. Certain studies,

insisting an association exists between health issues and living near landfill sites, omitted several outstanding factors. For example, Fielder et al. (2000) did not consider that the residents also were exposed to incinerator well emissions that caused an enormous amount of pollution, coupled with severe heath impacts.

2.3.2 Incineration

In this particular waste management method, after the separation of recyclable wastes, solid wastes are burnt at a high temperature in the huge incinerators. Ash and fly ash are the most popular by-products of this process; these substances may contain dangerous toxins and heavy metals. Potentially, the incineration process can bring about severe environmental and health issues due to highly toxic emissions, as well as remaining substances. The incineration process usually leads to emission of toxic metals such as arsenic, cadmium, lead, and mercury; toxic organics such as dioxins, more specifically polychlorinated dibenzo-p-dioxins, (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenils (PCBs) and lastly, carbon monoxide and acid gases (Birundha & Devi, 2007). The main problem with incineration becomes the emission of persistent toxic organics. An incomplete process of waste combustion, such as municipal, medical, and household wastes can generate PCDDs and PCDFs (Fielder, 2007).

Soft tissue sarcomas and non-Hodgkin’s lymphoma are the most common illnesses caused by the toxic incineration process. Many studies have been initiated in countries with the greatest number of incinerators, especially in France. The studies proved the existence of an association between being exposed to dioxin generated by the solid waste incineration and non-Hodgkin’s lymphoma, yet the findings were reported to be insufficiently convincing (Viel et al., 2008). Conversely, according to Zambon et al. (2007), an exposure of Venice residents to dioxin

substance increased the risk of getting soft tissue sarcomas. A total of 33 dioxin-producing sources encompassed a group of incinerators that disposed of municipal solid, industrial, and medical wastes, as well as some industrial sources of incineration such as oil refineries, also considered in this research. Research suggests that a lack of information regarding the level of dioxin emission and the level of exposure gives rise to uncertainties about the results of this research (Zambon et al., 2007).

Although the evidence indicates an increase of heavy metal and organic chemicals in the populations who reside in the proximity of incinerators, there remains no causal relationship (Hu & Shy, 2001). Overall, the National Research Council stated that the epidemiological studies failed to prove a link between incineration and diseases such as cancer (Hu & Shy, 2001). Yet the concerns regarding the environmental and health consequences of incineration produced emission still persist.

2.3.3 Composting

Since the process of producing soil fertilizers requires chemical and energy consumption, composting may be considered a sustainable method in solid waste managing, where the product may be utilized as soil fertilizer. The composting process has other advantages as well, including the enhancement of soil characteristics, such as improving the water-retaining capacity of the soil and reducing pesticide provisions. Composting methods can also help with energy production, should anaerobic composting be feasible (Castaldi, 2014).

The major problem with a composting method is related to the workers who are exposed to dust and bacteria, funghi, actinomycetes, endotoxins, and 1-3 β glucans that result from composting activities. These factors can potentially cause respiratory and dermal diseases for the workers (Bunger et al., 2000; Harrison, 2007). Although a few studies found a relationship between living

in the proximity of composting sites and an increased risk of acquiring respiratory and dermal problems, the studies were unable to propose a strong justification. After reviewing the health risks caused by the exposure of the workers to composting facility pollutants, Domingo and Nadal (2008) suggested a comprehensive plan in which to control the health condition of workers and to decrease the quantity of released pollutant.

2.3.4 Radioactive Waste Management

With the development of nuclear energy, radioactive waste management became a considerable issue. Management of radioactive waste emerged as a worldwide problem during past decades (Saling, 2001). Nevertheless, most studies regarding waste management effects on public health were unable to reach an agreement in conclusion. The root of uncertainty in these studies remains the lack of valid justification which relates human disease to the consequences of radioactive waste management activities (Cohen, 1995; Sutherland, 2003). A report by COMARE (2002) questioned the results of the research by Gardner et al. (1990), which related the spread of cancer in young people residing in the proximity of the Sellafield nuclear plant in England. Another study by Cardis et al. (2005) indicated that radioactive waste management activities may be the main reason for 2% of cancers which lead to death.

2.4 Drilling Wastes

Well-drilling activities generate large quantities of wastes, composed generally of drilling muds and cuttings. According to the American Petroleum Institute (API), more than 150 million barrels of drill cuttings were produced in the United States in 1995 (Veil, 2002). Drill cuttings are produced beneath a drill bit by a combination of operations which crush and fracture a rock, which in turn generates ground-up rock particles. Drill cuttings vary in size and texture, ranging from fine sand to gravel, which depends on the type of rock drilled, the drilling process

employed, the type of drill used, and the drilling fluid applied. Drilling mud − also called drilling fluid − is used to lubricate the drill bit and transport the drill cuttings to the surface, where the mud and cuttings are then separated.

Drilling muds are typically divided into three types: water-based (WB), oil-based (OB), and synthetic-based (SB) muds. Drilling a neater hole with less sloughing, in addition to producing a lower amount of drill cuttings, represent the most outstanding superiorities of synthetic based fluids (SBFs) and oil-based fluids (OBFs), in comparison with water-based fluids (WBFs). In regard to the capability of drilling a measure hole and minimizing drilling difficulties in moist applications, OBFs and SBFs are usually preferred over WBFs. However, the main drawbacks of an OBF application originate from the environmental impact and worker safety issues associated with diesel and mineral oil and poly-nuclear hydrocarbons production in the use of this method. SBFs have a lower toxicity, faster biodegradability, lower bioaccumulation potential, and are recyclable, while WBFs must be discharged to the sea at offshore locations in most cases (Ball, Stewart, & Schliephake, 2012). Generally, the synthetic-based muds are more often used, due to the fact that effects on the environment are less impactful and biodegradation occurs faster than with the water- and oil-based muds (Burke & Veil, 1995; Gonzales, Crawley, & Patton, 2007).

Drilling fluids are usually composed of mineral oil or synthetic oil-based compounds, weighting agents such as barite and clay, and stabilizing, organic materials such as lignite. The main component of drilling mud is bentonite clay. The clay is mixed with water and an oil or synthetic base, while several compounds are added to the mixture, such as cellulose polymers and barium sulfate, to increase viscosity. These additives increase the hazardous potential of the mud, which in turn influences the type of drill cuttings extracted from the ground (Bernier et al., 2003).

2.5 Available Alternatives for Drilling Waste Management

According to Reise (1992), planning an appropriate waste management strategy is one of the most important factors in mitigation of the environmental impacts of drilling activities. Therefore, waste producing operations should be identified and proper solutions must be applied to handle, treat, and dispose of the wastes .The preliminary step, as the most critical one, is to minimize the amount of waste production. The operators should attempt every possible strategy to reduce drilling wastes, and then move to the next step, which is to reuse and recycle the wastes. Furthermore, after applying these two strategies, the remaining waste might be treated or disposed of according to specific rules and standards. These four steps frame the waste management hierarchy, yet none of these steps should be applied individually, rather than as steps in a procedure (Onwukwe & Nwakaudu, 2012). These four steps are discussed briefly in this chapter.

2.5.1 Waste Control

The main objective of this stage is either to decrease the volume of the drill cuttings or to produce the least toxic cuttings − or both, if applicable. One of the simplest approaches is to change the drilling fluid system. This may be done in the planning phase by the generators. As a result, some drilling companies replace the diesel and mineral oils as fluids belonging to Groups I and II, and with a less toxic glycol, synthetic hydrocarbons, polymers, and esters from Group III. This strategy prevents the production of oil-based drill cuttings (Railroad Commission of Texas (RRC), 2001). As stated in the technical reports published by the Society of Petroleum Engineers (SPE), the industry plans to pursue innovative fluid systems, such as water-based drill cuttings. The drill cutting generated in these methods includes less toxic ingredients and additives. For example, elimination of barite, which includes barium (a toxic-heavy metal), can

reduce the toxicity of drill cuttings drastically. (Growcock, Curtis, Hoxha, Brooks, & Candler, 2002).

The other alternative to reduce the amount of waste is to utilize suitable drilling practices. Using directional drilling is one of the options to minimize the amount of waste in the drilling process. Directional drilling can be done through different procedures. Extended-Reach Drilling, Horizontal Drilling, and Multiple Lateral Drilling present three variations of Directional drilling. The amount of waste generated through drilling horizontal wells is significantly less than a traditional, vertical drilling. The reason is that the main well bore in horizontal wells generates the highest volume of drill cuttings, and is drilled only once through the entire process. A Multiple Lateral Drilling can also reduce the amount of waste when the formation consists of multiple oil-bearing zones. By means of this method, rather than drill several vertical wells, multiple lateral wells are drilled to support the main vertical well. This may also be beneficial when the zone/s are located in different depths. (Johnson, 1999). These advanced drilling practices are indicated in Figure 2. There are other drilling technologies that can decrease the amount of drill cuttings, such as slimhole drilling, coiled tubing drilling, and a closer spacing of successive casing strings. These approaches also are developed, and are purposed for drilling the smaller diameter wells. In addition, upgrading the equipment and applying secondary treatment procedures can always produce less dangerous cuttings.

2.5.2 Drill Cutting reuse and recycling

The next step in the drilling waste management hierarchy is a reuse and recycling of the contaminated cuttings. Hence, when an operator reaches this point, waste reduction is no longer feasible. According to Reis (1996), some of the constituent materials of the drill cuttings either may be reused or transformed into an utilizable substance. For instance, reconditioned drill

cuttings could be successfully used again for drilling other wells. Furthermore, used drill cuttings may be applied in the manufacture of cementitious material and various construction applications. However for these usages, it is recommended to remove the salt content as much as possible (Reis, 1996; RRC, 2001).

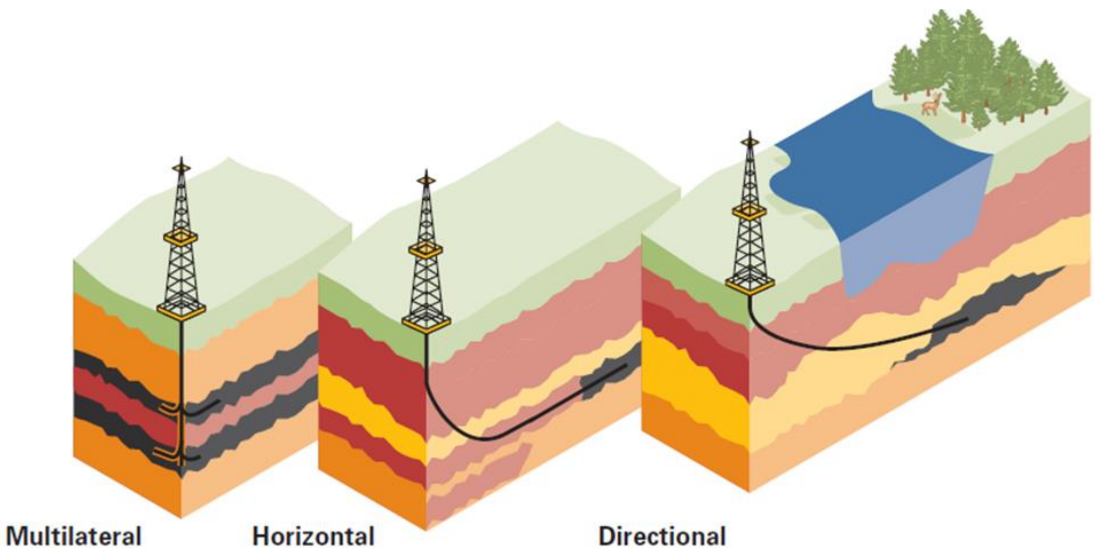


Figure 2. 2. Advanced Drilling Techniques (Johnson, 1999)

The waste reduction and recycling practices are the most favorable strategies among the whole waste management hierarchy of drill cuttings. Health issues and severe environmental impacts contributing to long-term economic damage may be stated as deterrent factors in the avoidance of disposal strategies. In addition, recycling a waste material which is normally disposed of in the ground, may have considerable benefits for the industry (Litvak, 2104).

2.5.3 Drill cutting Treatment Approaches

One of the implementations for drilling waste treatment is to allow the soil's naturally occurring microbial population to metabolize, transform, and assimilate waste constituents in place. This waste management approach is considered as both a treatment and a disposal (Onwukwe &

Nwakaudu, 2012). However, a review of the literature indicates that an oil-contaminated drill cutting can be treated and beneficially reused in some cases, which tends to be more sustainable. Various treatment steps are employed to render the cuttings suitable for re-use. Some cuttings are thermally treated to remove the hydrocarbon fractions, moisture content salinity, and clay content, leaving behind a relatively clean, solid material (Ifeadi & MNSE, 2004). Other cuttings are screened or filtered to remove most of the attached liquid mud. From a construction perspective, treated cuttings have been used as fill material, cover materials at landfills, or as aggregate or filler in concrete, brick, or block manufacturing (Mohammed & Cheeseman, 2011). Untreated cuttings are found to be relatively hard to reuse for construction purposes.

Drill cuttings treatment approaches are generally divided into two main methods: Non-biological treatment and Bioremediation technologies. Solidification, stabilization, and thermal treatment, as well as on- and off-site re-injections of cuttings are examples of the Non-biological treatment. A Bioremediation process may be categorized as any method that biologically breaks down contaminated soil into non-toxic residues by using organisms (bacteria, plants, and fungi) or their enzymes. Although there is a possibility of greenhouse gas formation, the Bioremediation process is considered to be one of the most environmentally friendly approaches in the treatment and recycling of drill cuttings. Composting and Biopile-based remediation, Land application, Land spreading, Bioreactors, and Vermiculture may all be included in the most popular methods of Bioremediation process. The rate of Bioremediation as a function of bioremediation environment rests on the composition of the organic pollutants to be degraded and the type of applied treatment method (Ball, Stewart, & Schliephake, 2012).

2.5.4 Drill Cuttings Disposal

On-site and off-site burials compose the two options for disposal of the drill cuttings. Since drilling waste contaminated with hydrocarbons, salts, and heavy metals cannot be disposed of directly, on-site disposal singularly involves re-injection of the synthetic oil-based drill cutting into a disposal well (Ball, 2011; Bernier et al., 2003). There are some limitations in applying the technology. For instance, an appropriate formation with proper properties for burial and control of drilling waste should be available. One of the high-risk consequences of this method is groundwater contamination, which may occur in the disposal wells (Onwukwe & Nwakaudu, 2012). ExxonMobil had a successful experience with on-shore re-injection of the cuttings in Sakhalin Island, Russia (Walker, 2012).

The other approach for disposal of drilling waste is to landfill both treated and untreated cuttings. The landfills designed for drill cutting disposal should meet some requirement to inhibit leaching or evaporating the toxic ingredients of the cuttings. Also, frequent inspection and continuous monitoring of these sites are needed to ensure the performance level. According to adverse health and environmental consequences associated with this type of drill cutting disposal, landfills for drill cutting disposals are considered the last priority of the operators, given concerns that groundwater or soil contamination can cause serious long-term problems, which may become irrecoverable (Bernier et al., 2003; RRC, 2001).

2.5.5 Reuse and Recycling Practices of Drill Cuttings

Potential reuse applications of the cuttings have been suggested in recent years. These suggestions include in-road construction applications that follow research undertaken on the inclusion of drill cuttings in concrete mixtures with an aim toward considering the level of cement substitution (Aboutabikh, Soliman, & El Naggar, 2016). Mostavi, Asadi, and

Ugochukwu (2015) replaced 5, 10, 15, and 20 percent of the cement content of concrete mixtures with oil-contaminated drill cuttings. The study concluded that the comprehensive strength of concrete decreased 20% when cement was replaced up to 20% by the drill cuttings. This comprehended reduction was compensated by using fly ash and silica fume that considerably contributed to the compressive strength. Likewise, Okoh (2105) conducted a study where 10%, 20% and 33% of the cement content of the mixture total weight were balanced out with drill cuttings. Results showed that the specimen met the limits for a sub-base course in road construction and controlled utilization, with only 10% cement content.

Mohammed and Cheeseman (2011) investigated the feasibility of recycling thermally treated drill cuttings in sandcrete. For this purpose, 50% of sand was replaced with treated waste material. The results of the study indicate that while the waste material replacement reduced the density of the sandcrete sample containing drill cuttings, the compressive strength of these samples did not change when compared with the control samples. Although the leaching properties and durability of the samples was not considered in this study, the potential for producing sandcrete with recycled material was firmly detected (Mohammed & Cheeseman, 2011).

Tuncan, Tuncan, and Koyuncu (2000) stabilized the drilling waste aggregate by using 5% cement, 10% fly ash, and 20% lime, in order to apply these as aggregates in a road sub-base. The unconfined compressive strength and bearing capacity ratio, PH, and durability of the stabilized mixtures improved significantly. On the other hand, the electrical conductivity and capacity of cation-exchange dropped. In addition, the leachate test illustrated that the metal concentration fell below the allowed limits. Therefore, the study concluded that the stabilized drill cuttings may be safely applied as a sub-base aggregate (Tuncan, Tuncan, & Koyuncu, 2000). In another study,

Aydilek, Demirkan, Seagren, and Rustagi (2007) examined the feasibility of stabilizing drilling waste aggregates with a high carbon content fly ash (HCCFA). The objective was to utilize the stabilized aggregates in the pavement sub-base. The Leachate test results illustrated that HCCFA could decrease the concentration of naphthalene and o-xylene in the stabilized samples (Aydilek, Demirkan, Seagren, & Rustagi, 2007). Also, Meegoda, Chen, Gunasekera, and Pederson (1998) attempted to fulfill the same objective. The conclusion was that the compaction characteristics of the contaminated soil could be improved, due to the lubricating effect of non-polar organic liquids.

Some studies investigated the possibility of incorporating drill cuttings in hot mix asphalts (HMA). According to the Massachusetts Department of Environmental Quality and Engineering, 5% of hot mix aggregates can be replaced with drilling wastes containing 3% oil, with no significant change in the performance of the hot mix asphalt (Czarnecki, 1988). Also, Meegoda, Ezeldin, Vaccari, and Muller (1993) attempted to produce HMA with petroleum-contaminated soil (PCS). The Marshal Stability Test results indicated that the strength of the PCS improved considerably and that the durability of the PCS was aligned with the control samples. The leachate test confirmed that up to 35% of the total weight of the aggregate in HMA could be replaced with PCS safely and effectively (Meegoda, Ezeldin, Vaccari, & Muller, 1993). Furthermore, Taha et al. (2007) replaced bitumen with oil tank sludge in the asphalt paving material, thereby producing three types of mixes with 3% to 7% of sludge and zero percent bitumen content. Different mixture types involved a) a hot mix in which both aggregates and sludge heated, b) a warm mix that only sludge heated, and c) a cold mix with no heat application. The hot mixture showing 6.5% of oil tank sludge provided the best performance among the

mixes. The produced asphalt mix was able to meet the requirements for both low and medium trafficked pavements (Taha et al., 2007).

Further, drill cuttings may be applied in roads or drilling pads in order to stabilize those surfaces which are exposed to erosion. Oil-based drill cuttings also are able to play a similar role as traditional tar-and-chip road surfacing. However, road spreading usually requires regulatory agency permission (Ball, Stewart, & Schliephake, 2012).

Properly cleaned and treated drill cuttings may be applied as filler material at landfills or as aggregates in bricks (Ball, Stewart, & Schliephake, 2012). Other construction applications include usage in cement manufacturing, bitumen, and asphalt pavements (Dhir, Csetenyi, Dyer, & Smith, 2010). Drill cuttings are also recycled for use as bulk particulate, solid construction materials, or as a major constituent of mixes for making substantially monolithic, specialized, civil engineering concrete structures of a larger size (Clean Earth, 2013).

Another recent application for drill cuttings uses the drill cuttings as a layer in restoring coastal wetlands. The results of several research projects in Louisiana found that well treated drill cuttings can contribute to the growth of wetlands vegetation. Over the next decade, research anticipates a bright perspective awaiting this promising reuse option, which might lead to an extension of this approach to a field scale in the US (Ball, Stewart, & Schliephake, 2012).

In most situations, the reuse or recycle of wastes or byproducts is a desirable practice. In light of the increased focus on duty of care as well as commercial considerations, viable alternatives are sought for the recycling and reuse of large volumes of material from future drilling programs.

2.6 Chemical Composition of Drilling Fluids and Drill Cuttings

2.6.1 Water Based Drilling Fluid (WBF)

A mixture of particulate materials, dissolved salts, and organic compounds in different types of seawater and freshwater produces a suspension which is known as water-based drilling fluid (WBF). The components of WBF are sorted into 18 functional categories, inclusive of weighting materials, viscosity, thinners, alkalinity (additives to control PH), bactericides, filtrates reducer, flocculants, foaming agents, lost circulation material, and pipe freeing agents (National Research Council, 1983; World oil, 1999).

Table 1 represents different types of chemicals which are commonly used in the aforementioned functional categories. Although a huge variety of chemicals are applied to solve the well-drilling related issue, the quantity of different additives in WBFs is relatively small. WBFs mainly consist of barite, which is considered to be a weighting material and salt, which can be found in many of the functional categories (Deeley, 1990). Figure 2.3 indicates the distribution of chemicals in the WBFs.

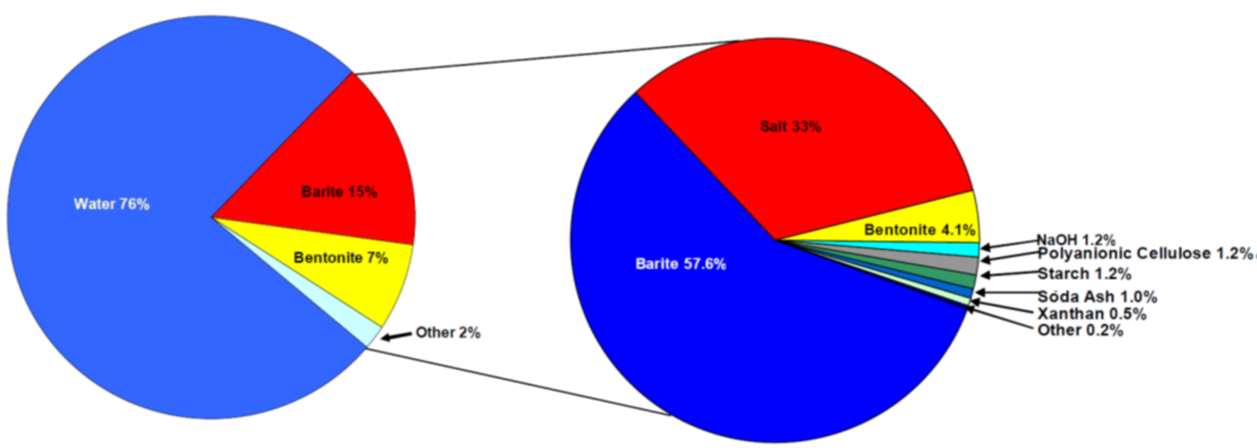


Figure 2.3. Distribution of Chemicals and Additives in the typical WFBs (Deeley, 1990).

Table 2. 1. Functional categories and types of chemical used in WFBs (Deeley, 1990).

Functional Category	Function	Typical Chemicals
Weighting Agents	Increase density (weight) of mud, balancing formation pressure, preventing a blowout	Barite, hematite, calcite, ilmenite
Viscosifiers	Increase viscosity of mud to suspend cuttings and weighting agent in mud	Bentonite or attapulgite clay, carboxymethyl cellulose, & other polymers
Thinners, dispersants, & temperature stability agents	Deflocculate clays to optimize viscosity and gel strength of mud	Tannins, polyphosphates, lignite, ligrosulfonates
Flocculants	Increase viscosity and gel strength of clays or clarify or de-water low-solids muds	Inorganic salts, hydrated lime, gypsum, sodium carbonate and bicarbonate, sodium tetraphosphate, acrylamide-based polymers
Filtrate reducers	Decrease fluid loss to the formation through the filter cake on the wellbore wall	Bentonite clay, lignite, Na-carboxymethyl cellulose, polyacrylate, pregelatinized starch
Alkalinity, pH control additives	Optimize pH and alkalinity of mud, controlling mud properties	Lime (CaO), caustic soda ($NaOH$), soda ash (Na_2CO_3), sodium bicarbonate ($NaHCO_3$), & other acids and bases
Lost circulation materials	Plug leaks in the welbore wall, preventing loss of whole drilling mud to the formation	Nut shells, natural fibrous materials, inorganic solids, and other inert insoluble solids
Lubricants	Reduce torque and drag on the drill string	Oils, synthetic liquids, graphite, surfactants, glycols, glycerin
Shale control materials	Control hydration of shales that causes swelling and dispersion of shale, collapsing the wellbore wall	Soluble calcium and potassium salts, other inorganic salts, and organics such as glycols
Bactericides	Prevent biodegradation of organic additives	Glutaraldehyde and other aldehydes

(Table 2.1 continued)

Emulsifiers & surfactants	Facilitate formation of stable dispersion of insoluble liquids in water phase of mud	Anionic, cationic, or nonionic detergents, soaps, organic acids, and water-based detergents
Defoamers	Reduce mud foaming	Alcohols, silicones, aluminum stearate ($C_{54}H_{105}AlO_6$), alkyl phosphates
Pipe-freeing agents	Prevent pipe from sticking to wellbore wall or free stuck pipe	Detergents, soaps, oils, surfactants
Calcium reducers	Counteract effects of calcium from seawater, cement, formation anhydrites, and gypsum on mud properties	Sodium carbonate and bicarbonate (Na2CO3 & NaHCO3) , sodium hydroxide (NaOH), polyphosphates
Corrosion inhibitors	Prevent corrosion of drill string by formation acids and acid gases	Amines, phosphates, specialty mixtures
Temperature stability agents	Increase stability of mud dispersions, emulsions and rheological properties at high temperatures	Acrylic or sulfonated polymers or copolymers, lignite, lignosulfonate, tannins

In this section, the literature review will discuss the characteristics of the different functional categories represented in Table 2.1.

2.6.1.1 Weighting Agents

Barite, or barium sulfate $BASO_4$, is the most popular type of weighting material used with various types of drilling mud. Normally, barium sulfate is a high density and odorless natural mineral with an outward matte white hue (National Research Council, 1983). To be used as a weighting material, barite must have a minimum specific gravity of 4.2 g/cm^3 and less than 3 % of the whole weight must remain on a 75-µm screen. Furthermore, barite is usually found blended with a variety of minerals such as silica, dolomite, limestone, iron oxide, and some

metal sulfides (API, 1993). Table 2.2 illustrates the concentration of these mineral impurities in a high purity barite.

Table 2. 2. Distribution of Different Minerals in a high purity barite (Nelson, Liu, & Sommers, 1984)

Element	Concentration	Element	Concentration
Barium	503,000	Potassium	350
Iron	1,600	Chromium	599
Sodium	2,920	Copper	6
Zinc	7	Arsenic	1
Calcium	610	Cadmium	0.2
Lead	1	Nickel	3.8
Magnesium	280	Mercury	0.2

Hematite and ilmenite are the most popular alternatives for barite. Hematite, or iron oxide Fe_2O_3, is used to produce high density WBM or OBF for deep drilling applications offshore in the U.S. Regularly, hematite is a high density mineral that can be found as a red powder, usually mixed with quartz, rutile, and pyrite (Chénard, 1984).

According to OSPAR (2004), ilmenite, or iron titanium oxide $FeTiO_3$, is considered to be a low risk substitute for barite, used in drilling mud disposed in the North Sea. The concentration of metal content in ilmenite is lower than barite and the other agents. Spinel, zircon, magnetite, and hematite also can be mentioned as the impurities of Ilmenite.

The amount of barite used in the drilling process varies according to the depth of drilling. Typically, about 6.3 kg/m^3 of barite is added for drilling near the surface and around 2000 kg/m^3

is applied in the proximity of bottom of the well (National Research Council, 1983). By adding barite as a weighting agent, it is feasible to generate a water based drilling fluid (WBF) with the density of 2276 kg/m^3 (Hudgins, 1991). The high density of WBF prevents the possibility of blowups caused by a drilling process in the formation.

2.6.1.2 Viscosifiers

According to Figure 2.3, the second ample substances in the drilling process are bentonite clay and viscosifiers. Bentonite clay produces a gel which suspends and lifts the drill aggregates to the surface. The gel can also inhibit any settling of the drill cuttings and barite ingredients, control the corrosion rate, viscose the drilling assembly, and seal the borehole’s wall to hamper any fluid leak to pervious formations (Growcock & Harvey, 2005).

The clay is usually replaced by polymers, partially or even completely during drilling of shale, which is a soft formation. Using organic polymers such as starch stabilizes the viscosity rate of the mud and induces little or no damage to the soft formation (Darley & Gray, 1988). Further, cellulose polymers such as Carboxymethyl cellulose (CMC) and Hydroxyethyl cellulose (HEC) also can be added to raise the amount of viscosity in the drilling mud (Hudgins, 1991).

Water-soluble polysaccharide polymers such as guar gum and starch are obtained from the plants. These polymers can be applied in a low temperature drilling condition in order to improve the rate of viscosity and to keep mud pumping to the surface. The drill cuttings contaminated by these types of polymers must be treated by biocides to prevent microbial conversion of the polysaccharides. The most popular biocide applied for drill cutting treatment is called Glutaraldehyde (Hudgins, 1991).

2.6.1.3 Thinners and Dispersants

By increasing the well depth, the amount of weighting material required to nullify down-hole pressure would increase drastically. Therefore, when more bentonite and barite are added to WBF, the process raises the viscosity and the required pumping pressure, thus increasing the risk of losing drill cuttings. As a result, the operators usually apply thinners and dispersants to balance the viscosity and pumping pressure. These additives prevent coagulum by reacting with positive charges of clay surface. The most popular thinners used since the 1950s are lignosulfonates, lignites, and tannins (Neff, 2005).

Lignosulfonates are obtained from the wood lignin and can be found as a byproduct in paper industry. A Lignosulfonate complex with cations such as chromium, iron, and calcium serves to negate the charge of the clay surface. In a Lignosulfonate complex, the process must occur at an alkaline PH to prevent a flocculation of the clay. For this purpose, NaOH (sodium hydroxide) is added to WBFs to keep the PH about 10. In addition, lignosulfonates can prevent any infiltration of drilling fluid to the permeable formation (Hudgins, 1991). Mud thinners such as ferrochrome, as well as chrome lignosulfonates, show the best performance and the least toxicity. However chromate, when coupled with chrome lignosulfonates in a high temperature drilling, is considered to be the highest toxic chemicals for use, and therefore are usually replaced with calcium and iron lignosulfonates (Conklin et al., 1983).

2.6.1.4 Other Additives

Various types of additives are applied to enhance the performance of drilling mud by changing its chemical characteristics (Ranney, 1979). The diversity of the additives used in WBF is usually higher than OBF and SBF; the majority of these are not toxic. Typically, these additives are utilized in tiny portions. Small amounts of sulfonated salt of asphalt or Gilsonite is applied to

WBF to prevent infiltration of fluid to the pervious formation. Asphalts are produced during the refining process of crude oil, and mainly contain resins and asphaltenes, which are classified as aromatics.

Various types of lubricants are usually applied to decrease the amount of torque on the drill string, especially during a deviating drilling. Typically, the concentration of lubricants such as diesel fuel and mineral oils is in the range of 5000 to 150000 mg/L. The lubricants should be applied whenever the drill bit becomes stuck in the well. Generally, the OBF pills that contain diesel or mineral oil are used to supply enough viscosity for the drilling process (Neff, 1987). The pills can be recovered later and disposed.

Water-soluble emulsifiers such as fatty acids, sulfonates, and polyoxylates can be added as a dispersing agent to separate the oil from the water phase of the drilling mud (Hudgins, 1991). Some of these additives increase the level of toxicity of drilling fluid. According to Getliff and James (1996), Octylphenol and nonylphenol, toxic degradation products, were replaced with less toxic chemicals during the drilling activities in the North Sea (Getliff & James, 1996).

2.6.1.5 Metals

Table 2.3 illustrates the most popular metal ingredients of drilling muds. Toxic metals such as arsenic, barium, chromium, cadmium, copper, iron, lead, mercury, nickel, and zinc represent the main source of concern regarding the chemical composition of drilling mud. Some of these toxic heavy metals are applied to improve the drilling process, while the rest are considered to be the impurities found in the drilling mud components (Neff, McKelvie, & Ayers, 2000). The amount of these metals can change the level of toxicity in different kind of drilling muds.

Table 2. 3. Range of Concentration of Different Metals in Drilling Muds, Clay-Loam Soils, and Sediments (Neff, 1987)

Metal	**Drilling Muds**	**Clay-Loam Soils**	**Sediments**
Barium	720 – 449,000	150 − 1,500	1 − 2,000
Chromium	0.1 – 5960	20 − 100	36 − 110
Cadmium	0.16 – 54.4	0.01 − 7	0.1 – 0.6
Copper	0.05 – 307	7 − 70	7 −33
Iron	0.002 – 27,000	---	20,000 – 60,000
Mercury	0.017 – 10.4	<0.01 – 0.90	0.03 − 0.14
Lead	0.4 – 4226	<10 – 70	10 − 33
Zinc	0.06 – 12,270	20 − 220	27 − 88
Nickel	3.8 – 19.9	5 − 50	13 − 45
Arsenic	1.8 – 2.3	1.7 − 27	6.9 − 26
Vanadium	14 – 28	---	63 − 238
Aluminum	10,800	---	10,000 – 90,000
Manganese	290 – 400	50 − 2,000	100 – 10,000

As shown in Table 2.3, heavy metals such as barium, chromium, lead, and zinc are the most abundant metal ingredients of drilling mud. In some cases, a high concentration of mercury was found in US, Canadian, and North Sea WBFs and OBFs. The existence of an elevated amount of mercury was accorded to the drilling mud barite contaminated with mercury (Neff, 2002). Since the US EPA (1993) had restricted the allowable amount of mercury in drilling mud planned for ocean disposal, the operators attempted to reduce the environmental impacts of ocean disposal by

using modern drilling technologies, which tended to reduce the required amount of barite during drilling activities (Parker & Smith, 2004). Also, utilizing low-trace-metal barite can contribute to a reduction in the amount of mercury in WBFs (Neff, 2005).

Barium is considered to be the most reliable drill cuttings tracer, due to the high level of concentration. Since barite is not soluble in seawater, it is not considered to be a high hazard waste for the environment. Approximately, all barium comes from barite ($BaSO_4$) which is utilized to raise the unit weight of drilling mud (Trocine & Trefry, 1983; Darley & Gray, 1988). The marine sediments also contain small amounts of barium. Generally, the sediments with a finer grain size contain a lesser amount of barium, when compared with coarse grain sediments (Schenau, Prins, De Lange, & Monnin, 2001).

Generally, a majority of other metals occasionally found in drilling fluids are referred to as impurities of barite, clays and drilling particles. As can be seen in Table 2.4, the concentration of zinc, lead, and iron are higher than the other metals. According to Ansari, Marr, and Coats (2001), barium feldspar, galena, pyrite, sphalerite, quartz, and silicates present the most popular ingredients of commercial barites. The presence of some metals in barite might be due to insoluble sulfide salts (Kramer, Grundy, & Hamer, 1980; Trefry, 1998; Trefry & Smith, 2003).

Table 2. 4. Average Concentration of Metals in Sample of Barite in US and Norwegian Sector of the North Sea (Trefry, Trocine, Metz, & Sisler 1986; Schaanning, Ruus, Bakke, Hylland, & Olsgard, 2002)

Metal	U.S. Barite	Norwegian Barite
Arsenic	2.2	2.0
Cadmium	0.03	0.7
Chromium	11	13.1

(Table 2.4 continued)

Copper	9.7	76.6
Iron	10,100	24,800
Lead	7.8	54.5
Mercury	0.12	0.31
Nickel	NA	1.2
Zinc	8.6	42.9

Also, using a drill collar dope or pipe thread for adding lubricity to a thread and enhancing electrical conduction through the whole pipe can lead to copper, lead, and zinc contamination. Typically, several metallic metals can be found in drill collar dope (Ayers, Sauer, Meek, & Bowers, 1980).

2.6.2 Oil Based Drilling Fluid (OBF)

The chemical composition of OBF is approximately similar to WBF. The most significant difference between these two is the different fluid phases. OBF contains refined petroleum production rather than different types of water such as seawater and freshwater (Bloys et al., 1994). Compared with WBFs, OBFs are superior in several fields, such as lubricity, wellbore stability, formation destruction, deviating drilling, and reuse capacity. The most critical issue that restricts OBF application relates to environmental concerns regarding waste disposal. Therefore, disposal of OBF is very risky and requires complicated and costly cutting-discharge systems (Gudmestad, Zolotukhin, & Jarlsby, 2010). Since the WBFs are not desirable material, and OBFs cannot be disposed of or re-injected due to costly procedures, OBFs are replaced with SBFs.

According to EPA regulations, the SBF can be discharged into federal waters, three miles from the shore (Burke & Veil, 1995).

2.6.3 Synthetic Based Drilling Fluid (SBF)

Due to having less environmental impacts, SBFs are preferred over OBFs. As the name of both drilling muds represent, the main factor differentiate between these two is the fluid phase (Candler, Rushing & Leuterman, 1993; Bloys et al., 1994). Synthetic organic compounds such as ester, olefin, ether, and acetyl are used in the fluid phase of SBFs. Esters, internal olefins, linear-α-olefins are the most popular compounds that are usually utilized in SBFs (Neff, 2005; Gudmestad, Zolotukhin, & Jarlsby, 2010). Table 2.5 indicates the name and chemical composition of different synthetic compounds used in the Gulf of Mexico.

Table 2. 5. Chemical composition of different synthetic compounds in the Gulf of Mexico (Neff, McKelvie, & Ayers, 2000)

Synthetic Chemical Type	**Generic Chemical Structure**
Linear-α-Olefin (LAO)	CH3 - (CH2)n - CH = CH2
Internal Olefin (IO)	CH3 - (CH2)m – CH =CH - (CH2)n - CH3
Ester	$CH_3 - (CH_2)_n - C = O$ \ $O - (CH_2)_m – CH_3$

The typical ingredients of the OBM and SBM include barite, lime, water, clays, calcium chloride, emulsifiers, and lignite. The water-in-organic phase emulsion is formed by dispersion of saline brine into the hydrocarbon phase (Norwegian Oil Industry Association Working Group, 1996). The emulsifiers, such as heavy metal soaps of fatty acids, are used to stabilize this

emulsification process. The amount of emulsifier that is usually added to the SBFs is in the range of 5 to 14 g/L (Chénard, 1984). Lime is also added to stabilize the emulsification of water and the oil. Typical bentonite is replaced with an organophilic clay, which is compliant with the synthetic polymer in the mud. Lignite is usually used in both SBFs and OBFs in order to inhibit the flocculation of clay (Candler, Rushing, & Leuterman, 1993).

2.6.4 Drill Cuttings Characterization

2.6.4.1 Mineralogy of Drill Cuttings

The aggregates generated by the milling action of the auger during earth drilling operations are called drill cuttings (Neff et al., 1987). Grain size distribution of drill cuttings vary from fine graded particles (~ 2 μm) to a coarser aggregate size (larger than 30 mm). Depletion of drilling aggregates from a shale shaker in the Mid-Atlantic continental shelf indicated the cuttings included various types of clays such as montmorillonite, illite, and chlorite, quartz, and small amounts of iron carbonates dolomite (EG&G, Environmental Consultants, 1982). The chemical and physical characteristics of the cuttings are a function of drilled layers and the types of drilling mud. As reported by Westerlund, Kjeilen, and Nordtug (2001), barite and quartz are the most plentiful substances in the drill aggregates of the Beryl A and Ekofisk 2/4A platforms. According to indications, sandstone should be the most probable source of quartz; the existence of barite results from contact with the cuttings and drilling fluid. Among the clay minerals, kaolinite and illite can be found abundantly in the North Sea drill cuttings, as well as the continental shelf of the North Atlantic (Griffin, Windom, & Goldberg, 1968).

2.6.4.2 Separation of Mud from Cuttings

Multiple separation devices are used to separate the drilling fluid from the drill cuttings. Separation is accomplished by a circulation of the mixture of drilling mud, thereby cutting

through the platform devices. Usually the coarse grade drilling aggregates are separated by using a shale shaker; finer sized cuttings that pass through the shale shaker will be introduced to hydrocyclones or on occasion, a decanting centrifuge (National Research Council, 1983). Normally, about 75 % of WBF drill cuttings are separated by the shale shakers on the platform, unless the drilling particles are dominated by clay-sized aggregates (CAPP, 2001). A schematic of the fluid/cuttings separation process is illustrated in Figure 2.4.

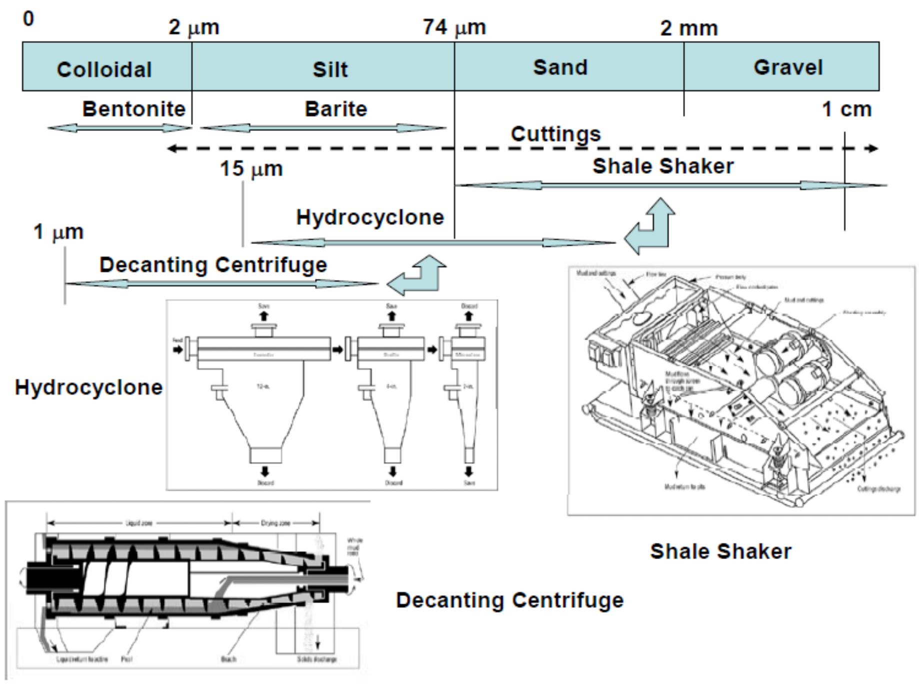


Figure 2.4. Schematic of fluid/cuttings separation process (Neff, 2005)

2.6.4.3 Chemical Characteristics of Drill Cuttings Components

Drilling fluids, drilling aggregates, and formation particles are all major components of the drill cuttings. The particle size of crushed rock in drilled strata controls the measure of drilling mud that remains on the drill cuttings. Compared with fine grade cuttings, the separation of coarser

aggregates from drilling fluid solids is much easier. Typically, after being filtered by the shale shaker on the platform, only 5 to 20 % of drilling mud remains (Neff, 2005).

Generally, the chemical characteristics of drill cuttings depend on the chemical structure of a drilled formation and the amount of drilling fluid ingredients that remain on the cuttings (Augustave, 2014). As reported by Phillips, Evans, Hom, and Clayton (1998), barium was the most abundant metal in the drilling particles discharged to southern California waters. This result can be justified by application of drilling mud. Also, the high concentration of zinc and lead in both platforms can be due to the geochemistry of formation rocks or aggregate contamination with pipe dope. The existence of other metals can be justified with the presence of various minerals in the formation. Table 2.6 represents a concentration of different metals from two different platforms in southern California waters.

Table 2. 6. Concentration of metals in drill cuttings discharged to southern California waters, concentrations are in ppm. (Phillips, Evans, Hom, & Clayton, 1998)

Metal	**Platform 1**		**Platform 2**	
	Drilling Mud	**Cuttings**	**Drilling Mud**	**Cuttings**
Barium	53,900	15,084	12,500	1180
Silver	0.37	0.50	0.39	0.63
Arsenic	10	10	9.3	13
Cadmium	1.17	2.89	1.75	3.62
Chromium	91	104	84	94
Copper	24	70	24	56
Mercury	0.09	0.07	0.06	0.04

(Table 2.6 continued)

Metal	Platform 1		Platform 2	
	Drilling Mud	Cuttings	Drilling Mud	Cuttings
Nickel	39	47	42	17
Lead	23	356	40	32
Zinc	167	664	235	972

In some cases, especially when WBFs are used as the drilling fluid, small amounts of hydrocarbon can be found in the drill cuttings. The source of these hydrocarbons are the spotting fluids, and the additives enhance the mud lubricity. Also, the geochemistry of the strata may play a significant role in controlling the rate of hydrocarbon concentration. Steinhauer, Crecelius, and Steinhauer (1994) investigated the concentration of hydrocarbons in the drill cutting samples mixed with WBFs. The research collected samples from three different depths in the Point Arguello Field in California. The results of the study indicated that the mixture of drill cuttings and WBFs contained hydrocarbons in all three depths. The small amounts of the Total PAH in all three depths proved that the drilled strata was the main source of the PAH (Steinhauer, Crecelius, & Steinhauer, 1994). Table 2.7 illustrates the findings of this research.

Table 2. 7. Hydrocarbon concentration in cuttings/mud mixture from three different depths in the Point Arguello Field in California (Steinhauer, Crecelius, & Steinhauer, 1994)

Chemical	Surface	Mid-well	Bottom	Average
Total Petroleum Hydrocarbons	159 (600)	137 (95)	988 (526)	390 (407)

(Table 2.7 continued)

Chemical	Surface	Mid-well	Bottom	Average
Total PAH	0.87 (2.3)	8.0 (12)	51 (121)	25 (45)
Naphthalenes	0.27 (1.2)	5.4 (8.9)	39 (96)	18 (35)
Fluorenes	ND (ND)	0.38 (0.35)	4.1 (8.2)	2.8
Phenanthrenes	0.34 (0.79)	0.94 (0.64)	4.5 (9.3)	2.8 (3.6)
Dibenzothiophenes	0.03 (ND)	0.71 (0.40)	3.9 (8.1)	1.9 (2.8)

2.7 Portland Cement Concrete and Recycling

Concrete is a cement based composite material consisting of coarse and fine aggregates, Portland cement, water, and chemical additives in an appropriate proportion (Brandt, 2009). Due to the safeness of concrete as a flexible design material, as well as its fire resistance and load carrying ability, concrete is the currently the most popular construction material (McGregor, 1997; Cement and Concrete Institute Australia, 2008; Bhattacharjee, 2010). Cement, as one of the most important components of concrete, plays a significant role in the determination of the mechanical properties of the concrete. Typically, 60 to 75 percent of the total volume of concrete consists of sand and gravel aggregates. According to the higher cost of cement, those concretes that are composed of more aggregates are considered to be more economical as composite materials (Kuruppu & Chandratilake, 2012).

Natural resources provide most of the aggregates used for concrete pouring. In the use of concrete, an increased demand calls for more natural resource consumption. In addition, cement production not only requires the consumption of much energy, but also causes a heavy environmental impact due to CO_2 emissions. According to Maier and Durham (2011), 70 billion

tons of cement produced in US in 2009 also resulted in the emission of 1 million tons of carbon dioxide. Therefore, the builders and researchers are investigating the feasibility of a partial replacement of concrete components with different types of material in order to enhance sustainability (Sadiq & Khattak, 2015). According to Limbachiya, Leelawat, and Dhir (2000), waste material, including concrete wastes, may be considered a valuable source of aggregates for cement based composites.

Since recycling different waste materials in concrete application has become a common practice, the mechanical and chemical characteristics of the recycled materials should be investigated. According to Watson (2005), a combination of material types, coupled with pouring and curing skills, determines the quality of a concrete. Orchard (1962) stated that the fundamental characteristics of concrete are elasticity, compressive strength, shrinkage, and permeability. One of the factors that directly affects concrete properties is the aggregate content (Neville, 1995). Arum and Olotuah (2006) mentioned that the characteristics of an aggregate can play a significant role in determination in the strength, density, thermal properties, and durability of concrete. The aggregate size can influence the compressive strength of the concrete indirectly. By increasing the nominal maximum size of the aggregate, the target workability can be reached with a lower water/cement ratio. This in turn can increase the compressive strength of the concrete by retaining the same workability (Kong & Evans, 2013). Furthermore, the shape of the aggregate can also affect the compressive strength of the concrete. Compared with round shape aggregates, angular and irregular aggregates require a higher water/cement ratio to reach a given workability. This can result in a lower compressive strength in the use of coarse, flaky aggregates. In this regard, flakiness in fine aggregate can bring about segregation and bleeding, which results in a drastic decrease in the amount of compressive strength (Kaplan, 1958; Neville,

1981; Raheem & Aderounmu, 2002). In the past, natural resources supplied approximately all of the aggregate and material utilized in concrete applications. However, the last decades brought an increased tendency among researchers and industry stakeholders toward producing an environmentally and economically sustainable product (Kuruppu & Chandratilake, 2012).

2.7.1 Unconventional Aggregates Used in Concrete

The utilization of unconventional aggregates in concrete applications is widely accepted according to economic and environmental considerations. Partial replacement of virgin aggregates with waste material benefits both quarrying and waste management systems (Oikonomou, 2005). The Cement and Concrete Institute Australia (2008) reported that lack of virgin aggregate for concrete production is a critical issue. On the other hand, a large quantity of demolished concretes has increased the amount of waste production. Hence, reuse and recycling waste aggregates may aid in solving the environmental issues caused by the concrete industry. The unconventional aggregates used in producing concrete may be sorted into three categories: manufactured aggregates, recycled aggregates, and reused by-product aggregates (Cement and Concrete Institute Australia, 2008). Table 2.8 illustrates different types of alternative aggregates used in concrete.

Table 2. 8. Unconventional aggregates in concrete applications (Kuruppu & Chandratilake, 2012; Dash, Patro, & Rath, 2016)

Type of aggregate		
Recycled Aggregates	**Reused by-product Aggregates**	**Manufactured Aggregates**
Recycled concrete aggregate (RAC)	Air cooled (BFS)	Foam Blast Furnace Slag
Recycled Concrete and Masonry	Granulated BFS	Fly Ash

(Table 2.8 continued)

Type of aggregate		
Recycled Aggregates	**Reused by-product Aggregates**	**Manufactured Aggregates**
Reclaimed Aggregate	Electric arc furnace slag	Polystyrene
Reclaimed Asphalt Pavement (RAP)	Steel Furnace Slag	Expanded clays
Reclaimed Asphalt Aggregate	Copper Slag	Shale and slates
Glass Cullet	ISF Slag	_
Scrap Tyres	Fly Ash	_
Drill Cuttings	Bottom Ash	_
_	Organic Material	_
_	Waste Foundry Sand	_
_	Palm Oil clinker (POC)	_
_	Wood Waste Ash	_
_	Drill Cuttings	_

2.8 Studies on Incorporation of Waste Material in Concrete

Researchers have evaluated the physical and mechanical properties of the concretes made by different types of waste materials, recycled aggregates, and manufactured aggregates. In most cases, the chemical composition of alternative aggregates is appraised to trace the variations in mechanical properties of the recycled concrete samples. In addition, investigators assessed the microstructure of the waste-based concretes to compare the microstructures with the control

concrete samples (Dash, Patro, & Rath, 2016). This part of the literature review will cover some of these studies.

2.8.1 Evaluation of Partial Replacement of Fine Aggregates with Waste Foundry Sand

Foundry sand is obtained from the casting industry, where the thermal conductivity of sand allows a beneficial moulding material. The foundry sands are classified based on the binder type utilized in the casting process. Clay bonded sand or green sand, as well as chemically bonded sands are two common types of foundry sands (Siddique, Kaur, & Rajor, 2010; Basar & Aksoy, 2012). Figure 2.5 indicates the wastes of foundry sand dumped along the highway. Many researchers have partially replaced the fine aggregates of concrete with waste foundry sand. Prabhu, Hyun and Kim (2014) replaced the fine aggregates with 10%, 20%, 30%, 40%, and 50% of waste foundry sand. According to these researchers, the compressive strength results were not improved in the concrete samples containing waste foundry sand. Although the mechanical performance of concrete samples containing 20% of alternative aggregate was similarly close to control samples, the compressive strength decreased in the samples with more than 20% of WFS. This reduction amount in compressive strength can be justified, due to the small size of the WFS aggregates that not only reduces workability, but also reduces the compressive strength as a consequence. An empirical equation suggested by Prabhu, Hyun and Kim (2014) suggested an evaluation of the dynamic modulus of the WFS based concrete as follows:

$$E = \frac{\rho(1+\mu)(1-2\mu)}{1-\mu} \times V^2$$

Where E is the dynamic modulus of elasticity (Mpa), ρ is the density (Kg/m^3), V is the velocity of ultrasonic wave in m/s, and μ is the poison ratio of the concrete. No significant changes are

observed in the dynamic modulus of elasticity of WFS based concrete, when compared with the control samples, (Prabhu, Hyun, & Kim, 2014).

Figure 2. 5. The foundry sand waste dumped along the highway

Basar and Aksoy (2012) conducted another study to evaluate the effects of reusing waste foundry sand in ready-mix concrete, in which the normal sand was substituted with 10%, 20%, 30%, and 40% of stabilized WFS. According to Basar and Aksoy (2012), waste foundry sand can be used as a substitute for the regular sand aggregates. However, the study found that an increase beyond 20% of the replacement level can cause a significant drop in the compressive strength of the WFS based mixtures. This decrement was justified due to a higher surface area of finer contents that disturbed the formation of water-cement paste. Furthermore, the estimation of the modulus of elasticity by empirical formulation confirmed that mixtures containing WFS are lower than mixes with normal aggregate. In addition, the morphological and compositional analysis of the samples with 20% WFS by SEM and EDS indicated no significant difference when compared with the control mixes (Basar & Aksoy, 2012). Figure 2.6 and 2.7 indicate the SEM photo and EDS spectra of the mixture with 20% WFS and the normal concrete.

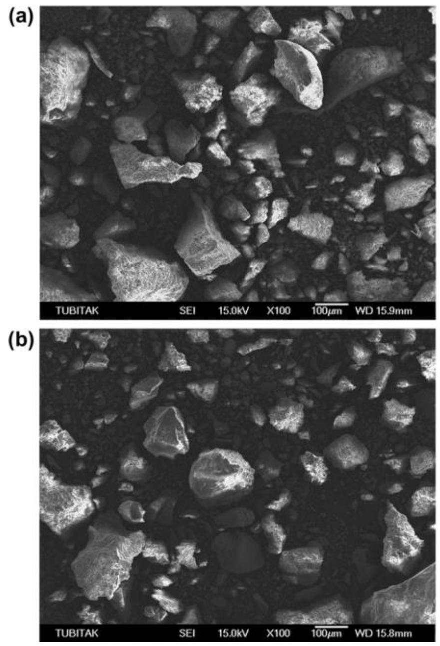


Figure 2. 6. SEM Pictures of (a) Control Sample and (b) mixtures contained 20% WFS (Basar & Aksoy, 2012)

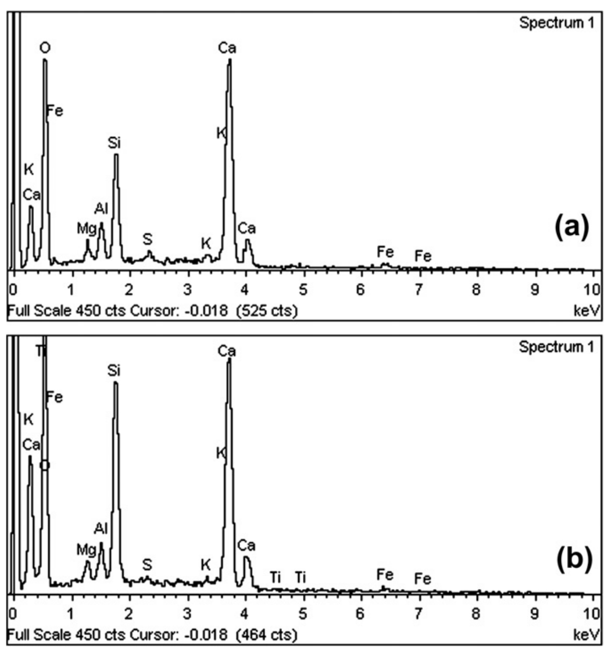


Figure 2.7. EDS spectra of (a) Control Sample and (b) mixtures containing 20% WFS (Basar & Aksoy, 2012)

On the other hand, the results of a study conducted by Singh and Siddique (2012) conflicted with the previous studies. The researchers accomplished an experimental investigation in the utilization of waste foundry sand by replacing the virgin sand with WFS in five different percentages (0% which was control mix, 5%, 10%, 15%, and 20%). The study reported that the replacement of 15% of fine aggregates resulted in a significant increase in the mechanical properties of WFS based concrete, such as compressive strength, splitting tensile strength, a modulus of elasticity, and abrasion resistance. With respect to these results, the 28 days of compressive strength of mixes with a target strength of 40 Mpa were improved up to 17% by replacing 15% of virgin aggregate (Singh & Siddique, 2012).

2.8.2 Evaluation of Partial Replacement of Fine and Coarse Aggregates with Steel Slag

Steel slag is a by-product of the steel production industry. This non-metallic material necessarily contains calcium silicates incorporated with fused iron oxide, magnesium, manganese, calcium, and aluminum (Rajan, 2014). Due to having less pozzolanic activity, electric arc furnace steel slag is not an appropriate substance to be used in production (Qasrawi, Shalabi, & Asi, 2009). Devi and Gnanavel (2014) conducted a research to examine the feasibility of producing a concrete with steel slag by utilizing steel slag as a substituent of fine and coarse aggregates through six different replacement schemes (0%, 10%, 20%, 30%, 40%, and 50%). According to compressive strength test results, the optimized percentage of replacement was 40% for fine aggregate and 30% for coarse aggregate. Furthermore, research concluded that some other properties of steel slag concretes, such as tensile and flexural strength, was improved significantly. The comparison between the mechanical properties of steel slag-based mixtures and the normal control sample is indicated in Figure 2.8. In addition, the acid resistivity of both 40% fine aggregate replacement and 30% coarse aggregate replacement was improved when

compared with the control samples. The research found that when samples with partial replacement are immersed in hydrochloric acid, the amount of weight loss is lower, compared to sulphuric acid immersion. Figure 2.9 indicates the texture of the concrete samples after immersion in Hcl and H_2SO_4 (Devi & Gnanavel, 2014).

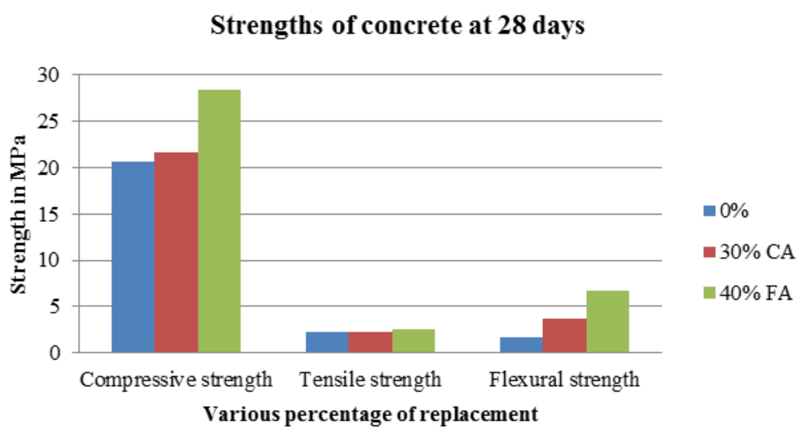


Figure 2. 8. Mechanical properties of the normal concrete mixtures and steel slag-based mixtures (Devi & Gnanavel, 2014)

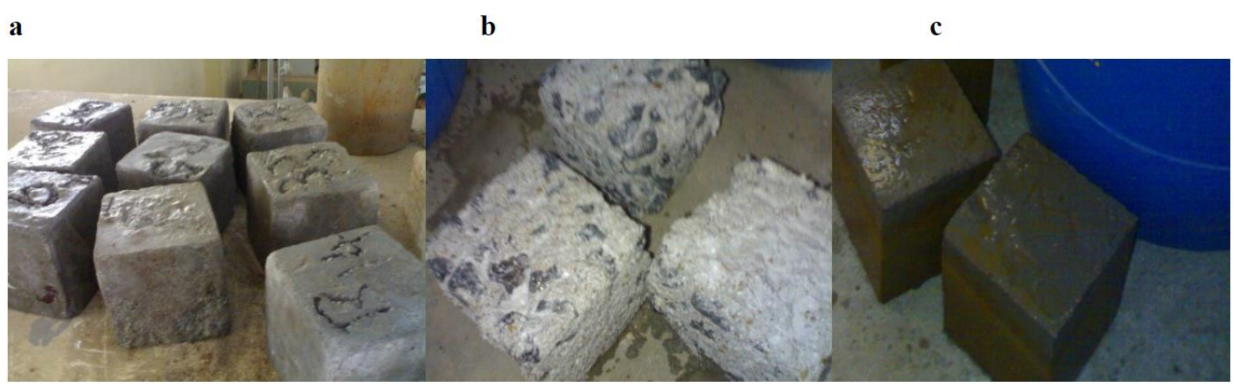


Figure 2. 9. Concrete Samples (a) before immersing in acid (b) After immersing in H2SO4 (c) After immersing in Hcl (Devi & Gnanavel, 2014)

In another research conducted by Qasrawi, Shalabi, and Asi (2009), different percentages (0%, 15%, 30%, 50%, and 100%) of low CaO steel slag produced waste-based mixtures. The study

used different amounts of steel slag rather than natural sand aggregates. The results indicated that the compressive and tensile strength of the slag contained mixtures improved in some replacement ratios. In terms of compressive strength, the slag-based concretes containing 30% of steel slag displayed the best performance. Also, a 50% replacement was found to be the optimal proportion of steel slag to improve the tensile strength of the concrete. Indeed, the high angularity steel slag aggregate increased bonding strength between the cement paste and aggregates in the concrete. Figure 2.10 indicates the variations of compressive strength through different replacement schemes. Although utilization of steel slag improved the mechanical properties of hardened mixtures, the workability of fresh concrete dropped significantly, especially where the replacement levels exceeded 50%. Replacing the natural sand with the finer aggregates that display a high angularity is considered to be the justification of the workability decrement (Qasrawi, et al., 2009).

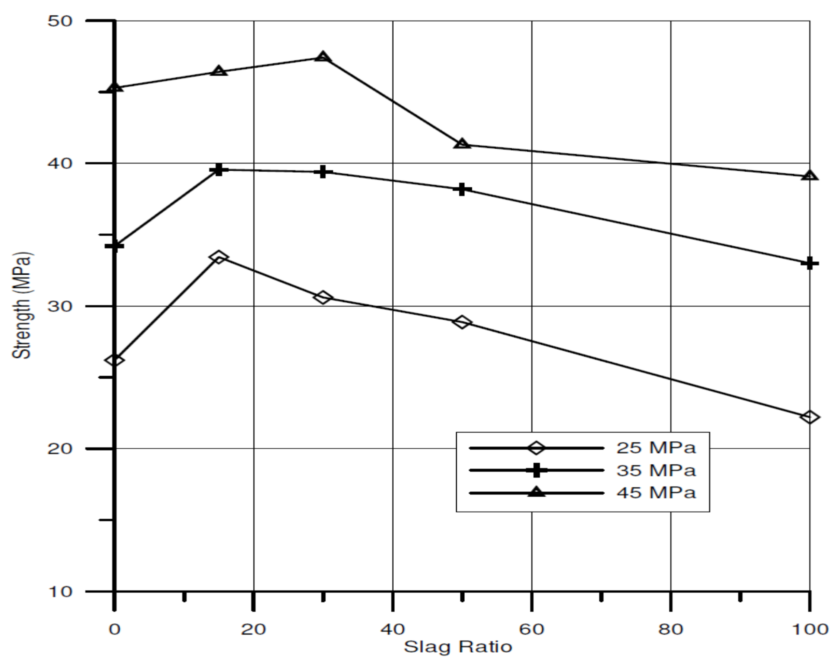


Figure 2. 10. Variation of compressive strength according to different steel slag ratios (Qasrawi, et al., 2009).

2.8.3 Evaluation of Partial Replacement of Fine Aggregates with Granulated Blast Furnace Slag

Granulated blast furnace slag (GBFS), the waste of the pig iron manufacturing process, results from a rapid cooling of the melted slag from a blast furnace. The chemical reactivity of the granulated blast furnace slag (GBFS) becomes an important factor in evaluating the productiveness of GBFS in cement-based mixtures (Pal, Mukherjee, & Pathak, 2003). Yüksel, Özkan, and Bilir (2006) prepared two sets of concrete mixtures so that the fine aggregate size in the first mixture was 0-7 mm, while the second set of concrete mixtures contained both 0-3 mm and 0-7 mm sand aggregates. In both sets, the natural sand was a substitute for the non-ground GBFS in five different percentages (0% which is control mixture, 25%, 50%, 75%, and 100%). Generally the second group, which contained finer sands, also performed better in terms of compressive strength and flexural strength. Yüksel et al. (2006) reported that increasing the percentages of replacement reduced the compressive strength of the GBFS mixtures, whereas the compressive strength of control sample, 25%, 50%, 75%, and 100% mixtures was 15.47 MPa, 14.83 MPa, 12.24 MPa, 10.92 MPa, and 9.66 MPa, respectively. In addition, based on the rapid chloride permeability test results, the chloride permeability of the GBFS contained samples reduced in comparison with the control mixtures, where the chloride permeability of the control concrete samples and replacement mixtures was found to be moderate and low, respectively. Although utilization of GFBS did reduce the amount of compressive strength and changed some physical and chemical characteristics of the concrete samples, Yüksel et al., 2006 concluded that non-ground granulated blast furnace slag may be utilized as a substitute for natural aggregates (Yüksel et al., 2006).

In further research, Valcuende, Benito, Parra, and Miñano (2015) used ground granulated furnace blast slag to produce a self-compacting concrete (SCC). The main objective of the

research was to investigate the variation of compressive strength and total shrinkage, based on the partial replacement of the sand aggregates with ground GFBS. Therefore, seven GFBS/Sand ratios (0%, 10%, 20%, 30%, 40%, 50%, 60%) were used as the replacement schemes. The results indicated that the difference between the mixtures was not statistically significant, but the compressive strength tended to reduce at early ages, such as seven days. On the other hand, the compressive strength trend in the samples with more advanced ages increased according to the increment of the GFBS replacement ratio. Table 2.9 represents the variation of compressive strength in different ages. In fact, this may be due to the long-term reactivity of slags that formed CSH around the aggregates, thus making a denser particle-paste interface, which resulted in a better particle-paste bonding. Figure 2.11 depicts the interface of slag and concrete paste at 120 days by using the SEM (Valcuende et al., 2015). Furthermore, the process evaluated the drying shrinkage of the mixtures and compared the results with one another. The research found that due to the higher porosity of the GFBS contained samples, the samples tended to lose water more quickly. Therefore, when the study utilized higher amounts of GFBS in the mixtures, the drying shrinkage increased considerably. Based on results, the drying shrinkage of the sample containing 60% GFBS was increased by 44% when compared with the control sample (Valcuende et al., 2015).

Table 2. 9. The Compressive Strength of different mixtures in MPa (Valcuende et al., 2015)

Mix ID	**Compressive Strength**			
	Age			
	7 days	**28 days**	**90 days**	**365 days**
SCC-0%	33	39.2	46.7	49.6
SCC-10%	31	38.9	46.5	49.2

(Table 2.9 Continued)

Mix ID	**Compressive Strength**			
	Age			
	7 days	**28 days**	**90 days**	**365 days**
SCC-20%	34	38.7	46.7	49.7
SCC-30%	32.8	39.2	47.5	51.1
SCC-40%	31.2	38.9	45.5	50.9
SCC-50%	31.3	38.2	48.7	51.8
SCC-60%	29.9	38.7	47.6	52.3

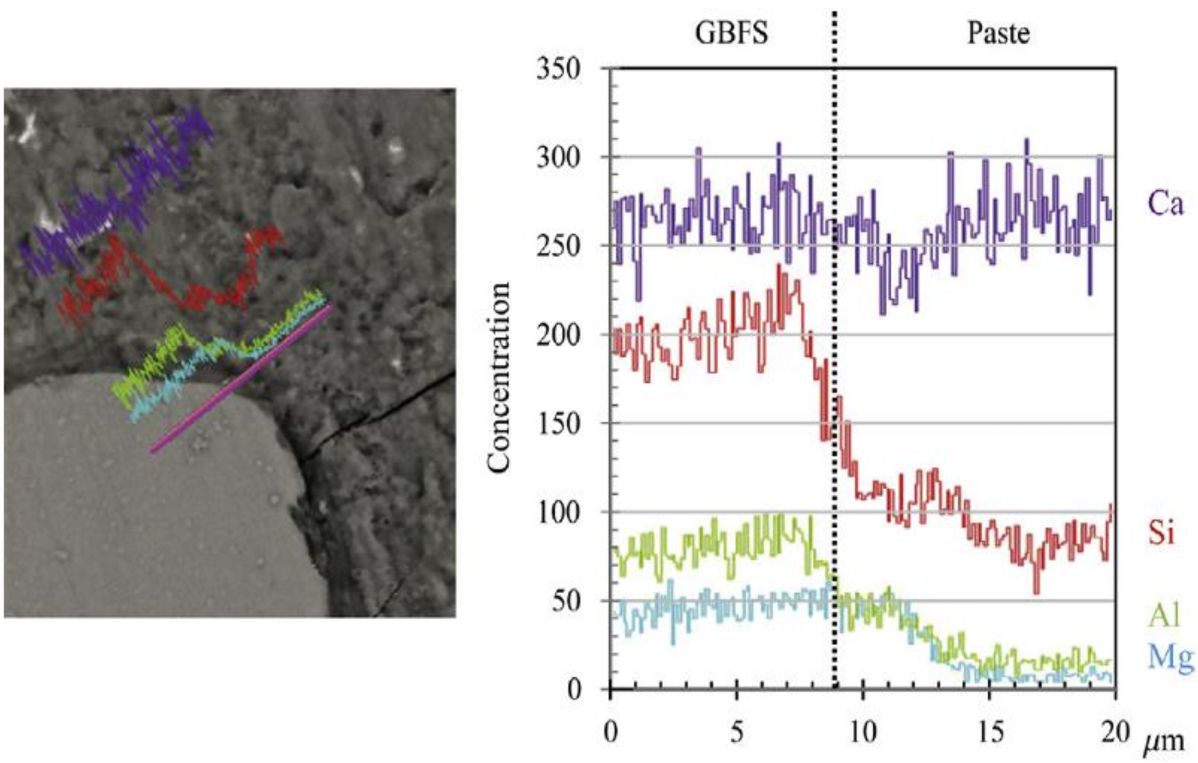


Figure 2. 11. SEM photograph of Chemical elements and slag-paste interface at 120 days (Valcuende et al., 2015)

2.8.4 Evaluation of Partial Replacement of Cement with Drill Cuttings

Drill cuttings are the hazardous waste of drilling activities that are usually discharged into the oceans. The increasing amount of drilling waste disturbs the balance of the marine ecosystem. A sample of this waste is illustrated in Figure 2.12.

Figure 2. 12. Drill cuttings (Mostavi, Asadi, & Ugochukwu, 2015)

Mostavi, Asadi, and Ugochukwu (2015) evaluated the partial replacement of cement with drill cuttings by investigating the preliminary stage at the level of cutting toxicity, where the drill cutting was classified as a non-hazardous by-product (Mostavi, et al., 2015). The researchers then replaced 5, 10, 15, 20, and 25 percent of the cement with drilling waste aggregates. The results indicated that by replacing different amounts of cement with drill cuttings. The study achieved a reduced amount of compressive strength. Since a steep drop in compressive strength existed when the replacement level exceeded 20%, the optimum percentage of replacing cement with the drill cuttings was considered to be 20 percent. Furthermore, the mixes contained 20% of drill cuttings, doped with different percentages of silica fumes and fly ash to monitor possible improvements in compressive strength. The results, when 7.5% of silica fume and fly ash were added simultaneously, improved the compressive strength by 40 percent. Overall, the study

concluded that a combination of drill cuttings and additives, such as fly and silica fumes, can enhance the compressive strength of concrete (Mostavi, et al., 2015).

2.8.5 Evaluation of Partial Replacement of Aggregates with Recycled Waste Glass

The amount of waste glass generated in large cities, causes major economic and environmental impacts (Chesner, 1992). Therefore, waste glass recycling has become a critical problem on a global scope. An amorphous characteristic, together with large amounts of silicon and calcium, made waste glass an attractive alternative material for the concrete production industry. Also, by considering the pozzolanic or cementitious properties, as well as the potential for replacing cement in a concrete mixture, glass could become a more valuable waste (Dyer & Dhir, 2001). Polley, Cramer, and Cruz (1998) conducted a research to investigate the effects of utilizing municipal glass waste as a concrete aggregate to produce a more sustainable concrete. Various gradations (fine and coarse) of glass in different percentages from 0 to 90% were used. Based on the results of partial replacement of the natural sand, a 20% replacement was found to be the optimum amount of fine glass to be used, rather than fine aggregates. Also, the research concluded that an incorporation of coarser glass aggregates (> 1.5 mm) could result in low compressive strength, due to high frangibility and poor surface properties. In addition, the durability of concrete mixtures containing higher amounts of waste glass was slightly lower than the reference mixes. The most critical problem concerning the mixtures produced with recycled glass was the potential of alkali silica reactivity, due to a high concentration of silica. Therefore, the study attempted to mitigate the adverse effects of alkali silica reactivity by adding different amounts of fly ash to mixtures. Overall, Polley et al. (1998) concluded that waste glass may be used as a substituent material in concrete mixtures. However, a more in-depth knowledge regarding the characteristics of cement-paste and waste glass interface was required.

Another research conducted by Corinaldesi, Gnappi, Moriconi, and Montenero (2005) investigated the feasibility of utilizing waste glass obtained from crushed containers and building destruction in mortar mixtures. Therefore, a total of seven mixtures (one control mix with natural aggregates, three mixes containing 30% waste glass with three different particle size distributions, and three mixes containing 70% waste glass with three different particle size distributions) were prepared. The finest waste glass aggregates with a maximum particle size of 36 μm were labeled "A," the medium size glasses ranging from 36 μm to 50 μm were labeled "B," and the waste glass particles with a maximum aggregate size of 100 μm were labeled "C." The study tested the mechanical properties of the mortar specimens after 180 days of curing. Results indicated that regardless of grading and replacement percentages, both the compressive and flexural strengths of the mixes containing waste glass improved significantly, compared with the referenced mortars. Figure 2.13 depicts the results of compressive strength and flexural strength in different mortars, where the first letter represents a type of gradation, and the following number indicates the percentage of replacement.

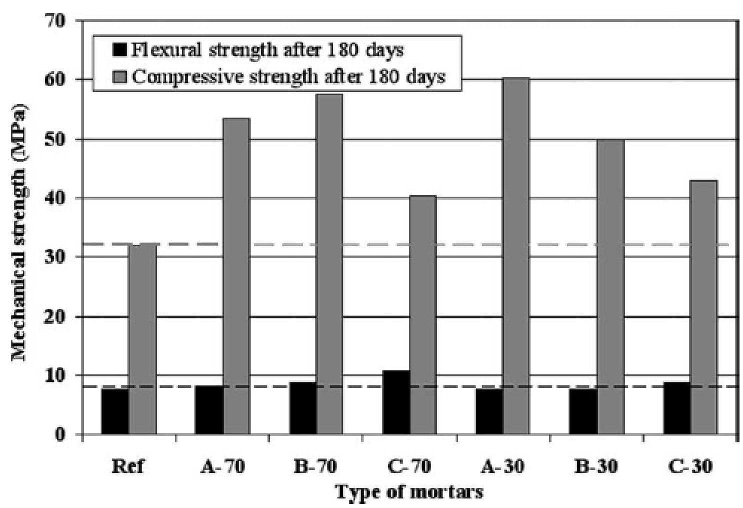


Figure 2. 13 Compressive and flexural strength of mortars in MPa (Corinaldesi et al., 2005)

Furthermore, the research evaluated the microstructure of the mortars to investigate the reason for strength improvement. The SEM photograph indicated that the mortar mixtures containing waste glass was considerably denser than the reference mixes (Corinaldesi et al., 2005). Figure 2.14 compares the SEM picture of the reference mix with the mixes containing 70% waste glass.

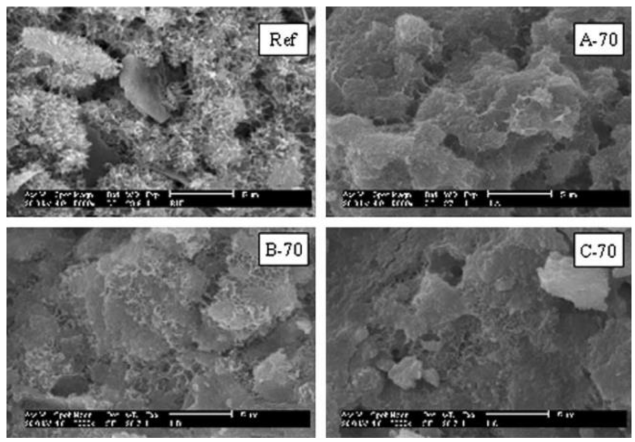
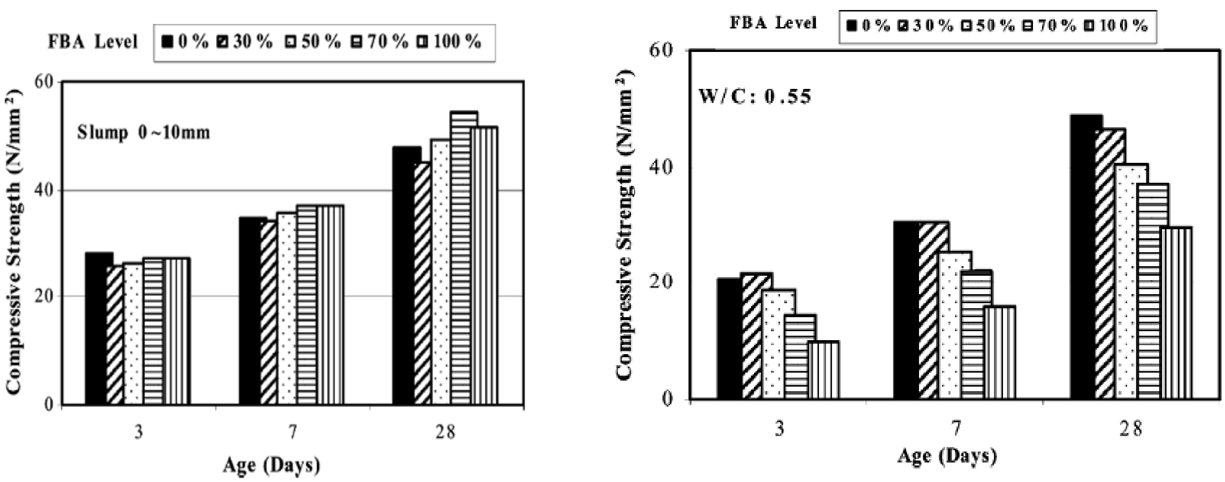


Figure 2. 14. SEM pictures of different mortar specimens (Corinaldesi et al., 2005)

2.8.6 Evaluation of Partial Replacement of Fine Aggregates with Furnace Bottom Ash

Furnace bottom ash is the by-product of a thermal power plant that is derived from residues of coal incineration in the furnaces. Since the furnace bottom ash (FBA) has no pozzolanic character, there is no point to use FBA as the substituent of cement material. On the contrary, the particle size distribution of FBA makes for an attractive alternative to natural sand (Dash et al., 2016). Therefore, many researchers attempt to use this waste material as concrete fine aggregates, in order to improve environmental and economic sustainability in the concrete industry. Bai, Darcy, and Basheer (2005) evaluated the influence of using bottom ash as a natural aggregate in concrete. The researchers investigated the compressive strength and shrinkage of the mixtures by means of a partial replacement (0% or reference concrete, 30%, 50%, 70%) of sand with furnace bottom ash. For this purpose, two different types of mixes were designed,

where the study (i) maintained the waster/cement ratio as a constant, and (ii) fixed the amount of workability. The results demonstrated that in the mixes with a constant water/cement ratio, both the compressive strength and the drying shrinkage continued to drop as the percentage of FBA replacement increased. As a result, the amount of compressive strength decrement was significant when the replacement level exceeded 30%. On the other hand, at a constant slump, the compressive strength of the concrete specimens containing FBA were slightly improved, when compared with the referenced concrete; however, the drying shrinkage was increased, especially when the FBA content exceeded 30%. Figure 2.14 illustrates the compressive strength of the different concrete samples. Overall, Bai et al. (2005) concluded that 30% of normal sand can be replaced with furnace bottom ash to make a concrete with no deleterious effects on permeability and drying shrinkage characteristics of the mixture.



(a) **(b)**

Figure 2. 15 Compressive strength at (a) constant slump and (b) constant W/C ratio (Bai et al., 2005)

In another study conducted by Yüksel, Bilir, and Özkan (2007), the effects of replacing fine aggregates with granulated blast furnace slag (GBFS) and furnace bottom ash (FBA) were

evaluated in terms of durability characteristics of the concrete. Therefore, five percentages (10%, 20%, 30%, 40%, 50%) of fine aggregate replacement were accomplished by using GBFS, FBA, and a mixture of the two (GBFS +FBA). According to results, the concrete mixtures containing GBFS and/or FBA were influenced by high temperature effects. Yet the extent of distress in these mixes showed a reduction, when compared with the control sample. Figure 2.15 confirms that the quantity of surface cracks decreased in the concrete samples containing 40% of GBFS and 40% of FBA. Furthermore, the amount of compressive strength dropped due to a freeze-thaw cycle, which showed a reduction after replacing 10-30% of sand aggregates with GBFS and/or FBA. An increase in the replacement percentage beyond 30% allowed the compressive strength loss to increase. Hence, up to 30% replacement of sand with alternative aggregates can enhance the durability of the concrete. Both GBFS and FBA increased the porosity of the concrete. The level of increment becomes higher when the FBA is applied separately. Therefore, the control sample had a denser microstructure, compared with the other groups of mixtures. Figure 2.16 compares the porosity of two different mixes with the control. All in all, Yüksel et al. (2007) concluded that it is possible to produce a durable concrete by using furnace bottom ash and granulated blast furnace slag.

Figure 2. 16. The amount of surface crack at (a) control sample, (b) concrete containing 40% GBFS, (c) concrete containing 40% FBA (Yüksel et al., 2007)

2.9 Controlled Low Strength Material (CLSM) and Recycled Materials

From a sustainability standpoint, and based on the above review, it is important to develop further construction materials that incorporate waste materials. Finding more uses for by-products can help reduce the disposal in landfills, and conserve the consumption of natural aggregates. One of the possible construction applications where waste material can be utilized is in CLSM mixtures.

The components of CLSM incorporate cementitious-binder material, aggregates, water, and additives. Cement is used in a limited quantity and provides the cohesion and strength for CLSM. Portland cement types I and II are commonly used, according to ASTM C 150. CLSMs can be used in a variety of applications, including backfills, structural fills, pavement bases, conduit beddings, and void fillings (López-Uceda et al., 2016). Materials used in the production of CLSM are usually the same as those used in traditional concrete; however, the mix proportion is different, since the strength of CLSM is much less than that of traditional concrete. CLSMs can also incorporate supplementary cementing materials, such as high-calcium fly ash and can co-generate products such as cement kiln dust (Lachemi, Şahmaran, Hossain, Lotfy, & Shehata, 2010).

The strength of CLSMs varies, depending on the application. For back-fills with possible future excavation such as some utility fills, the 28-day strength does not exceed 300 psi. For road bases and structural fills, such as foundation support above weak or uneven soil, the required compressive strength can reach 1,200 psi. The upper limit of 1,200 psi allows use of this material for applications where future excavation is unlikely, such as a structural fill under buildings (Etxeberria, Ainchil, Pérez, & González, 2013). Low density CLSM describes a material with

distinctive properties and mixing procedures. Future CLSM mixtures may be developed as anti-corrosion fills, thermal fills, and durable pavement bases.

2.10 Studies on Incorporation of Waste Material in CLSM

In the following section, the literature regarding the use of waste material as controlled low strength material will be reviewed to evaluate the feasibility of utilizing different kinds of waste material as the substituent of normal aggregates in CLSM.

2.10.1 Evaluation of Using Recycled Fine Aggregates in CLSM

Concrete, asphalt, brick, and ceramic are the most abundant materials that may be found in construction and destruction waste (Xing, Fraaij, Pietersen, Rem, & Van Dijk, 2004). Approximately half of these waste materials usually consist of fine aggregates. Using these materials as fine aggregates in controlled low strength material could be an appropriate alternative. A study by Etxeberria, Ainchil, Pérez, and González (2013) examined the usage of recycled aggregates received from a recycling plant in Barcelona. The aggregates were composed of 25–35% ceramic, 30–45% concrete, and 15–25% of raw aggregates. The rest was impurities, such as asphalt (2-17%) and gypsum (0-1.5%). The chemical structure of recycled aggregates, dominated by the presence of silica and aluminum, is represented in Table 2.10.

Table 2.10. Chemical structure of Recycled Aggregate (Etxeberria et al., 2013)

Type of aggregate	**Chemical Composition %**									
	Fe_2O_3	**MnO**	**TiO_2**	**CaO**	**K_2O**	**P_2O_5**	**SiO_2**	**AL_2O_3**	**MgO**	**Na_2O**
Recycled Aggregate	3.28	0.06	0.33	20.21	2.41	0.10	57.43	10.85	2.65	1.63

The natural aggregates are replaced with recycled aggregates in five different natural-aggregate/recycled-aggregate ratios (20%, 30%, 40%, 50%, and 100%). The properties, such as porosity, absorption, compressive strength, bleeding, and penetration of the new mixes were tested. According to the results when the amount of recycled aggregates exceeded 30%, the target compressive strength dropped drastically, especially in a 100% replacement. Therefore, the researchers changed the water/cement ratio by increasing the amount of cement in order to improve the compressive strength, yet still keeping the identical flowability. In the mixes containing high amounts of recycled aggregates, a significant compressive strength improvement occurred in the 28 days, compared with 7 days. This can be justified by the higher concentration of ceramic in those mixes containing higher amounts of recycled aggregates. The pozzolanic property of ceramic can cause a higher long-term strength. Overall, Etxeberria et al. (2013) concluded that up to 30% of natural aggregates may be replaced successfully by recycled aggregates with no significant change in the properties of the controlled low-strength material; however, by increasing the cement content, a 100% replacement also produced acceptable results (Etxeberria et al., 2013).

2.10.2 Evaluation of Using Cement kiln Dust and fly ash in CLSM

Cement kiln dust is the powder-like waste of cement production process in the rotative furnaces. The dusts are collected by an air-pollution control system. Usually the final destination of these material is landfill. The U.S. Environmental Agency (1993) reported the amount of cement kiln dust annually generated in the United States is about 12.9 million tons. The chemical characteristics of the cement kiln dust (CKD) are not constant and usually depend on various factors such as virgin materials, dust collection technology, furnace design, and type of fuel. According to lower concentration of oxides in CKD compared with Portland cement and fly ash,

less pozzolanic properties is considered for cement kiln dust. However, existence of silica and lime can enhance the cementitious properties of the CKD (ZHU, Zaman, & Laguros, 1999). A study conducted by Pierce, Tripathi, and Brown (2003) to evaluate the effects of a CLSM produced by CKD. At the initial stage, they have tried to investigate the cementitious characteristic of CKD by replacing the cement content of the concrete mortar with CKD in three percentages (0% or reference mix, 50%, 100%). As it was expected, the compressive strength of the mixtures reduced significantly by partially and entirely replacement of cement with CKD. The compressive strength of the mix contained 50% CKD was half of the reference mix. Although, the compressive strength was very low when the whole amount of cement substitute with CKD, it confirms that cement kiln dust has some pozzolanic characteristic that can be applied in controlled-low strength materials that high compressive strength is not required. Then they have prepared twelve mixes by using CKD coupled with fly ash (FA) in three CKD/FA ratios (1/12, 1/2, 1/6). Since no cement was used in these mixes, they have considered five different water/binder ratios (0.95, 1, 1.05, and 1.1) instead of water/cement ratio. In this study, the term binder stands for summation of CKD and fly ash weight. Results indicated that by increase the proportion of cement kiln dust in the mixes, the compressive strength of the CLSMs improved significantly. Table 2.11 represents the compressive strength results for different mixes (Pierce, Tripathi, & Brown, 2003)

Table 2.11. Compressive Strength and Elasticity modulus in kPa (Pierce et al., 2003)

CKD/FA ratios	w/b	Average Compressive Strength	Average elasticity modulus
1/2	0.95	62	5217
	1	44	3170

(Table 2.11 continued)

CKD/FA ratios	w/b	Average Compressive Strength	Average elasticity modulus
1/12	0.95	62	5217
	1	44	3170
	1.05	34	3298
	1.1	41	2525
1/6	0.95	90	5170
	1	75	3297
	1.05	55	3609
	1.1	72	7665
1/1	0.95	460	77793
	1	377	81877
	1.05	328	49585
	1.1	321	89067

2.10.3 Evaluation of Using Spent Foundry Sand in CLSM

Spent foundry sand is the waste of metal castings process that contains great quality silica sand. Typically, this by-product is reused and recycled for metal casting up to the point that the material is qualified anymore. The foundry sand that removed from this cycled is called spent foundry sand which is considered as an industrial waste (Javed and Lovell, 1994). The generic properties of the spent foundry sand is illustrated in Table 2.12.

Table 2. 12. Generic properties of Spent Foundry Sand (Javed and Lovell, 1994)

Property	Value
Specific gravity	2.39–2.55
Bulk relative density (kg/m3)	2589
Absorption (%)	0.45
Moisture content (%)	0.1–10.1
Clay lumps and friable particles	1–44
Coefficient of permeability (cm/s)	10^{-3}–10^{-6}
Plastic limit/plastic index	Non-plastic

Naik, Singh, and Ramme (2001) carried out a study to evaluate the effect of using clean foundry sand (FS1) and spent foundry sand (FS2) coupled with two types of fly ashes (F1 and F2) in controlled-low strength material. The study aimed. The objective of the study was to investigate the variation of bleeding, setting time period, permeability, shrinkage, and compressive strength. Two reference mixes poured by using F1 and F2 but without incorporation of any spent foundry sand. Sixteen mixes made by replacing fly ash in four different percentages (30%, 50%, 70%, and 85%) with FS1 and FS2. The results showed that the samples contained F1 and FS1/FS2 indicated some bleeding at early stage which decreased after 14 days. On the other hand when fly ash type two replaced with FS1 or FS2, no bleeding observed except in case 85% fly ash replacement. Furthermore, there was no shrinkage cracks in any types of the CLSM mixtures till 14 days. The compressive strength test results illustrated, generally, the compressive strength of mixes increased with age. Compared to the control samples, the compressive strength first increased up to a certain level of replacement and then decreased. Table 2.13 indicates the results

of compressive strength test. In addition the permeability test results indicated that the type of foundry sand (clean or spent) did not affect the permeability of CLSM. But the permeability increased sharply when 85% of fly ashes was replaced with FS1 or FS2 (Naik, Singh, & Ramme, 2001).

Table 2.13. Compressive strength results for different mixtures (Naik et al., 2001)

Foundry Sand (%)	Compressive Strength for F1 fly ash mixes (MPa)			Compressive Strength for F1 fly ash mixes (MPa)		
	7-days	28-days	91-days	7-days	28-days	91-days
0	0.24	0.28	0.31	0.31	0.38	0.48
30 FS1	0.34	0.52	0.59	0.34	0.55	0.62
50 FS1	0.24	0.52	0.66	0.34	0.55	0.59
70 FS1	0.24	0.41	0.48	0.38	0.62	0.76
85 FS1	0.17	0.28	0.31	0.28	0.45	0.52
30 FS2	0.34	0.55	0.76	0.34	0.59	0.66
50 FS2	0.28	0.34	0.45	0.41	0.55	0.62
70 FS2	0.17	0.31	0.48	0.41	0.52	0.59
85 FS2	0.21	0.28	0.38	0.28	0.34	0.38

2.11 References

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CHAPTER 3. EVALUATION OF DRILL CUTTINGS PERFORMANCE IN CONCRETE MIXTURES

3.1 Introduction

Material recycling in construction applications shows a global trend that is significantly increasing. This noticeable growth is essentially attributed to efforts to limit landfilling of waste and to decrease the consumption of virgin raw materials in new construction activities. Recycled materials are mostly being used as components in mixtures such as concrete – one of the most widely construction materials used in the world – production, which consumes a large amount of raw materials.

Concrete causes a significant burden on virgin resources and their extraction, which creates major environmental damages. In view of such environmental impacts, many researchers have studied the possibility of incorporating new aggregate into the concrete mix design, by replacing wholly or partially the natural aggregate component with waste materials such as coconut shells (Gunasekaran, Annadurai, & Kumar, 2015), blast furnace slag (Gutt, Teychenné, & Harrison, 1974), recycled glass, or demolished concrete constituents (Behera, Bhattacharyya, Minocha, Deoliya, & Maiti, 2014; Udaykumar et al., 2011). Others have tested the hypothesis that all components of the mixture, including cement, could be substituted by levels of replacement. Perumal and Sundarajan (Sundararajan, 2004). found that replacing 10% of silica fumes in cement rendered a more durable concrete. Dayahlan and Beulah (2014) evaluated the simultaneous replacement of cement, sand, and coarse aggregate with silica fume, waste ceramic tiles, and crushed animal bones, respectively, which yielded more positive results than when replaced individually. Another material that has also been considered to be a potential replacement is drill cuttings; a waste that is generated during petroleum exploration and production.

There are many issues in regard to the waste management process for drill cuttings. The environmental organizations passed new restrictions for drill cuttings, aimed at discharging the drill cuttings into seawaters. Oil and gas industries were pressured as well to mitigate the environmental consequences of drilling activities. Hence, several waste management strategies, such as waste control, reuse and recycling, and waste treatment were applied to reduce the environmental impacts of contaminated cuttings. Therefore, recycling and reusing drill cuttings in construction, such as pavement and building industries, gained much interest. Many researchers utilized drill cuttings as a substituent for natural aggregates. Mostavi, Asadi, and Ugochukwu (2015), as well as Okoh (2015), investigated the effects of partial cement replacement with drill cuttings. In addition, many studies examined the feasibility of using drill cuttings in different parts of the pavement structure (Czarnecki, 1988; Meegoda, Chen, Gunasekera, & Pederson, 1998; Tuncan, Tuncan, & Koyuncu, 2000; Aydilek, Demirkan, Seagren, & Rustagi, 2007).

3.2 Experimental Program

The objective of the experimental program was to evaluate the performance of drill cuttings incorporated in CLSM mixtures and to assess the potential use of the waste material in concrete applications. The test factorial was applied to each source of drill cuttings, separately. Table 3.1 (a and b) illustrates the experimental factorial for the drill cuttings sampled from Texas and Louisiana. The table 3.1 presents the test conditions, test variables, and ASTM standards, for each source of drill cuttings. The experimental program was divided into two phases. Phase 1 consisted of a comprehensive laboratory study on the physical, mechanical, and chemical properties of the cuttings. Laboratory experiments included particle size distribution, Atterberg limits, and specific gravity. An elemental analysis of drill cuttings was also performed in that

phase, using Environmental Scanning Electron Microscopy (E-SEM) coupled with Energy dispersive x-ray (EDS) and X-Ray Diffraction (XRD). Phase 2 consisted of preparing concrete test specimens by varying the content of drill cuttings in the concrete mix from 5 % and 20% as a partial replacement of fine aggregate. Prepared concrete mixes were evaluated in terms of strength for use in non-structural concrete applications.

Table 3.1. Test Factorial and Standards for (a) Texas and (b) Louisiana Drill Cuttings

(a)

Variable	Number of levels	Description	Test Methods
Types of Drill Cuttings	1	Treated	N/A
Fine Aggregate Replacement	1	20%	N/A
Phase I: Characterization of Drill Cuttings	N/A	Particle size distribution	ASTM D6913-04
		Specific Gravity	AASHTO ND-T84
		Atterberg limits	ASTM D4318-18
		Absorption	AASHTO ND-T84
		E-SEM, EDS, X-ray	ASTM C1723-10
Phase II: Testing of Concrete Properties	2	Compressive Strength	ASTM D 4832-10

(b)

Variable	Number of levels	Description	Test Methods
Types of Drill Cuttings	1	Untreated	N/A
Fine Aggregate Replacement	2	5%	N/A
		20%	
Phase I: Characterization of Drill Cuttings	N/A	Particle size distribution	ASTM D 6913-04
		Specific Gravity	AASHTO ND-T84
		Atterberg limits	ASTM D 4318-08
		Absorption	AASHTO ND-T84
		E-SEM, EDS, X-ray	ASTM C 1723-10
Phase II: Testing of Concrete Properties	4	Compressive Strength	ASTM D 4832-10

3.2.1 Material Description

Conventional CLSM mixtures usually contain Portland cement, water, fine and coarse aggregates, and possibly fly ash or other similar products. For the purpose of this study, cement, together with coarse and fine aggregates, was considered. The removal of some of the components in the CLSM mixture allowed a reduction in product variability for a more consistent evaluation of drill cuttings. Type 1 Portland cement, conforming to ASTM D 4832-10, was used to provide the necessary cohesion and strength for the mixtures. Water quality requirements also followed ASTM D 4832-10. Both coarse and fine aggregates were obtained from regional sources. Gradation and properties of the aggregates were measured as presented in Table 3.2 both coarse and fine aggregates complied with ASTM C 33.

Table 3.2. Aggregate and Cementitious Properties

Concrete Components	**Specific Gravity**	**Absorption (%)**	**Fineness Modulus**
Coarse Aggregate	2.71	0.8	5.53
Fine Aggregate	2.64	0.5	2.61
Cement	3.15	-	-

Samples of drill cuttings were collected from two different terrestrial drilling locations and were obtained from licensed processors. The first source of drill cuttings was from College Station, Texas, Figure 1a. The sample was obtained at a depth range between 3,000 ft. and 12,000 ft., where the formations are predominantly composed of sand. At this location, cutting samples were separated from drilling muds and shipped to shore for the removal of oil before being tested. The second source of drill cuttings was from Crawley, Louisiana, Figure 1b. This source was uncleaned and unprocessed.

(a) (b)

Figure 3.1. Drill Cuttings from (a) Texas and (b) Louisiana

3.2.2 Material Preparation

3.2.2.1 Drill Cuttings Preparation

The first two samples were obtained and processed by Brammer Engineering, a Texas-based company. The second set of samples was coated with oil-based drilling mud, which had to be completely dried out in order to conduct the experimental program. The oil-based cuttings were thus dried in a vacuum oven at 95oC for 48 hours until a constant weight was attained. Moisture content was determined following the heating process.

3.2.3 Chemical Composition Testing

Cuttings materials were prepared for Scanning Electron Microscopy (SEM). Fifteen grams (15g) of dried cuttings material were split for analysis. The analysis split was powdered and homogenized. Specimens were placed on an aluminum sample holder with adhesive tape. Specimens were then scanned for chemical composition by the Energy Dispersive X-ray (EDX) technique, using a scanning electron microscope with digital secondary and backscattered electron imaging capabilities. Data were collected over a selected area of the surface of the

sample that displayed spatial variations in properties, including chemical characterization, texture, and orientation of materials.

X-Ray Diffraction (XRD) was then performed to provide a more accurate mineralogical and elemental quantitative analysis of the cuttings. The samples were reduced to crystalline powder manually with a mortar and pestle, then poured and pressed into a specimen holder until a smooth surface was attained. A Plexiglas cover was placed over the XRD specimen holder top surface; both cover and holder were then placed in a diffractometer.

3.2.4 Physical Testing

The physical properties of the cuttings were determined through a suite of laboratory experiments. The particle sizes contained within the sample was determined by performing a particle size analysis, classifying each sample by type of soil. The plastic and liquid limits of the fine portion were also tested. The specific gravity of the cuttings was measured based on the saturated surface dry weights of the sample. The absorption capacity of each sample was also calculated. The particle size distribution, specific gravity and Atterberg limits testing procedures were in accordance with ASTM D 6930-04, AASHTO T84, and ASTM D 4318, respectively.

3.2.5 CLSM and Concrete Mix Design and Specimen Processing

The basic procedures and mix proportioning were performed for CLSM mixtures targeting compressive strengths of 2,800, 1200, 300, 200 and 80 psi at 28 days as per ASTM D 4832-10 for CLSM. The target compressive strength levels for CLSM mixtures set based on the ASTM D 4832-16 specification that suggests 1200 psi as the highest amount of compressive strength. Since proportions for CLSM mixtures are not specified, trial mixtures were prepared to determine how well the mixtures met certain goals in terms of strength. Subsequently, adjustments were made to achieve the desired properties. The mixtures of CLSM were prepared

with 5 and 20% of drill cuttings on substitution by volume of natural aggregates. The mixture proportions are shown in Table 3.3.

Table 3.3. CLSM and Concrete mix properties

Compressive Strength level	**Concrete Mixture**							
	Water (lb.)	Cement (lb.)	w/c	Coarse (lb.)	Fine (lb.)	Batch size (ft^3)	Drill Cuttings	
2800 psi	360	400	0.9	1600	1599	27	Sample1 20%	Sample2 20%
1200 psi	300	300	1	1724	1679	27	Sample3 5% & 20%	Sample4 5% & 20%
300 psi	250	500	2.0	1475	1437	27	Sample3 5% & 20%	Sample4 5% & 20%
200 psi	498	188	2.6	597	2374	27	Sample3 5% & 20%	Sample4 5% & 20%
80 psi (Mix 1)	400	100	4.0	1675	1632	27	Sample 1-20%	
80 psi (Mix 2)	288	125	2.3	715	2842	27	Sample3 5% & 20%	Sample4 5% & 20%

Concrete test specimens with and without drill cuttings were prepared. The specimens were cast from 25 separate batches of concrete: 6 controls and 19 mixes containing varying amounts of drill cuttings. During mixing and sampling, the raw materials were mixed thoroughly and continuously to avoid segregation and to maintain the desirable homogeneity. The same mixing process was used for all mixtures produced. The coarse aggregate and 2/3 of the total water amount were first introduced into the mixer. After three minutes of mixing, the fine aggregates combined with varying amounts of drill cuttings, cement, and the remaining water were added to the mixture. After three minutes, the mixer was stopped for a few minutes and then re-started for an additional three minutes of final mixing. The CLSM mixture was then poured in three 4 in. x

8 in. cylinders. The cylindrical specimens were covered to avoid moisture evaporation. The specimens were removed from their molds after 48 to 72 hours, as this type of mix is very fluid. The cylindrical specimens were then transported to a 100% curing room.

3.2.6 Mechanical Test

The compressive strength is commonly used to evaluate the acceptability of CLSM mixtures and whether the mixtures meet the requirements for use in non-structural components. The test was performed at 28 days. The preparation and testing procedure for compressive strength tests were in accordance with the specifications of ASTM D 4832.

3.3 Results and Analysis

3.3.1 Chemical Composition (XRD and SEM)

The mineralogical compositions of the drill cuttings are summarized in Table 3.4. Small sampling regions of each larger sample were tested to obtain a consistent quantitative analyses of natural and synthetic materials. The sedimentary nature of the soil is reflected in the elemental analysis. The results of X-ray diffraction, chemical analysis, and scanning electron microscopy were combined to identify and quantify the elemental constituents of the drill cuttings samples.

Table 3.4. Chemical composition of drill cuttings

Elements	**Sample 1-Texas (%)**	**Sample 2-Texas (%)**	**Sample 3- Louisiana (%)**	**Sample 4-Louisiana (%)**
Clay	9.1	-	6.12	4.81
Quartz	80.12	93.86	48.12	31.36
K-Feldspar	2.32	2.88	0.63	-
Plagioclase	2.8	3.26	1	1.27
Calcite	3.48	-	6.37	7.58
Barite	-	-	37.91	52.91
Pyrite	1.36	-	-	-
Dolomite	0.8	-	-	2.06

As shown in Table 4, the drill cuttings differed in their mineral compositions. Both Texas samples (sample1 and 2) contained a high amount of quartz, as well as a low amount of feldspar, and plagioclase. Yet, Sample2-Texas was not limited to these minerals, and contained low amounts of calcite, pyrite and dolomite. On the other hand, Louisiana samples consisted mostly of quartz and barite, representing more than 80% of these samples.

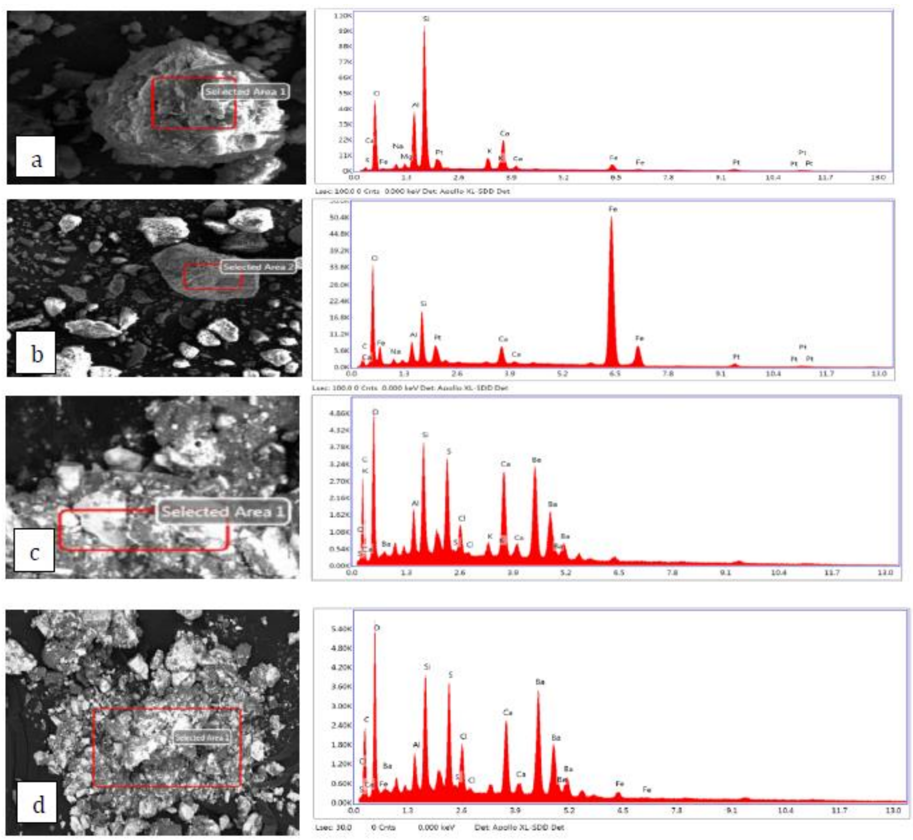


Figure 3.2. SEM images of drill cuttings (a) Sample 1-TX (b) Sample 2-TX (c) Sample 3- LA (d) Sample 4-LA

Figure 3.2 shows the EDS results of a fraction of constituents for all the samples. The chemical elements of each sample validated the presence of the minerals found in the XRD test. Figure 3.2 indicates that all four samples contained silicon (Si), which is compatible with the presence of high amounts of quartz (Silicon Oxide, SiO2) in these samples. Furthermore, the presence of

barium (Ba) and sulfur (S) in Figure 2(c and d) is due to the large content of barite ($BaSO_4$) in Sample3-LA and Sample4-LA. Chemical elements such as Al, Mg, K, Fe, and Na, are due to the presence of other minerals with lower concentrations such as clay, calcite, feldspar, plagioclase, and dolomite.

3.3.2 Particle Size Distribution and Soil Classification

Particle size distribution results are shown in Figure 3.3 for the samples collected from Texas and Louisiana. Results show that the drill cuttings are fine-grained with a gap-graded particle size distribution curve. Table 3.5 presents the Coefficient of Curvature (Cc), the Coefficient of Uniformity (Cu), and the fineness modulus for the drill cuttings from Texas and Louisiana.

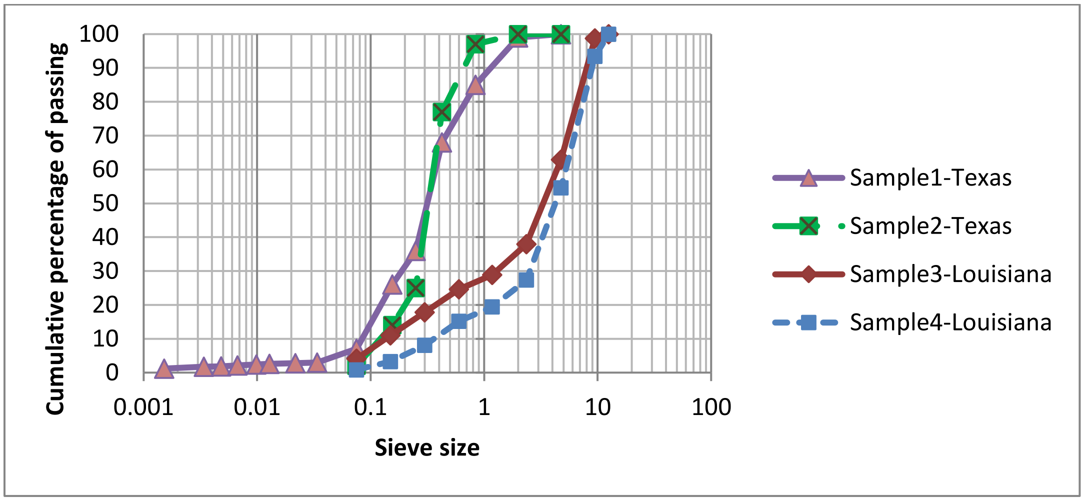


Figure 3.3. Grain-size distribution curve for the Texas and Louisiana samples

Table 3.5. Particle size distribution curve data

Physical Properties	Sample 1 Texas	Sample 2 Texas	Sample 3 Louisiana	Sample 4 Louisiana
Coefficient of Uniformity (Cu)	4.43	2.92	31.87	12.22
Coefficient of Curvature (Cc)	1.165	1.514	2.31	0.939
Fineness Modulus (FM)	4.13	2.69	4.18	3.65

The particle-size distribution curves shown in Figure 3 indicate that the percentage of fine-grained aggregate in the drill cuttings was more than 5%. Accordingly, the Atterberg limits experiments were conducted to quantify the plasticity of the samples. Results of the Atterberg limits test for Sample1 (Texas) is presented in Table 3.6.

According to particle-size analysis and Atterberg limits test results, the drill cuttings from Texas were classified as SW-SC (well graded sand with clay) and as SP (poorly graded sand). Conversely, the drill cuttings from Louisiana were classified as SW (well-graded sand) and SP (poorly-graded sand).

Table 3.6. Atterberg test result for sample 1-Texas

Atterberg Limits	Percentage
Liquid Limit (LL)	85
Plastic Limit (PL)	30
Plasticity Index (PI)	54

3.3.3 Bulk Specific Gravity and Absorption

Bulk specific gravity (SSD) and absorption capacity are presented in Table 3.7 for the two sources of drill cuttings. The results of the experiment indicated that the specific gravity SSD of the Texas samples was generally greater than that of the Louisiana samples. Furthermore, the absorption capacity of the Texas drill cuttings was significantly greater than that of the Louisiana samples.

Table 3.7. Bulk Specific Gravity and Absorption Capacity

Drill Cuttings	Specific Gravity (OD)	Specific Gravity (SSD)	Specific Gravity (apparent)	Absorption %
Sample 1-Texas	2.246	2.325	2.438	3.5
Sample 2-Texas	2.215	2.291	2.397	3.4

(Table 3.7 continued)

Drill Cuttings	Specific Gravity (OD)	Specific Gravity (SSD)	Specific Gravity (apparent)	Absorption %
Sample 3-Louisiana	2.132	2.350	2.720	9.9
Sample 4-Louisiana	2.208	2.470	2.960	12

3.3.4 Compressive Strength Test Results

Comparison was established between samples prepared with drill cuttings and the control sample at each strength level. Table 3.8 illustrates the compressive strength test results of the control samples, as well as the samples prepared with drill cuttings at two different contents (5 and 20%). In each case, the same mix design for the control concrete mixture was duplicated for the samples prepared with 5 and 20% drill cuttings. In addition, the elasticity modulus of each concrete mixture was estimated based on the following empirical relationship:

E=33×Wc1.5×$\sqrt{f_c'}$, (ACI, 2008).

Table 3.8. Compressive Strength Test Results

Description	Concrete Mixture	Classification	W/C Ratio	Average psi	Standard Deviation	Elasticity Modulus (KSI)
Texas Samples	2800 PSI	Control	0.9	2857	77.37	3089
	2800 PSI 20%	SW-SC		2882	191.32	3093
		SP		2641	145.74	2961
	80 PSI	Control	4	61	5.03	432
	80 PSI 20%	SP		44	5.03	359
Louisiana Samples	1200 PSI	Control	1	1275	129	2139
	1200 PSI 5%	SW		1223	23.62	2054
		SP		1183	25.6	2016
	1200 PSI 20%	SW		1191	64.5	2029
		SP		1175	35.5	2015
	300 PSI	Control	2	304	35.55	910
	300 PSI 5%	SW		300	39.29	897
		SP		288	9.46	882

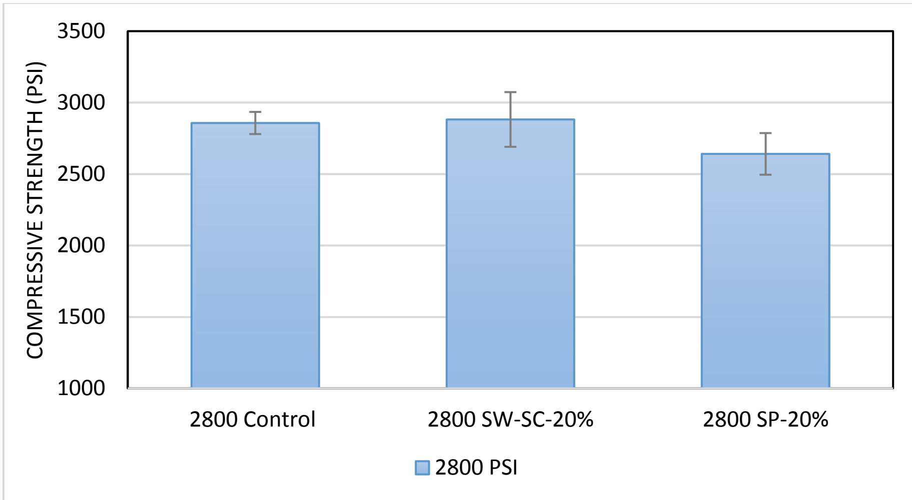
(Table 3.8 Continued)

Description	Concrete Mixture	Classification	W/C Ratio	Average psi	Standard Deviation	Elasticity Modulus (KSI)
Louisiana Sample	300 PSI 20%	SW	2	289	19.36	873
		SP		277	33.29	862
	200 PSI	Control	2.6	184	11.67	703
	200 PSI 5%	SW		172	5.71	675
		SP		164	2.49	661
	200 PSI 20%	SW		160	4.10	640
		SP		157	2.16	639
	80 PSI	Control	2.4	75	4.64	509
	80 PSI 5%	SW		65	0.70	469
		SP		58	1.41	446
	80 PSI 20%	SW		53	2.82	417
		SP		52	3.53	419

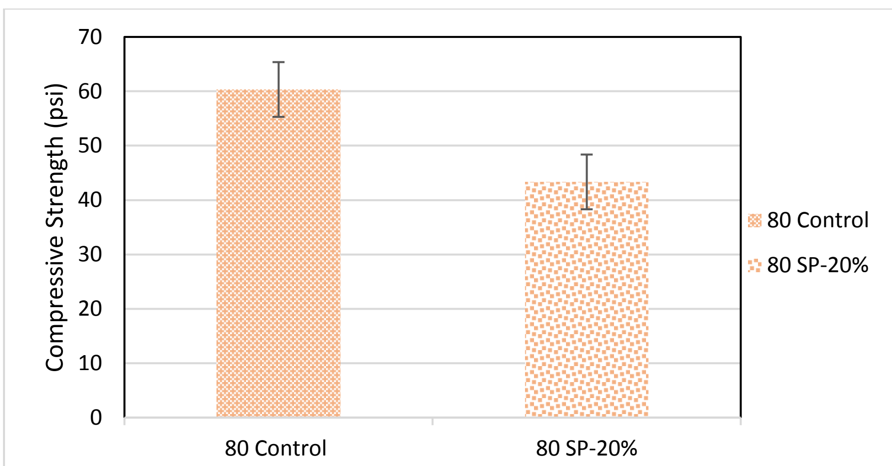
The mean values of the compressive strength for the 2,800 psi concrete mixture are presented in Figure 4a. As shown from these results, the compressive strength of the 2,800 mixture with a 20% replacement of the SW-SC drill cuttings was comparable to the control mix at the same strength level. Yet, the average compressive strength of the 2,800 psi concrete mixture with a 20% replacement of the SP drill cuttings was 7.5% lower than the control mixture, shown in Figure 3.4 (a). An Analysis of Variance (ANOVA) was conducted to statistically compare the control specimens to the specimens with drill cuttings and showed that the results were statistically equivalent (p-value=0.164).

Figure 3.4 (b) shows the compressive strength of the 80 psi concrete mixture both with and without drill cuttings from Texas. As shown in this figure, the average compressive strength of the control sample was 28% greater than the concrete mixture with 20% drill cuttings from

Texas. By running an ANOVA analysis between these two groups, it was found that the difference between the two data sets was statistically significant (p-value=0.0144).



(a)

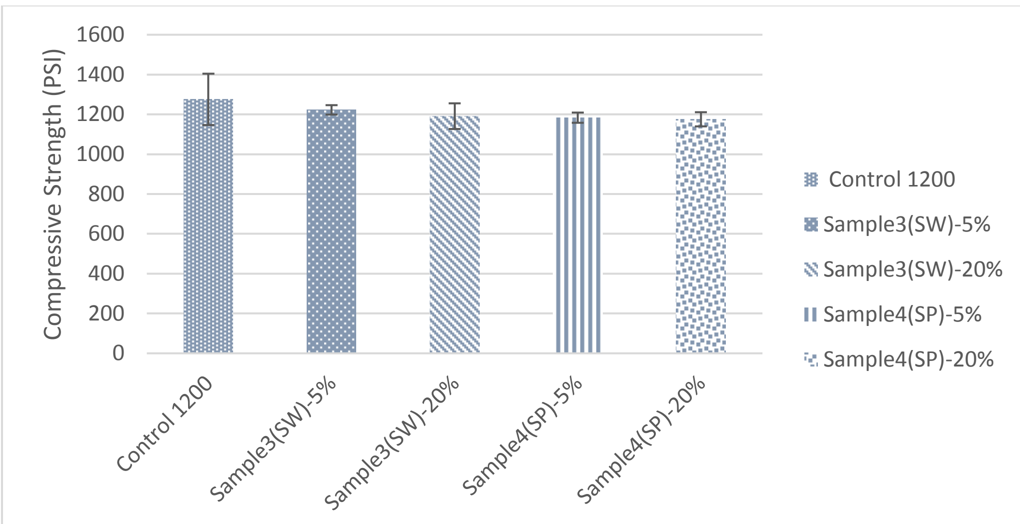


(b)

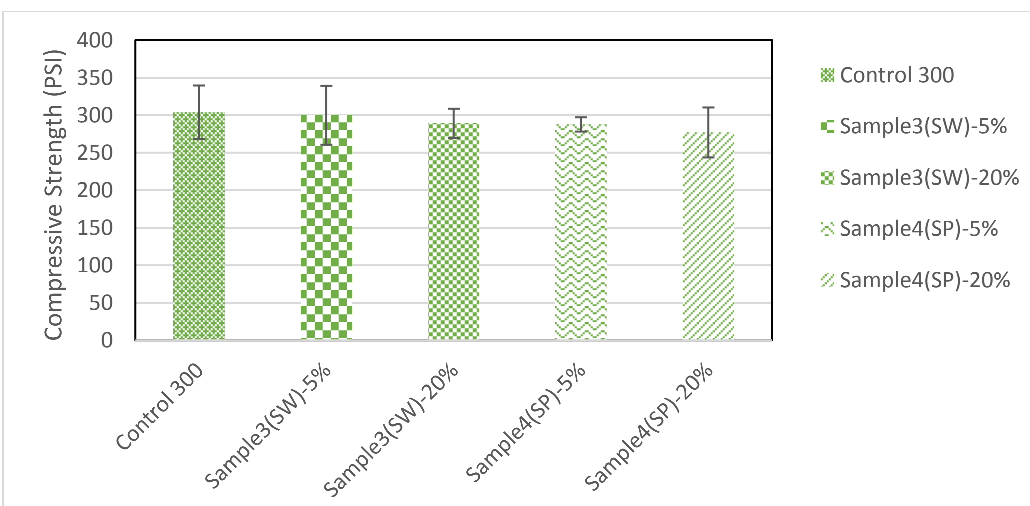
Figure 3. 4 Compressive Strength Test Results at (a) 2,800 psi and (b) 80 psi for Texas Drill Cuttings

Figure 3.5 represents the mean compressive strengths at the three target levels of strength (1200, 300, 200, 80 psi) for the control mix and the mixes prepared with 5 and 20% drill cuttings from Louisiana. In general, a slight reduction in compressive strength was observed when drill

cuttings from Louisiana were used. Yet statistical analysis of the test results showed that the observed differences were not statistically significant at a target compressive strength of 1200 and 300 psi. However, differences were statistically significant at a target compressive strength of 200 and 80 psi. A Tukey analysis was conducted to identify the test conditions that were statistically different. A summary of the Tukey analysis is presented in Table 3.9. In this table, letter A represents the best performer at the same-strength target, followed by B and C.



(a)



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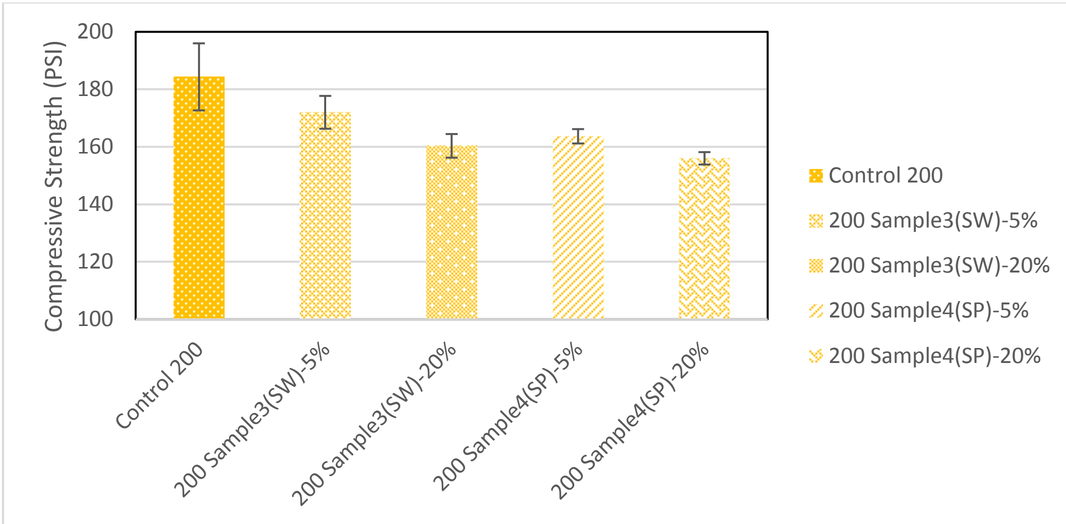

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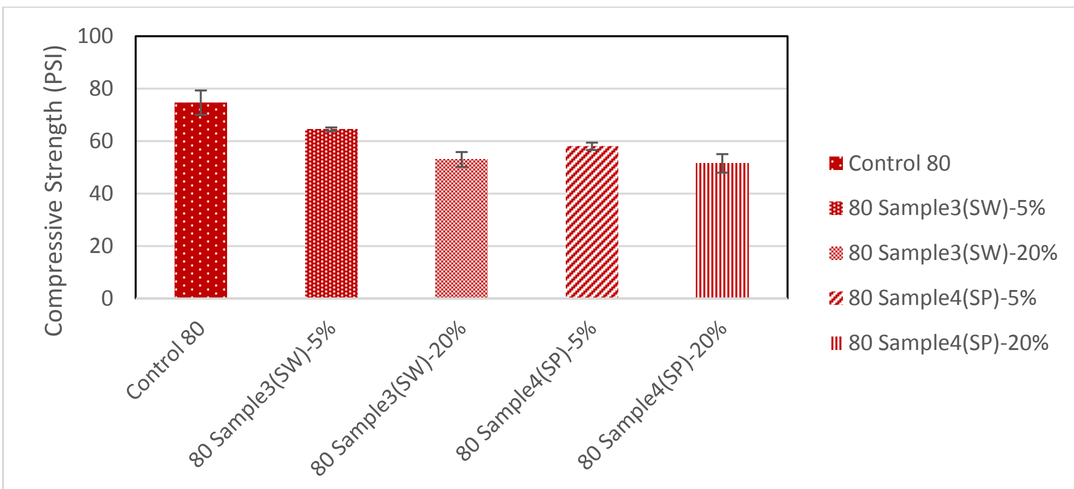

(d)

Figure 3. 5. Compressive Strength Test Results at (a) 300 psi, (b) 200 psi, and (c) 80 psi for Louisiana Drill Cuttings

Table 3.9. Summary of the Statistical Analysis

Target Compressive Strength (psi)	Concrete Mixture Description	Compressive Strength (psi)	Ranking
1200	Control	1275	A
	SW - 5%	1223	A
	SP- 5%	1183	A
	SW- 20%	1191	A
	SP- 20%	1175	A

(Table 3.9 continued)

Target Compressive Strength (psi)	Concrete Mixture Description	Compressive Strength (psi)	Ranking
300	Control	304	A
	SW - 5%	300	A
	SP- 5%	288	A
	SW- 20%	289	A
	SP- 20%	277	A
200	Control	184	A
	SW- 5%	172	A/B
	SP- 5%	164	B
	SW- 20%	160	B
	SP- 20%	157	B
80	Control	75	A
	SW- 5%	65	A/B
	SP- 5%	58	B/C
	SW- 20%	53	C
	SP- 20%	52	C

3.4 Conclusion

The study evaluates the performance of the concrete mixtures produced by partially replacement of fine aggregates with the drill cuttings in terms of compressive strength and elasticity modulus. The physical and mineralogical characteristics of the cuttings was investigated. Then the new samples poured according to the mix proportioning. Finally, the mechanical properties of the mixtures were evaluated. Based on the results of this study, the following conclusions may be drawn:

- The Louisiana samples were mostly dominated by barite which was due to the high concentration of this additive in oil based drilling fluids (OBMs). The drill cuttings from Texas were classified as SW-SC (well graded sand with clay) and as SP (poorly graded sand). Conversely, the drill cuttings from Louisiana were classified as SW (well-graded sand) and SP (poorly-graded sand).

- With respect to the compressive strength and for different types of drilled cuttings, the well-graded samples (SW and SC-SW) performed better than the poorly-graded samples (SP) at the same level of replacements. In general, the well-graded samples that had a good presentation of all size aggregates have performed better than poorly-graded samples. Better aggregate interlocking in well graded samples can increase density and compressive strength consequently.
- When compared to the control samples, no significant compressive strength reduction was observed for concrete mixes prepared with drilled cuttings at high strength targets (2800, 1200 and 300 psi). At these high strength targets, it is feasible to replace the fine aggregates up to 20% significantly without reducing the target compressive strength. The possibility exists that the higher content of cement in these high strength concrete mixtures compensates for the lack of strength as a result of utilizing drill cuttings.

In general, the results of this study indicate that fine aggregates can be successfully replaced by drill cuttings in the concrete mixtures designed for greater than 300 psi compressive strength. Future studies should consider the use of drill cuttings in normal strength concrete using a similar approach to the one presented in this study for CLSM.

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CHAPTER 4. SUMMARY AND CONCLUSIONS

Industrial waste management may be seen as one of the most critical problems of the new century. Waste recycling was found to be the most economical and environmental-friendly solution to this problem. Drill cutting is a major waste generated during the drilling activities. As a result, the subsequent contamination of drilling wastes with various toxic chemicals, initiated in order to improve drilling efficiency, served to raise public concerns regarding waste management and safe disposal of these aggregates. Therefore, recycling and reusing these aggregates in different industries, such as pavement and construction, gains much interest. Therefore, many researchers investigated drill cutting performance as an alternative to conventional material.

This study evaluated the feasibility of replacing fine aggregates with 5 and 20% of drill cuttings in concrete applications. To achieve the objective of the study, the project was divided into two phases. The first phase consisted of a comprehensive laboratory study on the physical, mechanical, and chemical properties of the cuttings. The second phase involved preparing concrete test specimens by varying the content of drill cuttings in the concrete mix from 5% and 20% as a partial replacement for fine aggregate.

To ascertain the properties of drill cutting samples, the initial step is to prepare the material for experimental characterization. Therefore, the material from the different sources dries in a vacuum oven at 95^{o} C for 48 hours. The study determined the initial moisture content by checking the samples weight until achieving a constant weight. The next step was to prepare the samples for an investigation of the chemical composition of the material. The sample was powdered and placed on the sample holder to be tested by a secondary electron microscopy (SEM). The backscatter electron (BSE) mode was used to identify the chemical composition of

material. Then, an X-Ray Diffraction (XRD) was performed to provide a more accurate mineralogical and elemental quantitative analysis of the cuttings. The finding was that Louisiana drill cuttings were mostly dominated by barite, which is compatible with the presence of barium and sulfate elements in an EDS mapping of the drill cuttings. Furthermore, the specific gravity, absorption capacity, Atterberg limits, and grain size distribution of the aggregate were all determined in order to understand the physical properties of the cuttings. Compared to the physical properties of virgin fine aggregates, the absorption capacity of the drill cuttings was significantly higher, especially in regard to the Louisiana samples. On the other hand, the specific gravity of the cuttings was lower, due to chemical and organic contaminations. According to the particle size distribution results and Atterberg limits values, Texas cuttings were classified as SW-SC (well graded sand with clay) and as SP (poorly graded sand). Conversely, the drill cuttings from Louisiana were classified as SW (well-graded sand) and SP (poorly-graded sand).

The second phase of the project was to prepare the concrete samples in 5 samples, targeting compressive strength (2800, 1200, 300, 200, and 80 psi). The study prepared the control samples by conventional aggregates, consisting of 20 percent and 5 percent of natural sand; the study then replaced the control samples with the drill cutting aggregates in order to produce more sustainable concrete mixtures at the same proportion of mix. The specimens were cast from 25 separate batches of concrete: 6 controls and 19 mixes that contained varying amounts of drill cuttings. The researchers then poured the mixtures into three 4 in. x 8 in. cylinders. The specimens were removed from their molds after 48 to 72 hours, due to a fluid type of mix. The next step required the transport of cylindrical specimens to a 100% curing room. After 28 days, the procedure performed a compressive strength test. The results indicated that the compressive

strength of the drill cutting contained a mixture with a targeting strength higher than 300 psi, comparable to the reference mixes. On the other hand, researchers observed a significant drop in compressive strength, when the fine aggregate replacement achieved in the mixtures showed a targeting strength lower than 300 psi (200 and 80 psi). In addition, the variation of elasticity modulus followed the same pattern as the compressive strength.

Based on the results of this study, the findings conclude that an incorporation of the drill cuttings in concrete application may be accomplished where the referenced compressive strength is higher than 300 psi. Future studies should consider the use of drill cuttings in normal strength concrete, using a similar approach to the one presented in this study for CLSM.

4.1 Limitation of Study and Recommendations for Future Works

Although the drill cuttings exhibited a great potential for being used as aggregate in high strength concretes, there were some inevitable limitations that restricted the scope of this research. This section involves these limitations and represent some recommendations for expanding this research topic in future.

4.1.1 Limitations

The most common restriction in every research projects is the time limitation. Accordingly, we were not able to investigate all properties of the mixtures produced by drill cuttings. The other restriction was limited amounts of treated drill cuttings, where we just replaced 20% of fine aggregates with drill cuttings. In addition, the treating process of untreated drill cuttings was really time consuming and required a perfect ventilation system. Consequently, the replacement program was not increased to higher levels.

4.1.2 Recommendations and Future Works

According to limitations of this project, more investigations can be done to expand the scope of this study. Here is the list of recommendations for future studies:

- The influence of drill cutting incorporation on the properties of the concrete such as workability, water absorption and permeability, Acid resistance, sulphate resistance, and shrinkage can be evaluated.
- Standard leaching test should be done on the concrete samples to investigate the amount of violating compound.
- More drill cutting from different sources can be utilized to investigate the effects of different chemical compositions on the mixture properties.
- The fine aggregate replacement with drill cuttings can be increase up to 100% in high targeting strengths.
- Cement and fine aggregates can be replaced with drill cutting at the same time to monitor the variation of concrete properties.

VITA

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