LANDFILL VOLUME GAIN FROM THE DIVERSION OF CONSTRUCTION AND DEMOLITION WASTE

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
May 2016

Acknowledgments

I would like to express my sincere gratitude to my supervisor, Dr. Sahadat Hossain, for his support and motivation throughout my graduate studies. Without his guidance, invaluable suggestions and constant encouragement, this thesis would not have been completed.

I would like to thank Dr. Melanie Sattler and Dr. Xinbao Yu for their willingness to serve as my committee members and also for their valuable time and suggestions.

I wish to acknowledge the City of Denton Landfill authority for their assistance in sample collection.

I am really grateful to Dr. Sadik Khan, Dr. Sonia Samir, and Dr. Dipak Tiwari for their unconditional support and valuable input throughout my graduate studies. I would further like to extend my sincere appreciation to my colleagues Zahangir, Ishtiaque, Arindam, Masrur, and Minh for their help during the sample collections and laboratory tests.

I would like to express my deepest gratitude to my parents and my brother for their love, support, guidance and assistance throughout my life.

December 4, 2015.

Abstract

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Construction and Demolition (C&D) waste is one of the major components of the solid waste and is defined as a waste stream resulting from the construction, renovation and demolition of structures such as buildings, roads, and bridges. The amount of C&D waste has been in an upsurge with rapid growth in construction works and is expected to grow even more. As such, the effective waste management for C&D disposal has been a global issue owing to the increasing construction works worldwide. Although landfill disposal of C&D waste is not the preferred method of the C&D waste management, a significant portion of C&D waste is disposed in the landfills. Apart from the environmental and health risks, the landfill disposal of C&D waste also consumes considerable amount of landfill volume. Due to the high construction cost and scarcity of land, it is important to take possible measures to save landfill volumes. Hence, diversion of C&D waste from the main waste stream can substantially help in gaining more landfill volume. However, to estimate the possible volume gain from the diversion of the C&D waste, it is important to understand the properties of the C&D waste. Therefore, the objective of this study was to evaluate the properties of the C&D waste and estimate the possible landfill volume gain from the diversion of C&D waste.

For the current study, five construction and five demolition waste samples were collected from the City of Denton landfill in October 2015. Based on the manual sorting of the samples, the average composition for the C&D waste with equal proportion of construction waste and demolition waste (50% Construction and 50% demolition waste) was found to consist of 36.6% wood products, 18.3% Portland cement concrete, 10% asphalt concrete, 12% brick and tiles, 1.3% metals, 11% drywall & plaster, 5% cardboard, and 6% C&D debris fine. The unit weights of the collected samples were determined using the standard proctor method. For C&D waste with equal proportion of construction waste and demolition waste (50% Construction and 50% demolition waste), the unit weight was found to be 62.13 pcf (0.84 tons per cubic yard). The average moisture content of construction waste was determined to be 5.93% and 6.33% on wet weight and dry weight basis respectively. Whereas, the average moisture content for demolition waste was found to be 2.73 % and 2.81% on wet weight and dry weight basis respectively. The volatile solids content of construction waste was found to be 82.7% in average.

The landfill volume gain was estimated based on the average annual tonnage and unit weight from the current study. Based on the results, for a landfill with 20 acres area, 100 feet design height and 3H:1V side slope, approximately 1.25% of total landfill volume which is approximately equal to 0.61% of total lift height can be obtained per year by diverting 90% of the C&D waste from the landfill.

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Chapter 1

Introduction

1.1 Background

Construction and demolition (C&D) waste is one of the major components of solid waste and occupies its significant portion. United States Environmental Protection Agency (US EPA, 1998) defines C&D waste as a waste stream resulting from the construction, renovation and demolition of structures such as buildings, roads, and bridges. The typical components of C&D waste are: drywall and plasters, brick, clay tiles, wood products, metal, Portland cement concrete, asphalt concrete, asphalt shingles, and soil. Construction of new structures, renovation, rebuilding, repair, demolition works, and infrastructure development projects generate large quantities of construction and demolition wastes. Hence, disposing C&D waste in the landfills becomes a critical issue considering cost and availability of land. Therefore, proper management of the C&D waste is very important (Marzouk & Azab, 2014). UNEP (2015) has identified C&D waste management as a global challenge.

C&D waste was not considered to be a critical waste stream in the past even though C&D waste sources have materials that may have been contaminated by potentially harmful compounds like asbestos, chromium, and arsenic. C&D waste materials were disposed either in MSW landfill or in C&D landfills in the past because of the seemingly inert nature of the C&D waste materials. Disposing C&D waste in the landfill, however, is not a preferred method of waste management (Peng et al., 1997). Disposing C&D waste in an unlined landfill can cause the intrusion of contaminated leachate into the ground water thereby degrading the quality of ground water. Studies (Johnson, 1986; Lee et.al., 2006) have found that C&D waste disposed in landfill produce hydrogen sulfide. Apart from being malodorous, hydrogen sulfide has adverse effect on human health and environment.

The three strategies (reduce, reuse, and recycle) in the waste management method hierarchy also known as 3R's of C&D waste management, has been used as basic principle for C&D waste management (Peng et at., 1997, Yuan & Shen, 2011). Reuse is the most preferred option after reduction as it requires minimum processing and energy use (Peng et al., 1997). Kartam et al. (2004) and Wang et al. (2008) have identified the major benefits from waste recycling, including: (1) reducing the demand for new resources; (2) cutting down on transport and production energy cost; (3) utilizing waste which would otherwise be lost to landfill sites; (4) preserving areas of land for future urban development; and (5) improving the general state of the environment (Yuan and Shen, 2011).

In the lack of federal regulations, C&D waste is regulated in state level in the United States. Different states have different requirements for the C&D waste landfills (Clark et.al, 2006). Some states have strict liner requirements whereas some states allow disposing C&D waste in unlined landfills (US EPA, 2010). C&D waste when disposed in landfill consumes landfill space apart from imposing risk to human health and environment. Diverting the C&D waste from landfilling can help us to save landfill volume which can be beneficial in the areas with scarcity of land where the expansion of landfill is impossible. This research focuses on characterizing the C&D wastes and estimating the landfill space gained by diverting the C&D waste from the landfills.

1.2 Problem Statement

The negative effects of C&D waste generation are numerous. They occupy a large amount of landfill space during the waste landfilling (Poon et al., 2003), harm the environment through the pollution (Esin and Cosgun, 2007), and cause wastage of the natural resources. Yet, C&D waste is unavoidable. Hence, many of the research works have been carried out in the recent decades to find out a feasible solution to minimize the generation of C&D waste (Yuan and Shen, 2011).

According to US EPA, about 530 million tons of C&D waste was generated in the United States in 2013 which is 10 million tons more than the generation in 2012. C&D waste is generally disposed in C&D landfill, MSW landfill and sometimes illegally in unpermitted areas thereby increasing the chances of ground water contamination. C&D waste produces hydrogen sulfide gas which is malodorous and detrimental to environment and human health. In addition, C&D waste consumes significant amount of landfill volume when disposed in landfills. Therefore, disposing C&D waste in the landfills becomes a critical issue considering cost and availability of land. Several studies have been done on the C&D waste management and these studies emphasized on diverting C&D waste from landfilling. The current study focuses on the primary objective of estimating the volume and lift height gain through C&D waste diversion from the City of Denton Landfill. The study will help understanding space recovery in a landfill cell by diverting C&D waste from the main waste stream.

1.3 Research Objective

The main objective of this study was to estimate the gain in landfill space that can be obtained by diverting C&D waste from landfill disposal. The main tasks that were undertaken to achieve this objective are as follows:

- Collection of C&D wastes.
- Determination of the physical composition of the collected waste.
- Determination of moisture content.
- Determination of unit weight.
- Determination of volatile solids.

- Collection of C&D waste annual tonnage data of City of Denton landfill.
- Estimation of gain in landfill volume by diverting C&D waste.

1.4 Thesis Organization

This thesis is comprised of five chapters: Introduction (Chapter 1), Literature Review (Chapter 2), Methodology (Chapter 3), Results & Discussion (Chapter 4) and Conclusions & Recommendation for future work (Chapter 5).

The first chapter presents general information of the study, problem statement, research objectives and a brief outline of the thesis organization.

The second chapter offers the literatures on C&D waste generation, composition of C&D waste, estimation methods, and C&D waste management.

The third chapter describes the location of area of study, experimental setups, and required laboratory test methodologies to address the research objective.

The fourth chapter discusses about the test results obtained from the various laboratory tests that was performed on the C&D waste samples and estimates the landfill space that can be gained by diverting C&D waste from landfill disposal.

The fifth chapter summarizes the main conclusions of the present study and some recommendations for future research work.

Chapter 2

Literature Review

2.1 Introduction

The term ‘‘C&D waste’’ is commonly used to refer to the solid waste generated in and from the construction sector. To be precise, it is defined as the waste which arises from construction, renovation and demolition activities which include land excavation or formation, civil and building construction, site clearance, demolition activities, roadwork, and building renovation (Shen et al., 2004).

US EPA (1998) has defined Construction and demolition (C&D) waste is the waste stream produced as a result of any construction, renovation and demolition of structures such as buildings, roads and bridges. Because new technologies are being used for the construction purposes, components of C&D waste vary largely. As such C&D components also vary a great deal with the construction type and the methods used by the construction industry (US EPA 1998).

C&D debris have been historically considered to be non-hazardous which are relatively inert and composed of materials that do not pose any undue environmental risk. However, potentially dangerous materials have been found in some C&D sources. Heavy metals such as lead (paint, pipe solder, flashing, batteries), mercury (lighting, electrical switches, thermostats), cadmium (batteries, paints), and arsenic (treated wood) are common ingredients of many building components which are categorized under environmentally dangerous substances, and these have been found in C&D wastes (Clark, Jambeck and Townsend 2006).

2.2 Sources and Origin of C&D Waste

From the inception of construction project to construction and demolition, C&D waste is produced from different sources. Based on the origination of C&D waste can be categorized into the following categories: contractual, design, procurement, transportation, on-site management and planning, material storage, material handling, site operations, residual, and other (Osmani et al., 2008). Various origins and causes of C&D waste are tabulated in Table 2.1.

Table 2.1 Sources and Origin of C&D Waste (Osmani et al., 2008)

Origins of Waste	**Causes of Waste**
Contractual	Errors in contract documents
	Contract documents incomplete at commencement of construction
Design	Design changes
	Design and detailing complexity
	Design and construction detail errors
	Unclear/unsuitable specification
	Poor coordination and communication (late information, last minute client requirements, slow drawing revision and distribution)
Procurement	Ordering errors (i.e., ordering items not in compliance with specification)
	Over allowances (i.e., difficulties to order small quantities)
	Supplier errors
Transportation	Damage during transportation
	Difficulties for delivery vehicles accessing construction sites
	Insufficient protection during unloading
	Inefficient methods of unloading
On-Site Management and Planning	Lack of on-site waste management plans
	Improper planning for required quantities
	Delays in passing information on types and sizes of materials and components to be used
	Lack of on-site material control
	Lack of supervision
Material Storage	Inappropriate site storage space leading to damage or deterioration
	Improper storing methods
	Materials stored far away from point of application

Table 2.1—*Continued*

Material Handling	Materials supplied in loose form
	On-site transportation methods from storage to the point of application
	Inadequate material handling
Site Operations	Accidents due to negligence
	Unused materials and products
	Equipment malfunction
	Poor craftsmanship
	Use of wrong materials resulting in their disposal
	Time pressure
	Poor work ethics
Residual	Waste from application processes (i.e., overpreparation of mortar)
	Off-cuts from cutting materials to length
	Waste from cutting uneconomical shapes
	Packaging
Other	Weather
	Vandalism
	Theft

About 33% of on-site waste is produced as a result of designers' failure to implement waste reduction measures during the design phase (Innes, 2004). A major origin of C&D waste production is the changes in design during the construction (Bossink and Brouwers, 1996; Faniran and Caban, 1998). There are two ways in which C&D waste is generated due to the change in design. First, if the design is changed after purchasing construction materials based on original design and the material cannot be resold or returned to the supplier, then it has to be discarded or disposed which causes the generation of C&D waste. Second, if there is a change in design of a structural part which has already been built, then that part might have to be dismantled causing the wastage of the material which cannot be salvaged for reuse (Faniran and Caban, 1998).

The process of minimizing the generation of construction waste through design is complex as buildings incorporate various materials and processes (Keys et al, 2000.). Also, involvement of number of stakeholders; clients, contractors, sub-contractors and suppliers who generate C&D waste directly or indirectly makes the process of designing out construction waste even more complex.

2.3 Components of C&D Waste

Wastes produced from the construction, renovation, and demolition of buildings, bridges and roads are included in C&D waste. Wood, asphalt, concrete, brick, metals, gypsum drywall and roofing are typical materials included in C&D waste. As C&D waste is regulated in state level, different states have different definition of C&D waste and also the materials included in C&D waste streams are different. Some states include site clearance waste such as soil, rocks and yard wastes such as stumps in their definitions (US EPA, 1998; Clark et al. 2006). Typical components of building related C&D waste is tabulated in table 2.2.

Table 2.2 Typical Components of Building Related C&D Waste (US EPA 1998)

Materials	Content examples
Wood	forming and framing lumber, stumps, plywood, laminates, scraps
Drywall	sheetrock, gypsum, plaster
Metals	pipes, rebar, flashing, steel, aluminum, copper, brass, stainless steel
Plastics	vinyl sliding, doors, windows, floor tiles, pipes
Roofing	asphalt and wood shingles, slate, tile, roofing felt
Rubble	asphalt, concrete, cinder blocks, rock, earth
Brick	bricks, decorative blocks
Glass	windows, mirrors, lights
Miscellaneous	carpeting fixtures, insulation, ceramic tile

The composition of the C&D waste depends on the activity generating the waste (Cochran, 2006; US EPA, 1998). As the materials used in buildings have not changed much over time, the composition of C&D waste has not changed and is not likely to change much in the near future as well. At construction and renovation sites, wood is found to be the most common material, whereas at the demolition site, concrete is the most common material (US EPA, 1998).

Out of 530 million tons of C&D waste generated in the United States in 2013, Portland cement concrete has a largest share of 67%, asphalt concrete accounted for 18%, wood products contributed 8% and the other products accounted for 7% combined (US EPA, 2015). Table 2.3 shows the composition of C&D waste based on the activity. And, the composition of C&D waste generated in 2013 is shown in Figure 2.1.

Table 2.3 C&D Waste Generation by Materials and Activity (US EPA, 2015)

	Waste During Construction (million tons)	**Demolition Debris (million tons)**	**Total C&D Debris (million tons)**
	2013	**2013**	**2013**
Portland Cement Concrete	17.5	335.4	352.9
Wood Products	2.5	37.7	40.2
Drywall and Plasters	3.1	9.9	13.1
Steel	0	4.3	4.3
Brick and Clay tile	0.3	11.8	12.1
Asphalt Shingles	1	11.6	12.6
Asphalt Concrete	0	95.1	95.1
Total	**24.4**	**505.8**	**530.3**

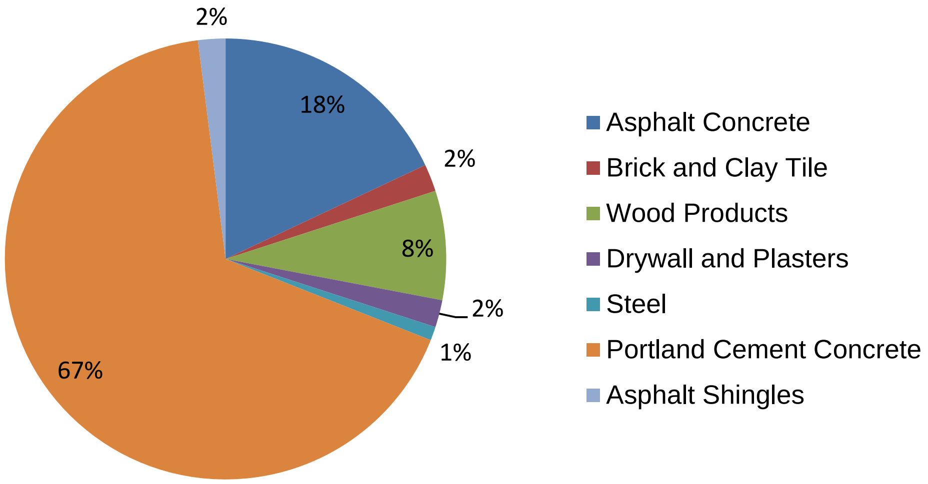


Figure 2.1 Composition of C&D Waste in 2013 (US EPA, 2015)

2.3.1 Methodologies to Identify Composition of C&D Waste

The physical composition C&D waste can be determined by mass sorting, visual characterization and photogrammetry.

2.3.1.1 Mass Sorting

Mass sorting is the method of estimating C&D waste composition by measuring the weight of each component in the waste stream. In this method, loads are chosen randomly at a landfill and are separated into different components. These components are thein weighed (Reinhart et al, 2002). Mass sorts can potentially provide the highest level of accuracy for waste characterization as they include hands-on information about the waste. But because of their labor intensive nature, they cannot always be feasible. It is also tedious, less cost efficient, more inefficient, and riskier than other waste characterization techniques (Reinhart, Behzadan & Toth, 2011).

Mass sorting, because of its onsite characteristic, is typically performed at operating landfills, MRFs, or transfer stations. Loads are diverted to predetermined sorting areas. Workers involved in the procedure are exposed to dust particles, hypodermic needles, and tetanus, seriously challenging their health. Scales, rakes, shovels, gloves, magnets, and knives are the tools that are used. These also add expenses to the process compared to other methods (Carr, 2009). To come up with a representative estimation, a large number of waste samples has to be examined which takes a lot of time. Also, this method is not suitable for waste stream containing heavy and bulky waste materials.

In 2004, mass sorting method was used by the researchers to characterize the waste stream in the greater Rustenburg municipal area of South Africa (Zitholele Consulting Group, 2007). Thirteen sorters, two supervisors, a truck driver, a municipal supervisor and three laborers collected 50 random samples of waste entering the local landfill. Also, California researchers in 2008 performed mass sorts to characterize its waste stream. More than 750 samples were sorted at 27 disposal facilities around the state with almost 7,000 vehicles being surveyed to determine the origin of waste (Cascadia Consulting Group, 2008). The process including the days used for sampling had taken a total of 61 days.

2.3.1.2 Visual Characterization

Visual characterization is the process of estimating the C&D waste volume composition load by observing the load, generally at the landfill, and estimating the percent volume distribution by visual observation (Reinhart et al, 2002). Multiple researchers visually estimate the waste load composition and the average value from such observations is used as the volume distribution. This volume data is then used for the debris inventories' construction on a volume basis. Reliable composition estimates can be obtained from the available data for C&D waste streams using visual characterization. Since it does not take a long time and no special tools as well, this method is more feasible both in terms of cost and time, and hence is preferred to the mass sorting method.

Many research works have employed this method for determining waste composition. University of Central Florida and the Florida Institute of Technology conducted a study on seven of the Florida landfills in 2002 (Reinhart et al, 2002). Similarly, a study was conducted for the North Central Texas Council of Governments in 2006 that used this method for waste characterization of C&D debris waste characterization arriving at the North Texas Municipal Water District (NTMWD) McKinney Landfill. Visual characterization was employed during two one-week waste characterization events. More than 600 loads totaling over 4,300 tons were visually inspected and categorized (R.W. Beck, 2007).

2.3.1.3 Photogrammetry

Photogrammetry is the science that makes reliable measurements by the use of photographs (Reinhart et al, 2002). It can be used to estimate size, mass, volumes and quantities of materials in C&D debris samples. This method holds best for waste characterization when direct access to C&D samples is difficult or is uneconomical. It is especially useful for waste characterization in post-disaster conditions. For example, the Federal Emergency Management Agency (FEMA) uses aerial and satellite photography to produce quick estimates of C&D debris after a disaster (FEMA, 2010). Such estimates are later validated through ground measurements or computer models. FEMA recommends using photogrammetric techniques when a disaster has made an area difficult to access or in cases where it is difficult to obtain a good perspective on debris quantities from the ground e.g., estimating the size of very large debris piles at debris management sites (FEMA, 2010).

In the photogrammetry method, C&D debris estimates are obtained selecting an object of reference within the photo to obtain a dimensional scale (Reinhart et al, 2002). After the dimensional scale has been obtained, it is applied to determine the size of C&D debris objects in the photograph. Then, debris estimating formulas are applied to estimate debris mass quantities (Reinhart & Behzadan, 2011).

2.4. Generation of C&D Waste.

Globally, quite a substantial amount of C&D waste is annually generated. Sandler and Swingle (2006) explored that approximately 136 million tons of building-related C&D debris is generated annually in the US alone, out of which only 20–30% is recycled.

In the UK, annual generation of C&D waste was reported to be around 70 million tons of C&D materials and soil, all of which was fond to be ended up as waste (DETR, 2000). And the rate of wastage production from the construction industry in the UK construction industry was found to be as high as 10–15% (McGrath and Anderson, 2000). In Australia, it accounts for 16–40% of the total solid waste (Bell, 1998). In Hong Kong, as per the Environment Protection Department (EPD) report, about 2900 tons of C&D waste was received at landfills on a daily basis (Hong Kong EPD, 2007). Emerging economy China produces 29% of the world’s municipal solid waste (MSW) each year, of which construction activities contribute for nearly 40%(Dong et al., 2001; Wang et al., 2008).

2.4.1 Factors Affecting Generation of C&D Waste.

A number of factors affect C&D waste generation such as volume of construction, demography and economy (Sullivan, 2012). The generation of C&D waste is significantly affected by the volume of construction work. More construction activities increase the possibilities of generation of more construction waste. With the increase in construction volume at present, the generation of C&D waste is certain to increase in the future when these structures are demolished at the end of their service lives.

Another factor affecting the C&D generation is demographic factor (US EPA, 2003). With the increase in population, the need for basic and supporting infrastructures is increased proportionally. As a result of which construction of residential, commercial and institutional structures such as houses, schools, offices, parking and other structures is increased which in turn increases the generation of C&D waste. This also implies that in the areas with considerably smaller population, there will be less wear and tear on the structures such as bridges, roads, and buildings. Thus, less renovation activities are required and hence the production of C&D can be expected to be less than that in the areas with larger population.

As economy of a region boosts, business in that region will flourish and new job opportunities will be created. Thus, construction activities in economically sound region will increase as there will be demand for offices for business and homes for workers. This will result in higher production of C&D waste in economically sound regions.

2.4.2 Methodologies for Estimating C&D Waste Generation.

The amount of C&D waste generated in the United States was first estimated by Franklin Associates in 1998 using a methodology similar to the waste-weight-per-construction-area method. In this method, average generation of waste per building area along with some measure of the construction, renovation, or demolition activity level in a region are used to determine the generation of waste. Waste generated can be calculated by using the equations 2-1 and 2-2. This method was adopted by Cochran et al. (2007) to determine the amount of waste generated in Florida, US.

$$\text{Waste Generated (kg)} = \text{[Area of Building Constructed, renovated, or demolished (m}^2\text{)]} \times \text{[Average Waste generated per area (kg/m}^2\text{)]} \quad (2\text{-}1)$$

$$\text{Waste Generated (kg)} = \frac{\text{[Cost of construction, renovation, or demolition in a region (\$)]}}{\text{[Average cost of construction, renovation, or demolition per area (\$/m}^2\text{)]}} \times \text{[Average Waste generated per area (kg/m}^2\text{)]} \quad (2\text{-}2)$$

C&D waste generation and composition can also be estimated by waste facility sorts, visual characterizations and monitoring. The amount of waste generated can be estimated by monitoring the wastes arriving to the waste management facilities. To come up with a representative estimation, a large number of waste samples has to be examined which takes a lot of time. Also, this method is not suitable for waste stream containing heavy and bulky waste materials.

Cochran and Townsend (2010) used material flow analysis method to estimate the generation of C&D waste in the United States. This method takes the amount and service life of materials into account and predicts the amount of waste generated at the end of the service life. The flow of materials in and out of the structures during construction, renovation and demolition is shown in the Figure 2.2.

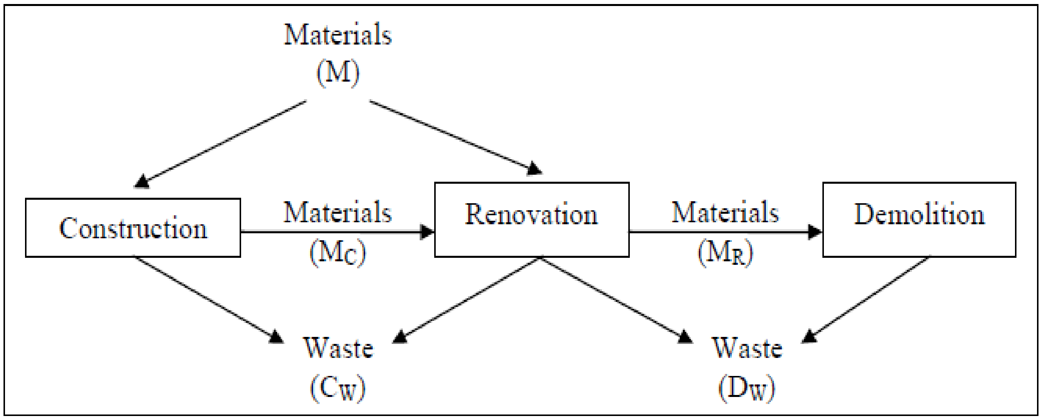


Figure 2.2 Flow of Material During Construction, Renovation and Demolition of Structures. (Cochran and Townsend, (2010))

This methodology does not consider the origin of materials; materials produced in the United States and imported to United States both contribute to the total (M). All material purchased (M) does not end up in the structures as part of it is discarded during construction and renovation (C_w). The amount discarded (C_w) is some portion (w_c) of the materials (M) and can be calculated using the equation 2-3. Table 2.4 lists the average portion discarded during construction.

$$C_w = M \times w_c \qquad (2\text{-}3)$$

Table 2.4 Percentage of Materials Discarded during Construction

Material	Percent
Concrete	3%
Asphalt Concrete	0%
Brick and other clay products	4%
Drywall and other calcined gysum products	10%
Steel/ Iron Products	0%
Wood Products	5%
Asphalt shingles	10%

Source: As cited in Cochran and Townsend (2010): DelPico (2004) and Thomas (1991)

Materials that are incorporated in any structure will remain in that structure until it is removed as demolition waste (D_w) during renovation and demolition. Demolition waste (D_w) can be calculated by subtracting construction waste (C_w) from total materials (M) as shown in equation 2-4.

$$D_w = M - C_w \qquad (2\text{-}4)$$

All materials have their own finite service life and different materials have different service life depending on their durability and desirability. When the service life of material is known, it can be determined when that material will come out of service and become a part of waste stream. Table 2.5 shows the range and typical service life of materials used by Cochran and Townsend (2010).

Table 2.5 Lifespan of Construction Materials by Source (Years)

Material	**Application**	**Service Life**	
		Range	**Typical**
Portland Cement Concrete	Building	50-100	75
	Roads/Bridges	23-40	25
	Other Structures	20-50	30
Asphalt Concrete	Roads	12-33	20
Masonry cement	Building	50-100	75
Brick	Building	50-100	75
Steel/Iron	Building	50-100	75
Wood lumber and Plywood	Building	50-100	75
Wood-wood panel	Building	20-30	25
Gypsum products	Building	25-75	50
Clay floor and wall tile	Building	15-25	20
Asphalt shingles	Building	20-30	25

Source: As cited in Cochran and Townsend (2010): Zapata and Gambatese (2005), Katz (2004), Park et al. (2003), Scheuer et al. (2003), Junnila and Horvath (2003), Chapman and Izzo (2002), Cross and Parsons (2002), Thormark (2002), Keoleian et al, (2001), Horvath and Hendrickson (1998), Bolt (1997), and Packard (1994).

2.5 C&D Waste in US

Construction and demolition activities occupy a large portion of the total solid waste stream in the United States. In 1998 the total annual C&D waste generation was 136 million tons (US EPA, 1998). The C&D waste is estimated to be around 40% of the total solid waste stream in the US (LEED 2003). This trend has been increasing annually. US EPA (2015) has reported the increment in C&D waste generation in 2013 compared to that in 2012. In 2012, total C&D waste generation was about 520 million tons which increased to 530 million tons in 2013. This growth can be attributed to the increased construction works. Roads and bridges were significant contributors to C&D waste generation in the United States in 2013 compared to buildings and other structures. Figure 2.3 illustrates generation of C&D waste in the US in 2013 by material and source. Over 90% of total C&D waste generated in 2013 was comprised of demolition debris (US EPA, 2015).

It has been estimated that average new construction yields 3.9 pounds of waste per square foot of building area and average building demolition yields 155 pounds per square foot (Dion and Tessicini. 2006). This means a 50,000 sq.f newly constructed building will yield 100 tons of C&D waste while demolishing a 50,000 sf building will yield 3875 tons of C&D waste. Further, building construction accounts for 40% of all raw materials used and 75% of that ends up as waste (Dion and Tessicini 2006).

The contribution of construction and demolition phases to total C&D Debris Generation in 2013 is shown in Figure 2.4.

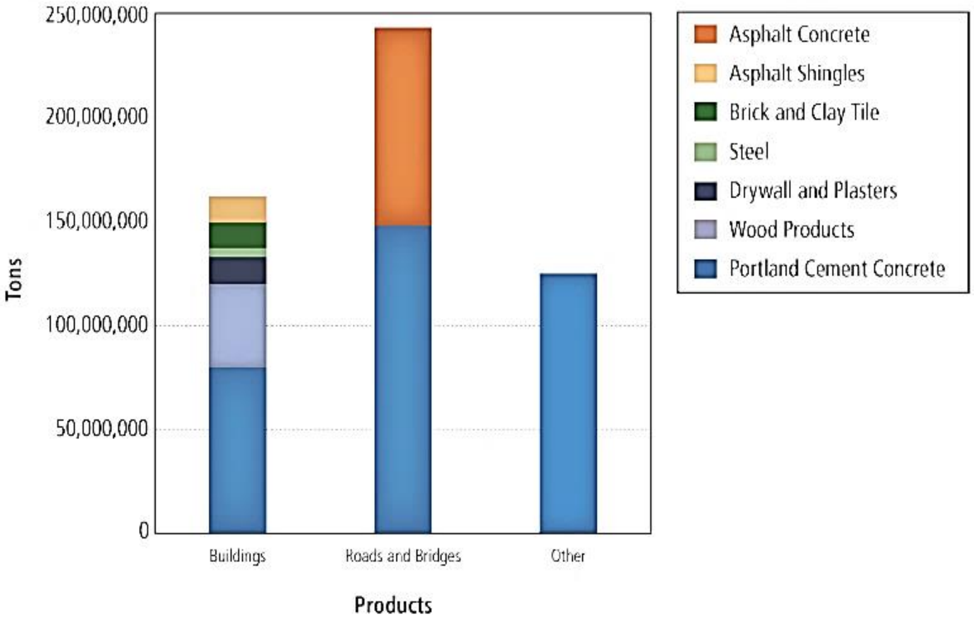


Figure 2.3 Generation of C&D Waste by Materials and Source in 2013. (US EPA, 2015)

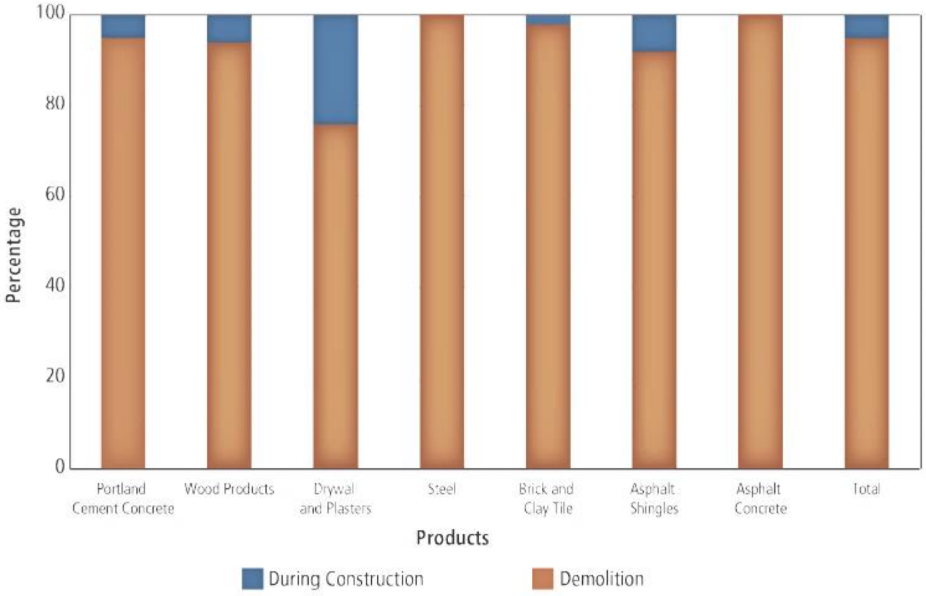


Figure 2.4 Contributions of Construction and Demolition Phases to Total C&D Debris Generation in 2013. (US EPA, 2015)

According to Texas Commission on Environmental Quality (TCEQ, 2014), in 2013, about 5,334,017 tons of C&D waste was disposed in landfills in Texas. After municipal waste, which accounted for 66% of the total waste disposed at landfill, C&D waste was the second largest waste type disposed in MSW landfill in Texas with about 17% of the occupancy. Figure 2.5 shows the types and amount of solid wastes landfilled in Texas in 2013.

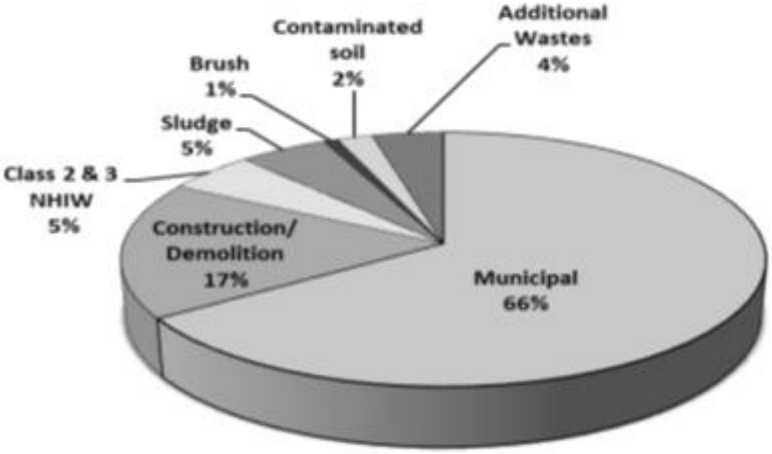


Figure 2.5 Types and Amounts of Solid Waste Landfilled in 2013 (TCEQ, 2014)

2.5.1 C&D Waste Regulations in US

2.5.1.1 Federal Regulations

There's no explicit regulation for C&D debris at federal level, the solid and hazardous waste disposal is covered by the Resource Conservation and Recovery Act (RCRA) of 1976. RCRA focuses on i) protection of human health and environment from the potential waste hazards, ii) conservation of energy and natural resources, iii) reduction of waste and iv) management of waste in environment friendly way (U.S. EPA, 2010).

The enactment of RCRA has led to several federal statutes which affect C&D debris. These include the National Emission Standards for Hazardous Air Pollutants (NESHAP) applied to asbestos, and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) applied to hazardous material in C&D debris. Similarly, the Toxic Substances Control Act regulates the disposal of Polychlorinated biphenyl ballasts generated due to renovation and demolition. These standards require the emissions from these pollutants be minimized through the Maximum Achievable Control Technology (MCAT) (Laquatra and Pierce, 2011).

2.5.1.2 State Regulations

Clark *et al.* (2006) have marked a high degree of variation in regulatory aspects of C&D waste among different states. To start with, definition of waste varies in each state. While some states separately define C&D waste, several others include it broadly into the definition of waste. And few others include it in other definitions of waste. For instance, Maryland defines C&D debris within the definition of *processed debris.* Mississippi includes it in its definition of *rubbish* and *industrial processed debris.* A total of 76% of the states in the US have defined C&D waste, 12% have combined it with the definition of other waste, and 8% have defined C&D waste individually as construction debris/waste and 4% have not defined C&D waste at all.

Other requirements such as groundwater monitoring, liner construction, site restrictions, financial assurance, training requirements, and recycling also differ among the states. The differences exist because of the peculiar characteristics of each state. Such peculiarities include annual rainfall, annual temperature range, land availability, and geologic stability. Further, requirements are also affected by the perceptions of the policymakers and regulator and how they value the C&D waste risk to human health and environment in general.

2.5.1.3 Texas Regulation

Texas defines Construction and demolition waste as the waste resulting from construction or demolition projects and includes all materials that are directly or indirectly the outputs of the construction works or that result from demolition of buildings, and other structures which can including, but not limited to, paper, cartons, gypsum board, wood, excelsior, rubber, and plastics. Nonhazardous solid waste is sent to different types of MSW landfills. Type IV MSW landfills can be authorized for the disposal of brush, construction-demolition waste, however the waste should be free of putrescible, household waste, and special wastes. A liner is required for such Type IV MSW landfills which can be composed of (1) at least 1.22 m (4 ft) of in situ soil with permeability no greater than 1×10^{-7} cm/sec between the deposited waste and groundwater or (2) at least 91 cm (3 ft) of compacted clay between the deposited waste and groundwater. Also, the compacted clay liner must have a minimum of 30 cm (1 ft) of protective cover after quality control testing and thickness determinations are complete. Groundwater monitoring is required for all the landfills other than those with arid exempt facilities.

2.6 Environmental and Economic Impacts of C&D Waste

C&D waste generation have a number of significant impacts, both environmental and economic. These require large amount of land for landfilling (Poon et al., 2003), thereby polluting the environment (Esin and Cosgun, 2007), and wasting natural resources. Despite the adverse effects, generation of C&D waste is almost impossible and unavoidable. As such, recent research works focus on minimization and generation of C&D wastes focusing on waste management method that includes hierarchy comprising of four strategies: waste reduction, reuse, recycling, and disposal (Peng et al., 1997). The environmental problems include: (1) diminishing landfill space due to incremental quantities of these disposed wastes in it; (2) depleted building materials; (3)

the increase in contamination from landfills that lead to serious negative health effects; (4) damage to the environment; and (5) the increase in energy consumption for transportation and manufacturing new materials (Roussat et al., 2009: as cited on Marzouk & Azab,2014).

Besides, C&D debris can contaminate water tables and surface waters through leachate. In developing countries, where landfills are not very popular, situation can grow really worse (Arslan, Cosgun and Salgin, 2012). Since the developmental constructions cannot be avoided, alternatives are explored for sustainable waste management. It can also be inferred that the disposal of C&D waste can be quite difficult if its hazardous contents are not taken into consideration. These wastes threaten the human health and the natural/artificial environment with various effects (Arslan, Cosgun and Salgin, 2012).

2.7 C&D Waste Management

With the increase in population and boost in economy, construction business is flourishing day by day. The upsurge in the construction, renovation and demolition activities has consequently increased the amount of C&D waste. The management of C&D waste is getting attention from researchers as well waste managers. In the lack of federal regulations, different waste management options have been adopted by different states.

2.7.1 Hierarchy of C&D Waste Management

C&D waste management is based on the ‘3Rs’ principle. Three R of this principle represent reduction, reuse, and recycling. A hierarchy is obtained when these waste management options are arranged on the basis of resource consumption and environmental impacts (Peng et al. 1997). The hierarchy of the C&D waste management is shown in the Figure 2.6.

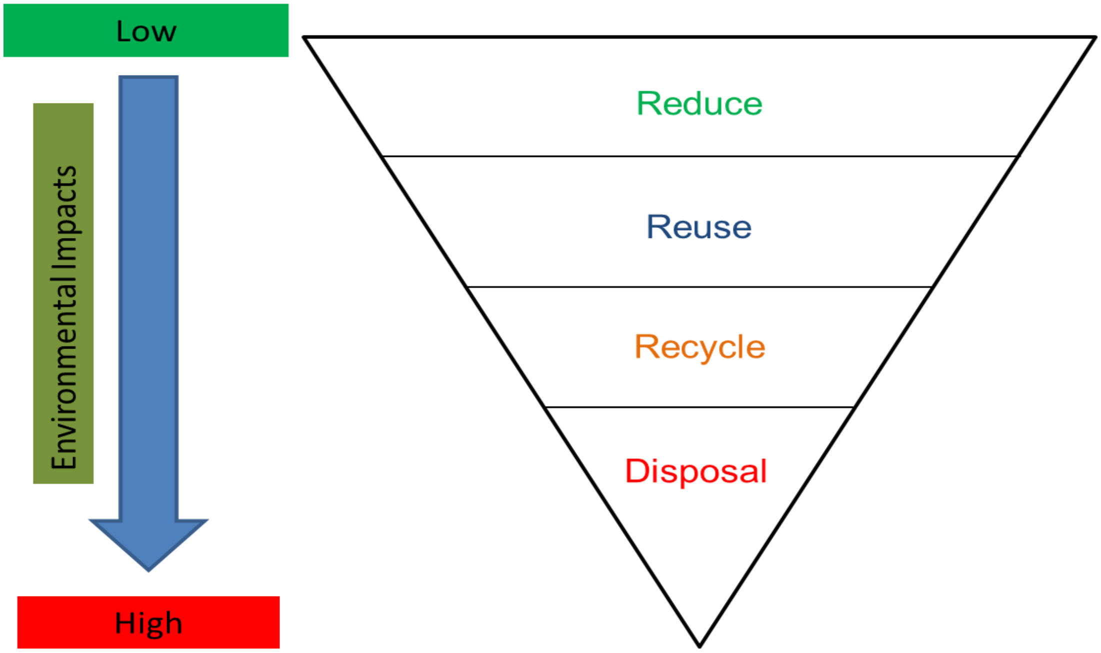


Figure 2.6 C&D Waste Management Hierarchy

2.7.1.1 Reduce

Reduction is the most preferred and effective method for C&D waste management. As this option of waste management focuses on minimizing the generation of C&D waste, the cost related to waste transportation, recycling and landfill disposal fees can be reduced. Also, reduction in C&D waste materials means less amount of waste material will be disposed of at landfill which will help to preserve the landfill space and also reduces the environmental impacts associated with landfilling. Since this method of C&D waste management has less environmental impacts, resorting more to reduction can help us to sustain our environment.

C&D waste can be reduced through governmental legislations. Previous studies have found that C&D waste generation can be reduced through stringent regulations. Also, higher tipping fees can encourage for the reduction of waste generation. Significant amount of C&D waste is produced as a result of design change (Osmani et al. 2008;

Faniran and Caban 1998). Thus, C&D waste can be reduced through proper project design. Low waste construction method such as prefabrication method has also been found to be helpful in reducing C&D wastes. C&D waste can be also be reduced by changing the attitudes of major stakeholders towards waste reduction. Osmani et al. (2008) studied the attitude of architects in the UK and found that they are hesitant to adopt strategies for waste reduction at the design phase as they believe C&D waste management is out of their control.

2.7.1.2 Reuse

Reuse is the second most desirable option after reduction as it less processing and energy is required for this process. Reuse is the process of using the same material several times either for the same purpose or for different purpose. Extraction of virgin raw materials and manufacturing process consumes lot of energy. Therefore, by reusing a material we can make an optimum use of the material, save natural resources, save cost, and preserve our environment. In addition, reusing can reduce the materials that are incinerated or disposed of in landfill and helps to save landfill space.

2.7.1.3 Recycle

Those materials which cannot be reused are collected and processed to make new products. These recycled products reduce the need for the virgin materials and also help to save money and energy associated with extraction of virgin materials (US EPA, 2008). Recycling helps us to divert waste material which will otherwise be incinerated for energy recovery or landfilled.

2.7.1.4 Disposal

Disposal is the process of landfilling waste material with or without energy recovery. It is the least preferred option of waste management as it has higher environmental impacts. When waste in landfilled, there is a possibility of ground water contamination which in turn can cause degradation of environment and human health (US EPA). Also, disposal of waste in landfill increase the potential of GHG emission which can cause the climate change.

2.8 C&D Waste Disposal

Although the landfill disposal of C&D waste is the least preferred option in the hierarchy of C&D waste management, still a significant amount of C&D is disposed in landfill; however, recycling is becoming more common (Clark et al. 2006). About 52% of the total building related C&D waste generated was discarded in 2003, most of which was disposed either in MSW landfills, or C&D landfills (US EPA, 2009). Generally, C&D waste materials are bulky in nature and can occupy 25-40% of landfill space (US EPA, 1998).

C&D waste is regulated in a state level and different states have different regulations for C&D waste landfills. Also, there is wide variation in the state regulations for groundwater monitoring independent of their regulation for liner in C&D landfills. Because of the seemingly inert nature of C&D waste, many states do not have strict regulations for C&D landfills. C&D waste is disposed in C&D landfills, MSW landfills and in some cases it is illegally disposed in unpermitted sites. Based on the study of Clark et al. (2006), twenty seven states do not require liners in C&D landfills. There are no requirements for liners and ground water monitoring in nineteen states, whereas there are nineteen other states which have both liners and groundwater monitoring requirements (Clark et al., 2006).

Studies have suggested that leachate from C&D waste can contaminate groundwater. Townsend (1998) found that leachate resulting from gypsum wallboard present in C&D wastes surpassed the secondary maximum contaminant levels for drinking water in total dissolved solids (TDS) and sulfate levels. In addition to that, Weber et al. (2002) found that the standard levels of water quality for metals such as iron, aluminum, arsenic, chromium and manganese are exceeded by leachate resulting from the disposal of residential construction waste in unlined landfill.

Unlike MSW landfills, C&D waste landfills were supposed to produce little or no biogas as C&D waste materials were considered inert (Flynn, 1998). However, several studies (Johnson, 1986; Lee et al., 2006) have found the generation of hydrogen sulfide (H_2S) gas at C&D waste landfills. Apart from being malodorous, hydrogen sulfide gas has been found to have adverse effect on human health and environment. Problems such as headaches, nosebleeds, nausea, vomiting, difficulty in breathing, depression, and personality changes has been reported by workers and residents exposed to hydrogen sulfide (Kilburn and Warshaw, 1995). At a concentration level of 0.5 parts per billion (ppb), the odor of hydrogen sulfide can be noticed and it can cause unconsciousness and death at approximately 500 ppb (Flynn, 1998). The H_2S emission in MSW landfill accepting C&D waste has been found to be significantly higher than the one not accepting C&D waste. H_2S Level as high as 12,000 ppb has been found at some landfills studied by Lee et al. (2006).

2.8.1 Factors Affecting the Cost of C&D Waste disposal.

Some of the factors which may affect the cost of C&D waste disposal are tipping fee, transportation cost, and equipment and labor cost.

2.8.1.1 Tipping Fee:

Tipping fee is the money charged for given quantity of waste received at waste processing facility for the disposal of waste. Tipping fee depends on the location of the waste processing facility and components of C&D waste being disposed. Waste processing facilities such as energy recovery facilities, material recovery facilities, and transfer stations charge tipping fee, whereas recycling facility may or may not charge tipping fee depending on the C&D waste components. Figure 2.7 shows the mean annual landfill tipping fees of the US from 1982-2013.

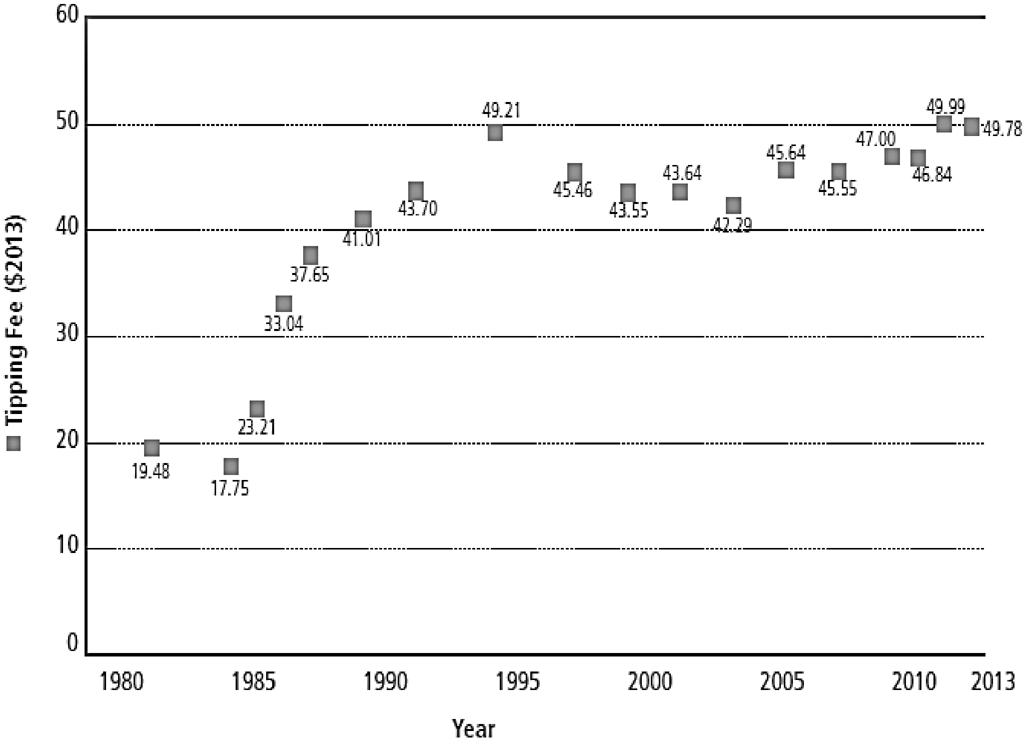


Figure 2.7 Mean Annual Landfill Tipping Fee, 1982-2013 (US EPA, 2015)

Disposal rates have been found to decrease with the increase in tipping fee which in turn increases the recycling rates. Campman (2001) found that people tend to dispose less and recycle more waste when tipping fee is increased so as to keep their costs down. A similar trend of increased recycling rates with the increase in tipping fee was found in another study done by Brooks (2005). Several studies and researchers have found a direct relationship between tipping fees and recycling and diversion rates.

2.8.1.2 Transportation Cost:

Factors such as hourly rate of driver, the cost to rent a truck, the hourly cost of operation and maintenance on the truck, the fuel cost, the distance between waste disposal facility and waste generation site, and any miscellaneous costs such as taxes, or storage fees determine the cost of transportation. The total cost of transportation is obtained by multiplying the hourly costs with the total hours required to drive to the waste disposal facility. The time required to take the waste from generation site to waste disposal facility depends on the distance between the site and facility and the traffic condition of road. The loading and unloading time is also considered while calculating the total number of hours required for transporting C&D waste.

2.8.1.3 Labor and Equipment Cost:

There are two categories in which labor cost for waste disposal can be divided. One category includes the cost of labor required to collect, separate, and load C&D wastes or different components of C&D wastes for recycling or reuse. This cost can be determined by using the hourly rate of each workers and the time required to do the assigned job. Another category includes the cost of labor required to prepare specific materials for acceptance by recycling centers.

Equipment is used for the collection, separation, loading and unloading of C&D waste. The costs of renting or owning such equipment, operating and maintaining the equipment are incorporated in the equipment cost. Total equipment cost can be calculated by multiplying hourly rate of equipment with the time required to perform the tasks.

2.9 C&D Waste diversion

Management of solid waste reduces the adverse environmental and health impacts and also supports economic development and improved quality of life. A number of processes are involved in effectively managing waste for a municipality. These include monitoring, collection, transport, processing, recycling and disposal.

With growing construction works, C&D waste generation has been increasing rapidly. However, land resources being limited, not all these waste can be dumped in the landfills. This would neither economically nor environmentally be feasible. Different waste management approaches have been applied to deal this issue, waste diversion being one of the most feasible approaches. Waste diversion is identified as a process of removing material from the waste stream that would otherwise end up in a landfill. Wastes may be diverted in many ways, including recycling and composting (USEPA, 1999).

C&D debris includes concrete, asphalt (pavement and shingles), wood, gypsum drywall, and metal. These are primary construction materials. It also includes a smaller amount of material such as packaging (paper, plastic, and buckets), carpet scraps, and insulation. In some cases, materials such as municipal solid waste (originating from worker and neighbor waste) and hazardous waste (e.g. lead flashings, fluorescent lamps) also are present in C&D debris. C&D debris is generated from many sources and the waste varies as a function of these sources (e.g. building vs. road construction, construction vs. demolition, residential construction vs. commercial construction). (Reinhart, Townsend and Heck, 2002)

The rise in the amount of C&D waste has caused serious problems both globally and locally. In this context, the management of C&D waste has become one of the major environmental issues in the construction industry. The environmental and economic effects of C&D wastes can be reduced by rational management. The aim of construction C&D waste management is waste minimization and appropriate disposal, both of which help to reduce negative environmental impacts. As C&D wastes are considered an important environmental problem in many countries, many regulations on these issues have been introduced (Arslan, Cosgun and Salgin, 2012).

2.10 C&D Waste Recycling

Recycling is a preferred method in C&D waste management after reduction and reuse option. Apart from environmental benefits, recycling also helps is economic development and reduces the demand for virgin raw materials. The study done by R. W. Beck, Inc. (2001), to quantify the economic impact of recycling has found that recycling industry create more jobs in comparison to any other industries and also, pays higher than the average national wage. By recycling, a material with negative value can be changed into a material or product which is demanded. This is the reason why recycling industry creates higher paying jobs even when the rate of recycling is not that high compared to waste discarded.

C&D waste streams contain a large portion of potentially recyclable materials, but only a fraction of these materials are recycled (US EPA, 1998; Cochran et al., 2007). From the C&D waste stream, concrete, metal, wood and asphalt are commonly recycled (US EPA 1998; US EPA 2008). About 20-30% of the C&D waste was recovered for recycling in 2003. Availability of land, tipping fees, and the market for recycled products are some of the factors that determine the recycling rates. In the states like New York and Massachusetts, recycling rates has been found higher (Cochran, 2004) as the land for disposal is not readily available and the tipping fee is higher.

C&D recycling facilities are costly as the initial capital investment is higher and the sorting process is mechanical and labor intensive. C&D recycling facility is not feasible without appropriate markets, and investment. Moreover, there is always the risk of contamination of recycled products as hazardous material like asbestos, lead, mercury etc. are present in building at demolition time. In comparison to demolition waste, construction waste is cleaner and hence easier to recycle (US EPA 2008). In most of the building demolition cases, the hazardous waste is not removed from building before demolition even though it is recommended to do so (Townsend et al. 2004).

2.10.1 Recyclable C&D materials.

C&D waste materials like concrete, asphalt paving, metals, wood, asphalt shingles, gypsum wallboard, and bricks can be recycled. US EPA (2008) has identified the commonly recyclable materials and their end of life use which are as follows:

- <u>Concrete:</u> Concrete is one of the commonly recycled materials of C&D waste stream. Concrete is first crushed, reinforcement bars if any present is then removed and the crushed concrete is screened for size. Recycled concrete is used as base for road; fill for lakes, aggregates for pavement and as drainage media (US EPA, 2008).
- <u>Asphalt paving:</u> Asphalt paving is first crushed and recycled back into new asphalt. These recycled asphalt paving can be used as aggregates for new asphalt hot mixes and as sub base for road (US EPA, 2008).
- <u>Metals:</u> Metals such as steel, aluminum, and copper are commonly found at construction, renovation and demolition sites and can be easily recycled. These metals are melted and reformed into desired metallic products. Recycled metal has a well-established market (US EPA, 2008).
- <u>Wood:</u> Clean and untreated wood waste is recycled, re-milled into flooring, or chipped to make engineered board, boiler fuel, and mulch. Plywood, large dimensions lumber, timbers, molding and lumber longer than 6 feet can be reused (US EPA, 2008).
- <u>Asphalt Shingles:</u> Nails are first removed from the asphalt shingles and asphalt shingles are then ground and recycled. Recycled asphalt shingles are largely used in hot-mix asphalt. It is also used in the

production of cold patch for potholes, and other asphalt road maintenance. It can also be burned as a fuel and or can be used to make new shingles (US EPA, 2008).

- Gypsum Wallboards: Gypsum drywall is primarily composed of Calcium sulfate (Gypsum) with paper facing and backing. Pieces of gypsum drywall/wallboard found in C&D waste stream can be recycled. The recycled gypsum wallboard can be used to manufacture new wallboard. Also, recovered gypsum can be used as a component in manufacturing cement, compost and some organic fertilizers (US EPA, 2008).
- Bricks: Clean bricks obtained in C&D waste streams is first crushed and then recycled. The recycled brick materials can be used as aggregate, drainage media and general fill material. (US EPA, 2008)

2.10.2 Barriers for C&D Waste Recycling.

C&D waste recycling is affected by several factors including economic, educational, political, and behavioral (Cochran, 2006; US EPA 2008). These barriers are as follows:

- Higher initial investment and excessive permit fees for the recycling facilities.
- Higher cost for collection, sorting, and processing of C&D waste.
- Lower tipping fee for landfill disposal.
- Lower value of recycled material in comparison to virgin materials.
- Stringent regulations for the operation of C&D waste recycling facilities.
- Limited collection area for C&D waste.
- Strict regulations for mobile C&D waste recycling facilities.
- Lack of market for some materials.

- Lack of promotion by states and government for the use of recycled C&D materials.

2.10.3 Benefits of C&D Waste Recycling

Recycling C&D waste has several economic, environmental and social benefits (US EPA , 2008). Some of these benefits are as follows:

- Reduction in greenhouse gas (GHG) emission: By recycling C&D waste materials, we can make use of recoverable materials and eliminate the need of extracting virgin materials. Extraction of virgin raw materials and their transportation to factory can cause the increase in GHG emission and other pollutants which can deteriorate the environment as well as human health.
- Conservation of landfill space: Recycling encourages the recovery of reusable and recoverable materials. In the absence of recycling options, the C&D waste generated has to be disposed in the landfill. C&D waste has bulky nature and can occupy 25-40% of landfill space (US EPA 1998). Thus recycling helps to reduce the quantity of waste to be disposed in the landfill and in turn conserves landfill space.
- Saves energy: Substantial amount of energy is consumed for the extraction of virgin raw materials and manufactural processes of different materials. Recycling reduces the demand for virgin raw materials and also eliminates the manufacturing processes and hence a significant amount of energy can be saved.
- Economic Growth: Recycling involves processes such as collection, sorting and processing of waste materials. For these processes, manpower is required and hence job opportunities will be created by the

recycling facilities. Also, recycling add value to negative value materials and creates something valuable which can be later sold in the market.

- Saves Money: Recycled materials cost less than new materials. Also, there is tipping fee to dispose C&D wastes in the landfill. So, by recycling one can save money associated with the costs of disposal and new materials.

Chapter 3

Methodology

3.1 Introduction

The main objective of this study was to characterize construction and demolition waste samples collected from the city of Denton landfill and to evaluate the landfill space that can be gained by diverting C&D waste from the landfill. A series of laboratory tests were conducted to meet this objective. This chapter mainly focuses on the sample collection and the laboratory test methods conducted to achieve the objective of this study.

To characterize construction and demolition waste, physical composition, moisture content, unit weight, and volatile solids content of C&D waste samples were determined in the laboratory. The volume gain estimation was then based on the unit weight of C&D waste and total amount of C&D waste.

3.2 Study Location

C&D waste samples were collected from the City of Denton Landfill. The City of Denton Landfill is located at 1527 S Mayhill Road on the southeast side of Denton, Texas. An aerial view of the City of Denton landfill is shown in the Figure 3.1.

Figure 3.1 Aerial View of the City of Denton Landfill.

The city of Denton landfill was built in 1983 and it got the permit (permit number 1590) to accept waste on March 7, 1983. The permit was later modified and the permit number changed to 1590 A. The landfill initially had an area of 32 acres which was later expanded in 1998. After the expansion, it now has a total of 252 acres, out of which 152 acres is for waste disposal and the remaining 100 acres is for office buildings, buffer zone, and composting facility. The city of Denton landfill is a type I landfill which means that it is a standard landfill for the disposal of municipal solid waste (MSW). At present the city of Denton landfill has six cells and the former cell is considered as cell zero or cell 1590 A. In 2009, Texas Commission on Environmental Quality approved this landfill to recirculate leachate and storm water for the enhancement of gas production. Approximately 550 tons of municipal waste is received every day in this landfill, of which 80% are commercial waste and remaining 20% are residential. In 2015, the city of Denton landfill received about 20,500 tons of C&D waste.

3.3 Sample Collection and Storage

A total of 10 buckets of C&D waste samples were collected from the City of Denton landfill on October 2015. In the city of Denton landfill, the incoming construction waste and demolition waste are piled up separately in the ground which exposes them to atmospheric conditions. JCB JS160 excavator was used to scoop out the construction waste and demolition waste samples from the pile of the waste. Construction waste samples were collected in five bigger buckets whereas demolition waste samples were collected in smaller buckets. Samples were collected from random locations to ensure collection of the representative samples. For each buckets, 25-40 lbs of C&D waste was collected manually. Buckets containing construction waste were tagged as CW-1, CW-2, CW-3 CW-4 and CW-5 and those containing demolition wastes were tagged as DW-1, DW-2, DW-3, DW-4, and DW-5 based on the sequence of sample collection. The sample collection is shown in Figure 3.2.

Figure 3.2 Collection of C&D waste samples

Collected samples were brought to the Civil Engineering Laboratory Building where these samples were stored and preserved at 4 °C (38 °F) in an environmental growth chamber in order to preserve the moisture and other initial properties of waste. The environmental growth chamber and the storage of sample are shown in Figure 3.3 and Figure 3.4 respectively.

Figure 3.3 Environmental Growth Chambers

Figure 3.4 Samples Stored in Cold Room

3.4 Experimental Program

To determine physical characteristics of the C&D waste, an extensive laboratory investigation was conducted. The details of the experimental program are presented in Table 3.1.

Table 3.1 Experimental Test Program

Test Type	Sample	No of Tests
Physical Composition	Construction Waste	5
	Demolition Waste	5
Moisture Content	Construction Waste	5
	Demolition Waste	5
Unit Weight	Construction Waste	5
	Demolition Waste	5
Volatile Solids	Construction Waste	5

The methodologies adopted to determine the physical characteristics of the C&D waste are described in the following subsections.

3.4.1 Physical Composition

Physical composition of C&D waste samples were performed on weight basis. Each bag of C&D waste samples was poured onto a large plastic sheet and manually sorted into the following categories: Portland cement concrete, asphalt concrete, wood products, drywall and plaster, metals, brick and tiles, cardboard, and C&D debris fines as shown in Figure 3.5. Metal category included items like pipes, rebar, ferrous and non-ferrous metals like steel, copper, brass, aluminum etc. Stumps, plywood, forming and framing lumbers etc. were categorized as wood products. Bricks, decorative blocks, slates, and clay tiles were categorized as bricks and tiles.

Figure 3.5 Physical Composition of C&D waste

After sorting the samples manually, all the components were weighed and expressed in percentage of total waste weight. The total weight in wood products and cardboard were considered as degradable waste fraction and the rest of the weight as non-degradable fraction. The weights of degradable and non-degradable waste were expressed in percentage of total waste weight and the decomposable fraction of the collected C&D waste sample was determined.

3.4.2 Moisture Content

After sorting C&D waste, each component was taken proportionately according to their physical composition to determine the moisture content. ASTM D2974 -14 was followed to determine the moisture content of the C&D samples. A minimum of 2 lbs of C&D waste samples were taken and dried in an oven maintained at 105°C for 24 hours to determine the moisture content. The moisture content of C&D waste samples was determined on both dry weight and wet weight basis. To determine moisture content on wet weight basis and dry weight basis, equations 3-1 and 3-2 were used respectively.

$$\text{Moisture Content, \% (Wet wt. basis)} = \frac{A-B}{A} * 100 \qquad (3\text{-}1)$$

$$\text{Moisture Content, \% (Dry wt. basis)} = \frac{A-B}{B} * 100 \qquad (3\text{-}2)$$

Where, A=Initial weight of sample specimen as delivered.

B = Weight of oven dried sample.

Figure 3.6 shows the sample placed in an oven for the determination of the moisture content.

Figure 3.6 Samples Kept in Oven for Determination of Moisture Content.

3.4.3 Unit Weight

The unit weight of C&D waste samples was measured at their in-situ moisture content according to the Standard Proctor Compaction method (ASTM D698). A larger compaction mold with 6 inch inside diameter, 6.1 inch height, with a volume of 1/10 cubic feet with detachable collar was used. The mold was filled with three layers of C&D waste up to the rim. A 5.5 lbs. hammer was dropped 75 times with a fall height of 12 inch on each layers of C&D waste. Based on calculation of compaction energy per volume, it was found that 75 blows will be required in each layer when mold with volume of 1/10 cubic feet is used.

Energy transferred per unit volume in Standard Proctor test, $E = n \times h \times (P/V)$

Where, n = number of blows, h = fall height, P = weight of hammer and V = volume of the mold.

P and h are equal for the regular sized and larger mold.

For normal sized mold, $E_1 = n_1 \times h \times (P/V_1)$

For larger sized mold, $E_2 = n_2 \times h \times (P/V_2)$

As the compaction energy is to be same,

$$E_1 = E_2$$

$$n_1 \times h \times (P/V_1) = n_2 \times h \times (P/V_2)$$

$$n_2 = n_1 \times (V_2/V_1)$$

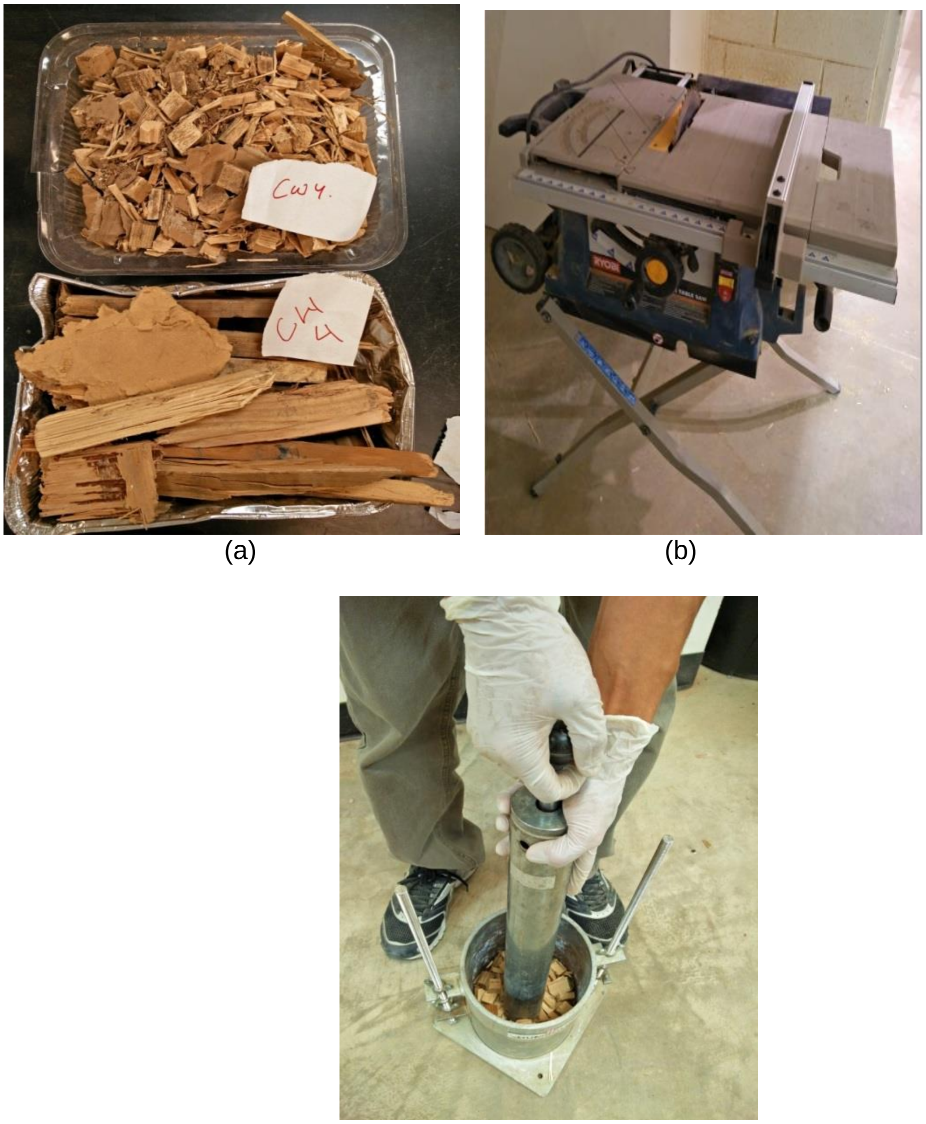
$$n_2 = 25 \times (1/10)/(1/30)$$

$$n_2 = 75$$

As C&D waste samples were bulky in size, it was first broken into smaller pieces. Concrete was broken by hammering whereas automatic woodcutter was used to cut wood into smaller pieces. The smaller pieces were then used for the compaction test. Figure 3.7 shows the compaction of C&D waste for the unit weight determination.

The unit weight of the solid waste was calculated using equation 3-3.

$$\text{Unit weight} = \frac{\text{Weight of compacted C\&D waste in the mold (lb)}}{\text{Volume of the mold (ft3)}} \qquad (3\text{-}3)$$



(a) (b)

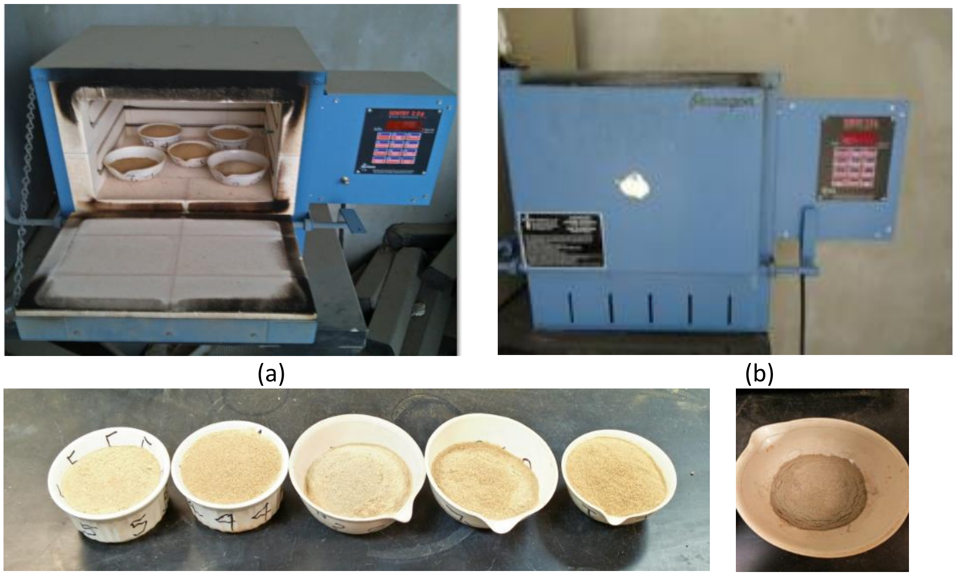
(c)

Figure 3.7 (a) Size Reduction of the Sample for Compaction, (b) Automatic Woodcutter, (c) Compaction of C&D Waste

3.4.4 Volatile Solids

Only construction waste was used for the determination of volatile solids as demolition waste majorly consisted of concrete, brick and tiles for which the volatile solids is low. To determine the volatile solids present in construction waste sample, modified version of Standard Methods APHA Method 2440-E was adopted. For the determination of volatile solids, construction waste samples oven dried at 105°C were first ground into smaller pieces. For each test, approximately 50 grams of dried sample were taken in pre-weighed porcelain crucibles and were placed in the muffle furnace at 550°C for two hours to burn completely to ashes. Test equipment and setup are shown in Figure 3.8. The burnt sample was then weighed to determine the loss in weight due to burning. The percentage of total weight of dry C&D sample lost during burning gives the volatile solid content of the sample, and the volatile solids can be determined using the equation 3-4.

$$\text{Volatile Solids} = \frac{\text{Weight lost due to burning}}{\text{Dry weight of the sample before burning}} \times 100\ \% \qquad (3\text{-}4)$$



(a) (b)

(c) (d)

Figure 3.8 (a) Muffle Furnace, (b) Construction Waste Sample Placed in Muffle Furnace, (c) Construction Waste Sample for Volatile Solid Tests, (d) Burnt Sample

Chapter 4

Results and Discussions

4.1 Introduction

In this chapter, the results of the laboratory tests that were conducted on the C&D waste samples are presented and analyzed to evaluate the gain in landfill volume by diverting the C&D waste from disposing off in landfill. A total of 10 samples of C&D waste; 5 samples of construction and 5 samples of demolition waste; were collected from the City of Denton landfill. All the samples were sorted out to determine the physical composition. In addition, moisture content, unit weight and volatile solids content of the waste samples were also determined.

The test results for the physical composition, moisture content, unit weight, and volatile solids of all the waste samples are presented in first subsection. These test results along with the C&D waste tonnage data obtained from the city of Denton landfill were used to evaluate the gain in landfill volume resulting from the diversion of C&D waste. The volume gain estimation is presented in the second subsection.

4.2 Test Results

The results of the tests conducted to characterize C&D waste is discussed in this section. Physical composition, moisture content, unit weight and volatile solids were determined to achieve the objective of this study.

4.2.1 Physical Composition

Ten buckets of samples were collected from the City of Denton Landfill. Among those10 samples, 5 samples were construction waste and 5 samples were demolition waste. All these waste samples were sorted out manually and physical composition was determined on the weight basis. Results obtained from physical composition of construction waste samples are presented in Table 4.1, Figure 4.1 and Figure 4.2.

Table 4.1 Physical Composition (% by weight) of Construction Waste

Sample No.	Sample Designation	Physical Composition (% by weight)							
		Portland Cement Concrete	Asphalt Concrete	Brick & tiles	Wood Products	Metals	Drywall & Plaster	Cardboard	C&D Debris Fines
1	CW-1	0.00	0.00	0.48	83.31	3.03	1.91	3.69	7.58
2	CW-2	0.00	0.78	0.00	71.36	5.78	0.00	10.80	11.27
3	CW-3	0.00	0.00	0.00	45.94	0.76	45.99	7.31	0.00
4	CW-4	0.00	0.00	0.00	82.78	0.00	0.00	13.39	3.83
5	CW-5	1.62	0.00	0.00	81.82	3.21	0.00	10.40	2.94
	Average	0.32	0.16	0.10	73.04	2.56	9.58	9.12	5.12
	Standard Deviation	0.72	0.35	0.22	15.93	2.28	20.37	3.72	4.37
	Maximum	1.62	0.78	0.48	83.31	5.78	45.99	13.39	11.27
	Minimum	0.00	0.00	0.00	45.94	0.00	0.00	3.69	0.00

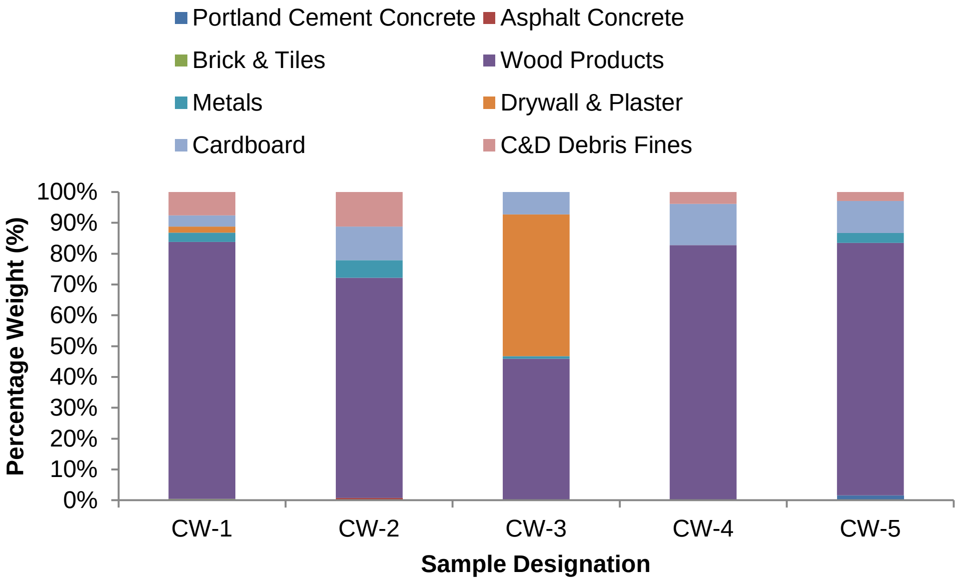


Figure 4.1 Physical Composition of Construction Waste Samples by Weight

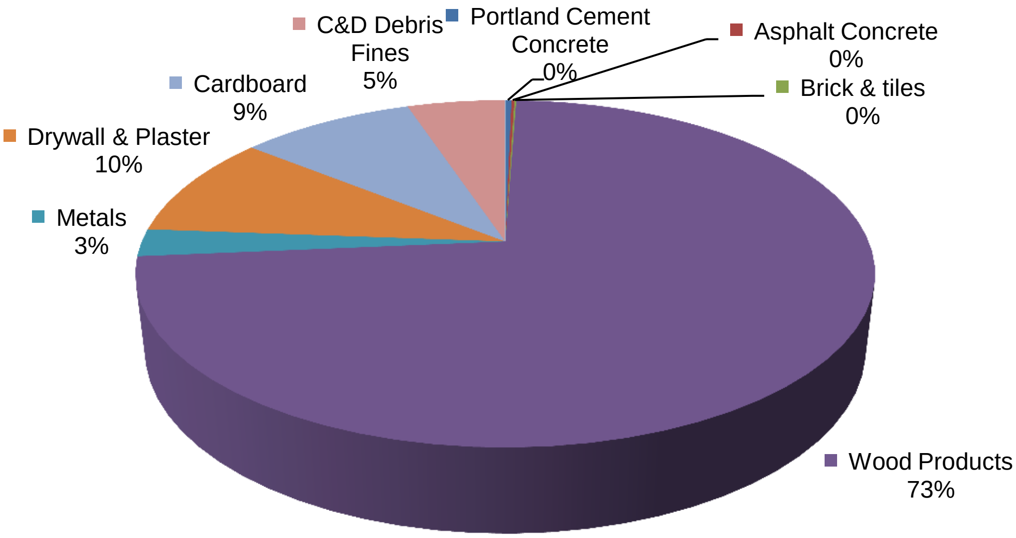


Figure 4.2 Average Physical Composition by Weight of Construction Waste

Physical composition results of demolition waste samples are presented in Table 4.2, Figure 4.3 and Figure 4.4.

Table 4.2 Physical Composition (% by weight) of Demolition waste

Sample No.	Sample Designation	Physical Composition (% by weight)							
		Portland Cement Concrete	Asphalt Concrete	Brick & Tiles	Wood Products	Metals	Drywall & Plaster	Cardboard	C&D Debris Fines
1	DW-1	17.15	9.75	52.55	0.00	0.00	14.61	0.00	5.94
2	DW-2	33.34	8.57	31.68	0.90	0.00	11.78	0.00	13.74
3	DW-3	54.72	36.23	0.46	0.00	0.00	2.15	0.00	6.44
4	DW-4	45.86	35.75	7.42	0.00	0.00	8.60	0.00	2.38
5	DW-5	30.44	8.28	27.30	0.00	0.00	26.61	0.00	7.37
	Average	36.30	19.71	23.88	0.18	0.00	12.75	0.00	7.17
	Standard Deviation	14.50	14.87	20.70	0.40	0.00	9.03	0.00	4.13
	Maximum	54.72	36.23	52.55	0.90	0.00	26.61	0.00	13.74
	Minimum	17.15	8.28	0.46	0.00	0.00	2.15	0.00	2.38

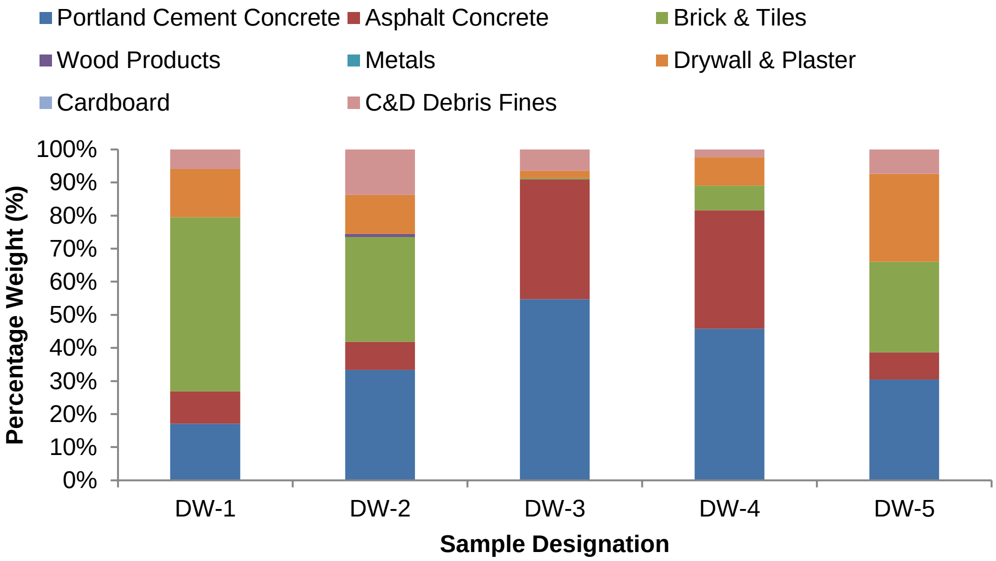


Figure 4.3 Physical Composition of Demolition Waste Samples by Weight

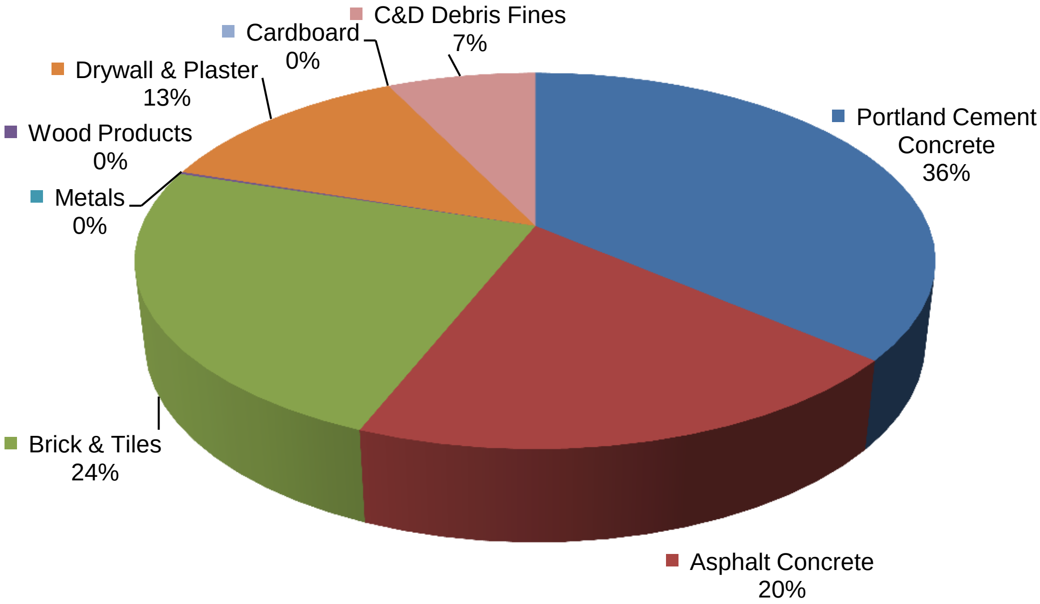


Figure 4.4 Average Physical Composition by Weight of Demolition Waste

Based on the experimental results, wood product was found to be a major component of construction waste. On weight basis, about 73% of the construction waste sample consisted of wood products in average. Portland cement concrete, asphalt concrete, and brick & tiles were not found in construction waste sample. Sample CW-3 consisted of 45% of drywall and plasters, but there were no drywall and plasters found in other construction waste samples. In average, about 9% of cardboard, 2.5% of metals, and 5% of fines were found in the construction waste sample.

Portland cement concrete, asphalt concrete, and brick & tiles were found to be major constituents of demolition waste samples. On weight basis, about 36% of Portland cement concrete, 19% of asphalt concrete, and 23% of bricks and tiles were found in average. About 13% of drywall and plasters were found in the demolition waste samples. Unlike construction waste samples, cardboard, metals, and wood products were not found in demolition waste samples.

The physical composition of C&D waste with equal proportion of construction and demolition waste was calculated by taking arithmetic mean and is tabulated in the Table 4.3.

Table 4.3 Physical Composition of C&D Waste with 50% Construction Waste and 50% Demolition Waste.

S.N.	Components	Construction waste	Demolition waste	C&D Waste
1	Portland Cement Concrete	0.32	36.30	18.31
2	Asphalt Concrete	0.16	19.71	9.94
3	Brick & Tiles	0.10	23.88	11.99
4	Wood Products	73.04	0.18	36.61
5	Metals	2.56	0.00	1.28
6	Drywall & Plaster	9.58	12.75	11.17
7	Cardboard	9.12	0.00	4.56
8	C&D Debris Fines	5.12	7.17	6.15

For C&D waste with equal proportion of construction waste and demolition waste, the average composition illustrates wood products as 37%, Portland cement concrete

18%, asphalt concrete 10%, brick and tiles 12%, metals 1%, Drywall & plaster 11%, cardboard 5%, and C&D debris fine as 6%.

The result of this study was compared with the previous studies results. Table 4.4 shows the results of the physical composition of C&D waste from various studies.

Table 4.4 Comparison of Physical Composition with Previous Studies

S.N.	Study	Year	Components (% by weight)				
			Concrete (and mixed rubble)	Wood	Drywall	Metals	Bricks
1	US EPA	1997	40-50	20-30	5-15	1-5	1-5
2	Florida	2003	32.4	14.8	11.7	5.4	-
3	Wisconsin	2003	12.1	26.3	4.1	3.9	-
4	California	2005	10.8	20.2	8.1	4	-
5	King County, Washington	2002	2.3	45.3	7.1	10.9	-
6	US EPA	2013	84.48	7.58	2.47	0.8	2.28
7	Current Study, Denton, TX	2015	28.25	36.61	11.17	1.28	11.99

The variation in the results of different studies may be because of:

- Methodology adopted for C&D waste characterization: Visual characterization technique was adopted for the characterization of C&D waste in Wisconsin, California and Kings County whereas mass sort technique was used for the current study and for the study conducted in Florida both visual characterization and mas sort techniques were used. Visual characterization is an approximate method whereas mass sorting is more accurate method and provides precise results.
- In addition, US EPA (1997) study shows the results of the characterization of building related C&D waste only whereas the study of

US EPA (2013) includes C&D waste produced from other sources such as road, bridges etc. The components of C&D waste varies with the source and activities producing the waste. Thus, the variation in the results might be due to the variation in source producing C&D waste.

- Also, the study conducted in Wisconsin, California and Kings County, C&D waste sent to landfill disposal excluding C&D materials diverted for recycling, or for fills were characterized whereas for the current study the C&D waste before being diverted for recycling was characterized. As concrete is readily recyclable, the percentage of concrete is relatively lower for the study conducted in Wisconsin, California and Kings county than that for the present study.

In MSW landfill, C&D waste is disposed along with the fresh waste. Thus, the comparison of the physical components of C&D waste with the fresh waste was done to see how C&D waste differs from fresh waste. Based on the study done by Taufiq,T.(2010) on the fresh waste of the city of Denton landfill, the fresh waste contains 40% paper, 18% plastic, and 9% wood. Paper and plastic are compressible in nature and hence occupy less landfill space. On the other hand, C&D waste is mainly composed of woods, concrete, and bricks which are incompressible and occupy more landfill space. Also, the percentage of paper is high in fresh waste and paper being degradable; there will be gain in landfill space with time as paper decomposes. On the other hand, C&D waste has higher percentage of woods, concrete and bricks. Woods degrade slowly and on the other hand concrete and bricks are non-degradable. Therefore, no space could be recovered over time if C&D is disposed in the landfills. C&D volumes will remain constant in the landfills as C&D mostly comprises of non-degradable or slowly degradable components.

4.2.2 Moisture Content

The moisture content of the collected construction and demolition waste samples was determined both on dry and wet weight basis. For the determination of moisture content, about 2 pounds of samples were taken after sorting the samples and were dried at 105 °C for 24 hours as mentioned in section 3.4.2. In average, the moisture content of construction waste was found to be 5.93% on wet weight basis and it was found to be 6.33% on dry weight basis. The result of the moisture content of all construction waste samples is shown in Table 4.5 and Figure 4.5.

Table 4.5 Moisture Content of Construction Waste

Sample No.	Sample Designation	Moisture Content (%) After Sorting	
		Wet Weight Basis	Dry weight basis
1	CW-1	6.47	6.92
2	CW-2	7.92	8.60
3	CW-3	4.18	4.36
4	CW-4	4.93	5.18
5	CW-5	6.17	6.58
	Average	5.93	6.33
	Standard Deviation	1.45	1.64
	Maximum	7.92	8.60
	Minimum	4.18	4.36

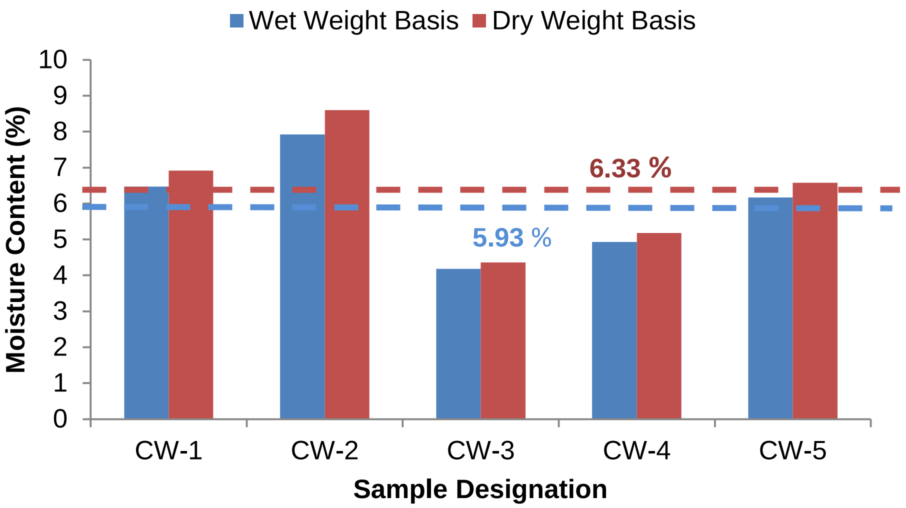


Figure 4.5 Moisture Content of Construction Waste

Moisture content of demolition waste was found to be lower than that of the construction waste. In average the moisture content of demolition waste was found to be 2.73% on dry weight basis and 2.81% on wet weight basis. The result of the moisture content is shown in the table 4.6 and figure 4.6.

Table 4.6 Moisture Content of Demolition Waste

Sample No.	Sample Designation	Moisture Content (%) After Sorting (Uncompacted)	
		Wet Weight Basis	Dry weight basis
1	DW-1	1.47	1.49
2	DW-2	3.44	3.57
3	DW-3	3.33	3.44
4	DW-4	3.21	3.32
5	DW-5	2.19	2.24
	Average	2.73	2.81
	Standard Deviation	0.86	0.91
	Maximum	3.44	3.57
	Minimum	1.47	1.49

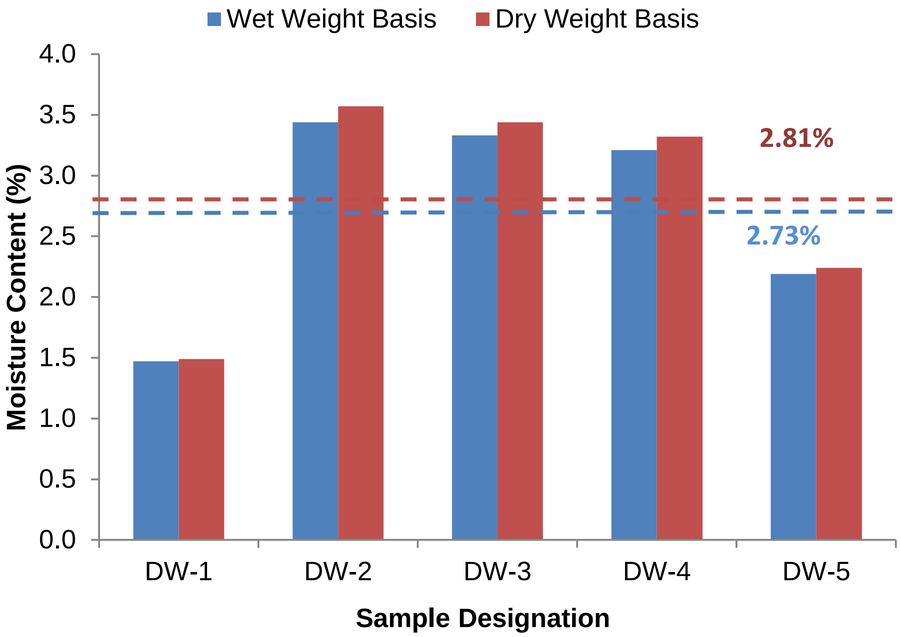


Figure 4.6 Moisture Content of Demolition Waste

Taufiq,T.(2010) found the moisture content of fresh waste from the city of Denton landfill to be about 38% in wet weight basis which is significantly higher than that of the C&D waste. Higher moisture content of fresh waste is mainly due to the higher organic contents present in the waste.

Asakura et al (2010) found the moisture content of finely processed C&D waste in Japan to be in the range of 14.5 -15 % but for our study the moisture content of C&D waste is relatively lower. This might be because the samples were not collected right after the waste was received in the landfill. They were collected from C&D waste pile exposed to open air in the landfill site which may have resulted in lower moisture content than the actual. The variation might also have been caused by the variation in the weather condition of the site from which the samples were collected.

4.2.3 Unit Weight

The unit weight of the samples was determined based on standard proctor test as discussed in section 3.4.3. The test results of standard proctor tests for construction sample is tabulated in the Table 4.7 and Figure 4.7. The unit weight of the construction waste sample was found to be 23.59 pcf in average.

Table 4.7 Unit Weight of Construction Waste Sample

Sample No.	Sample Designation	Compacted Unit Weight		
		pcf	kg/m^3	KN/m^3
1	CW-1	24.60	394.05	3.87
2	CW-2	26.10	418.08	4.10
3	CW-3	22.10	354.01	3.47
4	CW-4	20.80	333.18	3.27
5	CW-5	24.35	390.05	3.83
	Average	23.59	377.88	3.71
	Standard Deviation	2.12	33.89	0.33
	Maximum	26.10	418.08	4.10
	Minimum	20.80	333.18	3.27

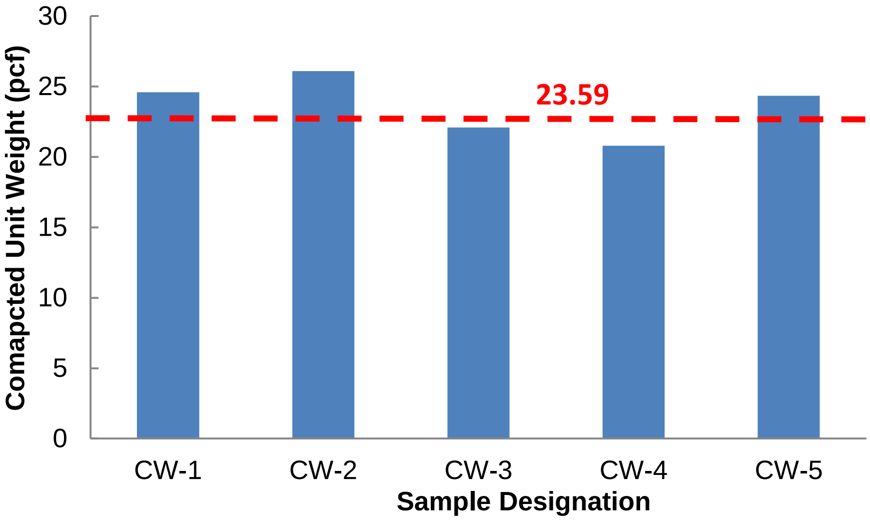


Figure 4.7 Compacted Unit Weight of Construction Waste Samples

The unit weight of demolition waste is tabulated in Table 4.8. In average, the compacted unit weight of the demolition waste was found to be 100.66 pcf. Since concrete, brick and tiles comprise the major portion of demolition waste, higher compacted unit weight of demolition waste was observed. Figure 4.8 shows the unit weight of all demolition waste samples.

Table 4.8 Unit Weight of Demolition Waste Sample

Sample No.	Sample Designation	Compacted Unit Weight		
		pcf	kg/m^3	KN/m^3
1	DW-1	92.35	1479.31	14.51
2	DW-2	104.80	1678.74	16.46
3	DW-3	106.70	1709.17	16.76
4	DW-4	102.95	1649.10	16.17
5	DW-5	96.50	1545.78	15.16
	Average	100.66	1612.42	15.81
	Standard Deviation	6.03	96.52	0.95
	Maximum	106.70	1709.17	16.76
	Minimum	92.35	1479.31	14.51

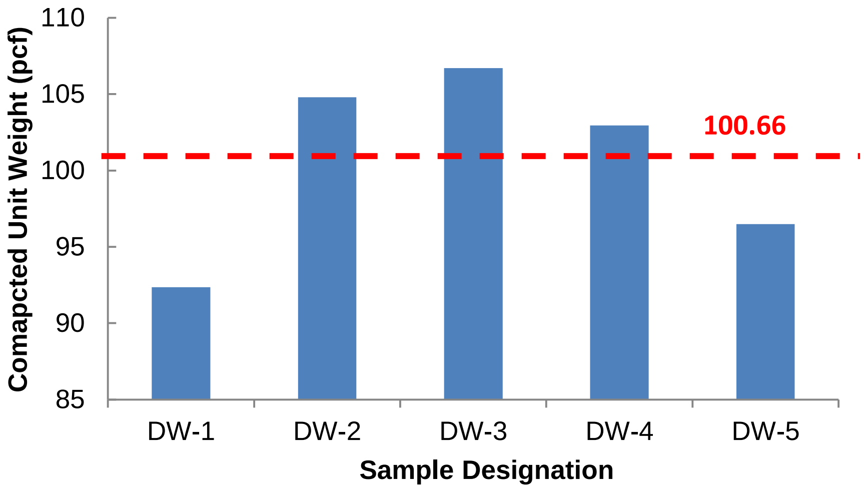


Figure 4.8 Compacted Unit Weight of Demolition Waste Samples

For C&D waste with equal proportion of construction waste and demolition waste, the combined unit weight was calculated by taking arithmetic mean of the unit weight of construction weight and demolition weight and was found to be 62.14 pcf which is equal to 0.84 tons per cubic yards. Townsend (2000) found the bulk average density of C&D waste to be 0.24 tons per cubic yard. Townsend determined the average bulk density by measuring 171 different loads of C&D debris at 10 facilities in the Florida state in tons and recording the volume, in cubic yards, of each truck or container weighed. For our study we used standard proctor test to determine the unit weight of the C&D waste. The variation in the result can be due to the different method adopted and also due to the composition of the C&D waste.

Based on the study of Taufiq, T.(2010) on the fresh waste of the city of Denton landfill, the unit weight of the fresh waste was found to be 35.85 pcf. But, from the current study, the unit weight of C&D waste was found to be 62.14 pcf. The higher unit weight of C&D waste is mainly due to the higher percentage of concrete and drywall in the C&D waste.

4.2.4 Volatile Solids

Construction waste samples were tested for volatile solids content. The result of the volatile solids tests is presented in the Table 4.9 and Figure 4.9. As the amount of wood product was significant in construction waste samples, the volatile solids content was found to be higher. In average, the volatile solids content of construction waste was found to be 82.71%.

Table 4.9 Volatile Solids Content of Construction Waste

Sample No.	Sample Designation	Volatile Solids (%)
1	CW-1	88.00
2	CW-2	80.00
3	CW-3	76.92
4	CW-4	84.00
5	CW-5	84.62
	Average	82.71
	Standard Deviation	4.30
	Maximum	88.00
	Minimum	76.92

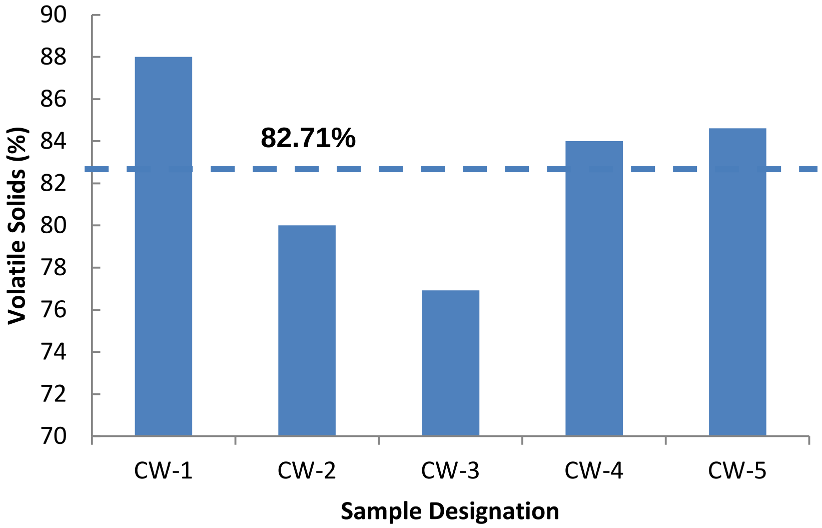


Figure 4.9 Volatile Solids Content of Construction Waste Samples

4.3 Estimation of Gain in Landfill Volume

C&D waste when diverted from landfill disposal saves landfill volume. For the estimation of gain in landfill volume resulting from the diversion of C&D waste, the average unit weight of construction waste and that of demolition waste obtained from the Standard Proctor tests along with the annual tonnage data of C&D waste provided by the city of Denton landfill were used. Nine different combinations of construction waste and demolition waste were assumed and these combinations are listed below:

- 10% of Construction waste & 90% of Demolition waste (10% CW + 90% DW)
- 20% of Construction waste & 80% of Demolition waste (20% CW + 80% DW)
- 30% of Construction waste & 70% of Demolition waste (30% CW + 70% DW)
- 40% of Construction waste & 60% of Demolition waste (40% CW + 60% DW)
- 50% of Construction waste & 50% of Demolition waste (50% CW + 50% DW)
- 60% of Construction waste & 40% of Demolition waste (60% CW + 40% DW)
- 70% of Construction waste & 30% of Demolition waste (70% CW + 30% DW)
- 80% of Construction waste & 20% of Demolition waste (80% CW + 20% DW)
- 90% of Construction waste & 10% of Demolition waste (90% CW + 10% DW)

For the assumed combinations of construction waste and demolition waste, combined unit weight of C&D waste was calculated. For the calculation of the combined unit weight, weighted arithmetic mean of the unit weight of construction waste and demolition waste was taken using the equation 4-1.

Combined unit weight = $(\% \text{ of CW} \times \text{UW}_{CW} + \% \text{ of DW} \times \text{UW}_{DW})/100$ (4-1)

where, CW = Construction Waste

DW = Demolition waste

UW_{CW} = Unit weight of Construction waste

UW_{DW} = Unit weight of Demolition waste

Based on the annual tonnage data provided by the city of Denton landfill, average annual tonnage of C&D waste was calculated. Nine different diversion percentages- 10, 20, 30, 40, 50, 60, 70, 80, and 90- were assumed. For each diversion rate, the amount (in tons) of C&D waste diverted was calculated by using the equation 4-2.

Diverted amount of C&D waste (in tons) =

$$\frac{\text{Diversion Percentage} * \text{Average Annual Tonnage}}{100} \quad (4\text{-}2)$$

Townsend (2010) proposed a volume- weight conversion for C&D waste. For the volume to weight conversion of C&D waste, Townsend used average bulk density as conversion factor as shown in the equation 4-3.

$$\text{Weight of C\&D Debris} = \text{Volume of C\&D Debris x Average bulk density} \quad (4\text{-}3)$$

The volume of C&D waste diverted was calculated using equation 4-3 and combined unit weight was used instead of average bulk density while calculating the volume.

For a landfill cell of 20 acres (968 ft * 900 ft) and design height of 100 ft with side slopes of (3H:1V), the gain in landfill volume was calculated by dividing the volume of diverted C&D waste with the total volume of landfill and is expressed in percentage. Equation 4-4 was used to calculate the gain in landfill volume.

$$\text{Gain in landfill volume (\%)} = \frac{\text{Volume of C\&D waste diverted} * 100}{\text{Total landfill volume}} \quad (4\text{-}4)$$

Total landfill volume was calculated using the equation (4-5).

$$\text{Total landfill volume, } V = h(A_b + \sqrt{(A_b * A_t)} + A_t)/3 \quad (4\text{-}5)$$

where, h= design height of landfill.

A_b= Area of the base of landfill.

A_t = Area of the top of landfill.

4.3.1 C&D Waste Tonnage Data for The City of Denton Landfill.

City of Denton landfill provided the annual daily tonnage data from September 2014 to August 2015 along with the annual tonnage data of the past three years. Based on the annual daily tonnage data, monthly tonnage of C&D waste was calculated for the fiscal year 2015 and is tabulated in the Table 4.10.

Table 4.10 Monthly Tonnage Data of C&D Waste for Denton landfill

S.N	Month	Tonnage
1	09/2014	1997.03
2	10/2014	2303.75
3	11/2014	1294.31
4	12/2014	1431.32
5	01/2015	1394.61
6	02/2015	1224.49
7	03/2015	1225.6
8	04/2015	1742.63
9	05/2015	1182.41
10	06/2015	2836.6
11	07/2015	1862.7
12	08/2015	2033.81

Figure 4.10 shows the monthly variation in the amount of C&D waste that the city of Denton landfill received for the fiscal year 2015. From the figure it can be observed that lesser amount of C&D waste was received by Denton landfill from November 2014 to May 2015 with the least tonnage being received for the month of May. The amount of C&D waste received during September, October 2014 and from June 2015 to August 2015 was relatively higher. And, the highest amount of C&D was received in June 2015 based on the data of last 12 months.

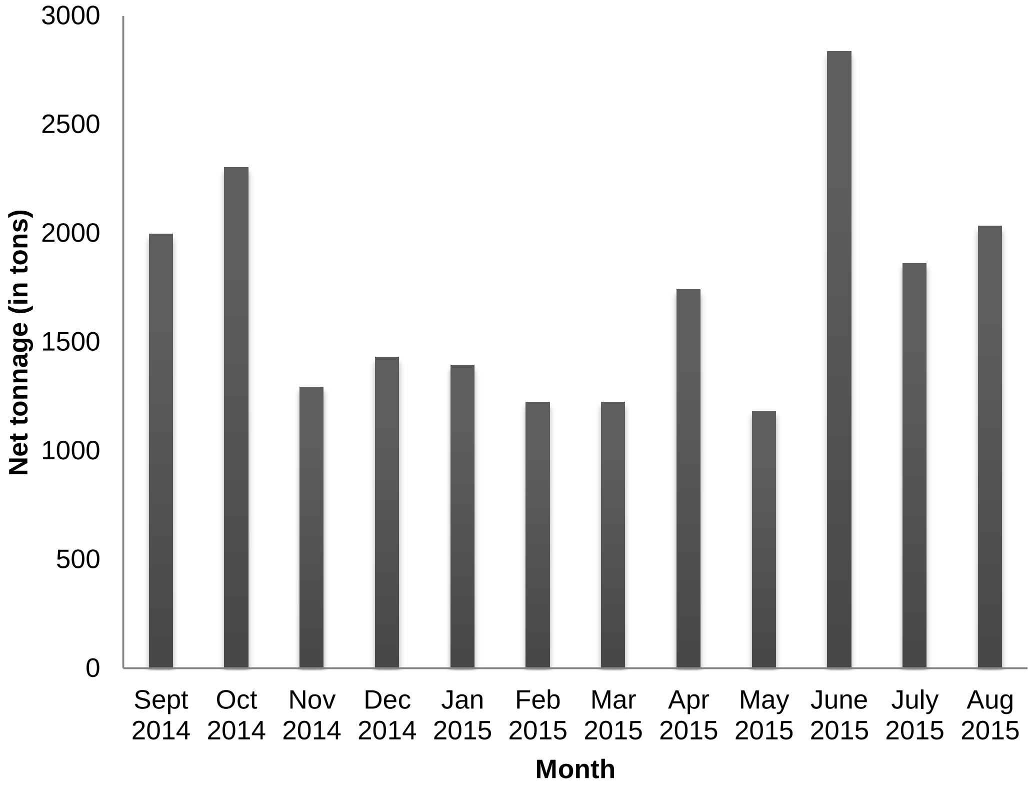


Figure 4.10 Monthly Variation in the Amount of C&D Waste for the Denton landfill

The annual tonnage data for the past three years provided by the city of Denton landfill is tabulated in the Table 4.11 which shows that quantity of C&D waste is increasing over the years in the Denton landfill. The average annual tonnage value of C&D waste was then calculated based on these data.

Table 4.11 Annual Tonnage of C&D Waste for the Denton Landfill

S.N.	Year	Annual Tonnage (in tons)
1	2015	20529.26
2	2014	18682.31
3	2013	15922.13
	Average	18377.9

4.3.2 Determination of Combined Unit Weight.

For the different proportion of construction and demolition waste assumed, combined unit weight of C&D waste was calculated using the equation 4-1. For the combination with the higher percentage of demolition waste, the combined unit weight was found to be higher as the unit weight of demolition waste is higher than that of construction waste. Table 4.12 shows the combined unit weight of C&D waste for nine different combinations of construction waste and demolition waste.

Table 4.12 Combined Unit Weight of Construction and Demolition Waste

Percentage of		Unit Weight			
Construction waste(CW)	Demolition waste(DW)	CW	DW	C&D Waste	
		lb/ft^3	lb/ft^3	lb/ft^3	ton/yd^3
10	90	23.59	100.66	92.953	1.255
20	80	23.59	100.66	85.246	1.151
30	70	23.59	100.66	77.539	1.047
40	60	23.59	100.66	69.832	0.943
50	50	23.59	100.66	62.125	0.839
60	40	23.59	100.66	54.418	0.735
70	30	23.59	100.66	46.711	0.631
80	20	23.59	100.66	39.004	0.527
90	10	23.59	100.66	31.297	0.423

The variation in the unit weight of C&D waste for the different proportion of construction waste and demolition waste is shown in the Figure 4.11.

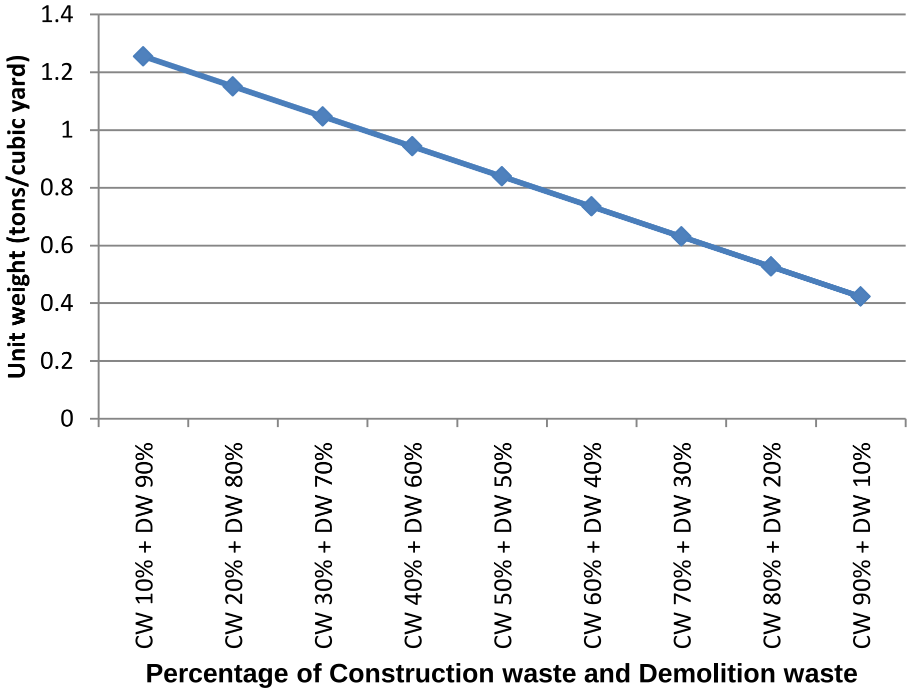


Figure 4.11 Unit Weight of C&D Waste for Different Proportions of Construction Waste and Demolition Waste

4.3.3 Gain in Landfill Volume

The gain in landfill space was determined for different diversion rates. Based on the average annual tonnage of C&D waste and combined unit weight of C&D waste sample for different proportion of construction waste and demolition waste, gain in landfill volume was calculated for different diversion rates. For different diversion rate and for the nine different combinations of construction waste and demolition waste, the volume of C&D waste diverted was calculated first using equation (4-3) and the result is tabulated in the tabulated in the Table 4.13 and the variation is plotted in the Figure 4.12. Then, the gain in landfill volume was calculated and expressed in percentage of total landfill capacity of landfill with 20 acres of landfilling area and design height of 100 feet using equation (4-4) and the result is tabulated in Table 4.14.

Table 4.13 Diverted Volume of C&D Waste for Different Diversion Rates

Percentage of Construction Waste and Demolition waste	Volume of C&D waste Diverted (in yd^3)								
	Diversion Percentage								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
CW 10% + DW 90%	1464.37	2928.75	4393.12	5857.5	7321.87	8786.25	10250.62	11715	13179.37
CW 20% + DW 80%	1596.69	3193.38	4790.07	6386.76	7983.45	9580.14	11176.83	12773.52	14370.21
CW 30% + DW 70%	1755.29	3510.58	5265.87	7021.17	8776.46	10531.75	12287.04	14042.33	15797.62
CW 40% + DW 60%	1948.88	3897.75	5846.63	7795.5	9744.38	11693.26	13642.13	15591.01	17539.88
CW 50% + DW 50%	2190.45	4380.91	6571.36	8761.81	10952.26	13142.72	15333.17	17523.62	19714.08
CW 60% + DW 40%	2500.39	5000.79	7501.18	10001.58	12501.97	15002.37	17502.76	20003.16	22503.55
CW 70% + DW 30%	2912.5	5825.01	8737.51	11650.02	14562.52	17475.02	20387.53	23300.03	26212.54
CW 80% + DW 20%	3487.27	6974.54	10461.8	13949.07	17436.34	20923.61	24410.87	27898.14	31385.41
CW 90% + DW 10%	4344.66	8689.31	13033.97	17378.63	21723.29	26067.94	30412.6	34757.26	39101.91

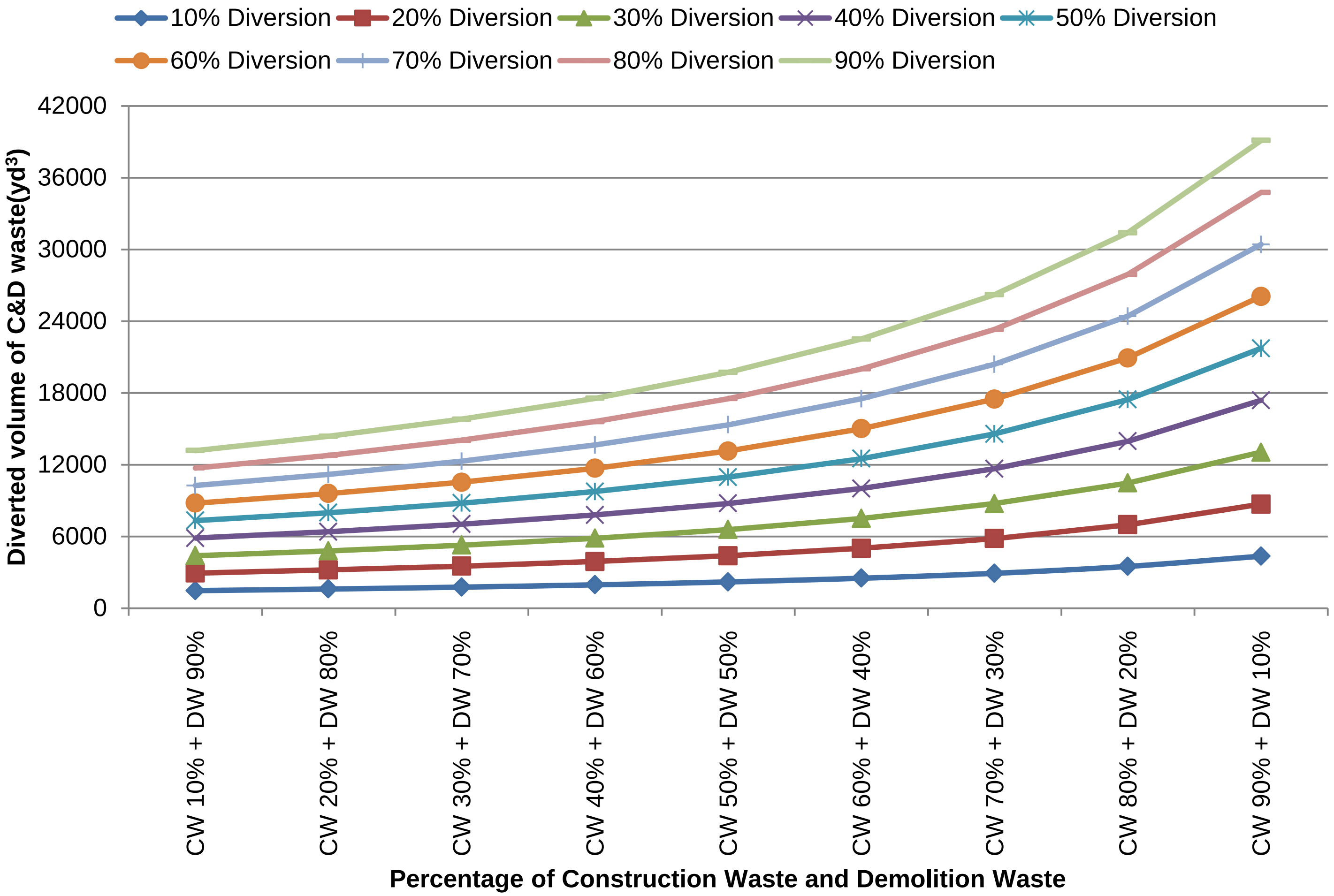


Figure 4.12 Landfill Space Gain for Different Diversion Rate

Table 4.14 Gain in Landfill Volume

Percentage of Construction Waste and Demolition waste	Gain in landfill volume in a year (in %)								
	Diversion Percentage								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
CW 10% + DW 90%	0.09	0.18	0.28	0.37	0.46	0.55	0.64	0.73	0.83
CW 20% + DW 80%	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
CW 30% + DW 70%	0.11	0.22	0.33	0.44	0.55	0.66	0.77	0.88	0.99
CW 40% + DW 60%	0.12	0.24	0.37	0.49	0.61	0.73	0.86	0.98	1.10
CW 50% + DW 50%	0.14	0.27	0.41	0.55	0.69	0.82	0.96	1.10	1.24
CW 60% + DW 40%	0.16	0.31	0.47	0.63	0.78	0.94	1.10	1.25	1.41
CW 70% + DW 30%	0.18	0.37	0.55	0.73	0.91	1.10	1.28	1.46	1.64
CW 80% + DW 20%	0.22	0.44	0.66	0.87	1.09	1.31	1.53	1.75	1.97
CW 90% + DW 10%	0.27	0.54	0.82	1.09	1.36	1.63	1.91	2.18	2.45

The result shows that for the combination with higher percentage of construction waste, the volume of C&D waste diverted will be higher for the same diversion rate. This is because the combination with higher percentage of construction waste has lower combined unit weight. For the C&D waste with 10 % of demolition waste and 90% of construction waste, the volume of C&D waste diverted at 90% diversion rate is almost three times higher than the diverted volume of C&D waste containing 10% construction waste and 90% demolition waste at same diversion rate.

For 20 acres landfill with design height of 100 feet, about 1.25% of landfill space can be gained in a year by diverting 90% of C&D waste containing 50% of construction waste and 50% of demolition waste. From the Table 4.14 it can be seen that for the same diversion rate, the gain in landfill space is higher for C&D waste with higher proportion of construction waste.

The lift height that can be gained in a year by diverting C&D waste from landfilling into a 20 acres landfill with 100 ft design height was back calculated using the equation (4-5) and the result was expressed in the percentage of the design height. Table 4.15 shows the gain in lift height.

Table 4.15 Lift Height Gained for Different Diversion Rate

Percentage of Construction Waste and Demolition waste	Gain in lift height (%)								
	Diversion Percentage								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
CW 10% + DW 90%	0.045	0.091	0.136	0.182	0.227	0.272	0.318	0.363	0.409
CW 20% + DW 80%	0.050	0.099	0.149	0.198	0.248	0.297	0.347	0.396	0.446
CW 30% + DW 70%	0.054	0.109	0.163	0.218	0.272	0.326	0.381	0.435	0.490
CW 40% + DW 60%	0.060	0.121	0.181	0.242	0.302	0.362	0.423	0.483	0.544
CW 50% + DW 50%	0.068	0.136	0.204	0.272	0.340	0.407	0.475	0.543	0.611
CW 60% + DW 40%	0.078	0.155	0.233	0.310	0.388	0.465	0.543	0.620	0.698
CW 70% + DW 30%	0.090	0.181	0.271	0.361	0.452	0.542	0.632	0.722	0.813
CW 80% + DW 20%	0.108	0.216	0.325	0.433	0.541	0.649	0.757	0.866	0.974
CW 90% + DW 10%	0.135	0.270	0.404	0.539	0.674	0.809	0.944	1.078	1.213

The result shows that about 0.6% of landfill height can be gained in a year if 90% of C&D waste containing 50% of construction waste and 50% of demolition waste is diverted from a landfill of 20 acres area and 100 ft design height. For the same rate of diversion, the percentage of landfill height gained is higher for C&D waste with higher percentage of construction waste. About 1.2% of landfill height can be gained in one year by diverting 90% of C&D waste containing 90% of construction waste.

Chapter 5

Conclusions and Recommendations

Construction and demolition waste production is increasing globally due to the increase in construction works for advancement in infrastructures. C&D waste occupies considerable amount of landfill space when disposed in landfill and remains constant over the years due to its non-degradable nature. Disposing C&D waste in the landfills becomes a critical issue considering cost of landfill construction and availability of land. Thus, it is important to take possible measures to save landfill volumes.

The main objective of the current study was to estimate the gain in volume of landfill space by diverting C&D waste from landfill disposal. The current study presents the characteristics of construction and demolition waste samples, collected from the City of Denton landfill, Texas. Five buckets of construction waste and five buckets of demolition waste samples were collected from the landfill. The collected construction waste and demolition waste samples were utilized to determine physical properties of the construction and demolition waste such as physical composition, compacted unit weight, moisture content and volatile solids.

5.1 Summary and Conclusions

The work completed for the present study can be summarized as follows:

- Construction waste and demolition waste samples were collected from the City of Denton Landfill. A total of 10 buckets of samples; 5 buckets of construction waste and 5 buckets of demolition waste; were collected. Each sample weighed approximately 25 to 40 lbs.
- The composition of construction waste and demolition waste was determined by manual sorting for each sample individually. The overall average composition by weight of construction waste indicated Wood

products (73.04%), Cardboard (9.12%), and Drywall & Plaster (9.58%) to be major components of construction waste. On the other hand, Portland cement concrete (36.30%), Brick & Tiles (23.88%), Asphalt concrete (19.72%), and Drywall & Plaster (12.75%) were found to be major components of demolition waste.

- For C&D waste with equal proportion of construction waste and demolition waste the average composition indicated wood products (36.6%), Portland cement concrete (18.3%), asphalt concrete (10%), brick and tiles (12%), metals (1.3)%, Drywall & plaster (11%), cardboard (5%), and C&D debris fine as (6%).
- The compacted unit weight was determined for all the samples using standard proctor compaction method. The average unit weight of construction waste was found to be 23.59 pcf. , whereas that of demolition waste was found to be 100.66 pcf. As the percentage of Portland cement concrete, asphalt concrete, and brick & tiles were higher in demolition waste the unit weight of demolition waste was found to be significantly higher than that of construction waste which was basically composed of wood products and cardboard.
- For C&D waste with equal percentage of construction waste and demolition waste, the unit weight was found to be 62.13 pcf which is equal to 0.84 tons per cubic yard.
- The moisture content of the construction waste samples ranged from 4.18% to 7.92% on wet weight basis and 4.36% to 8.6% on dry weight basis. The average moisture content of construction waste was determined to be 5.93% and 6.33% on wet weight and dry weight basis

respectively. For the demolition waste, the moisture content varied from 1.47% to 3.44% on wet weight basis and 1.49% to 3.57% on dry weight basis. And the average moisture content was found to be 2.73 % and 2.81% on wet weight and dry weight basis respectively.

- Volatile Solids tests were conducted on construction waste sample and the volatile solids content value ranged from 76.92% to 88% and the average volatile solids content was found to be 82.71%. The higher volatile solid content of construction waste sample showed the possibility of gas generation from construction waste. As demolition waste was composed mainly of non-degradable components, volatile solids tests were not conducted for demolition waste samples.
- Nine different proportions of construction waste and demolition waste were assumed and combined unit weight was determined for each proportion by taking weighted arithmetic mean of the unit weight of construction waste and demolition waste. For the proportion with higher percentage of demolition waste, the combined unit weight was found to be higher. The combined unit weight was found to be maximum for the combination with 10% of construction waste and 90% of demolition waste and was found to be minimum for the combination with 90% of construction waste and 10% of demolition waste.
- Last three years annual tonnage data of C&D waste at the City of Denton landfill was obtained and the average annual tonnage was found to be 18377.9 tons. Based on the average annual tonnage of C&D waste and the combined unit weight of C&D waste for different proportions of construction and demolition waste, the landfill space that can be gained

by diverting different percentage of C&D waste was calculated. For same diversion rate, more landfill volume can be gained if C&D waste has higher proportion of construction waste than demolition waste.

- It was found that about 13179.37 cubic yard of landfill space can be gained in a year by diverting 90% of C&D waste consisting 10% of construction waste and 90% of demolition waste. For the same diversion rate and for C&D waste consisting 50% of construction waste and 50% of demolition waste, about 19714.08 cubic yard of landfill space can be gained in a year. The maximum landfill space that can be gained in a year with 90% diversion was found to be 39101.91 cubic yard for the C&D waste consisting 90% construction waste and 10% demolition waste. Therefore, it can be concluded that if the proportion of construction waste is higher in C&D waste, higher landfill volume can be gained by diverting the waste from landfill.
- For a landfill with 20 acres of area, 100 feet of design height and side slope of 3H:1V, the percentage gain in landfill space in a year by diverting 90 % of C&D waste containing equal proportion of construction and demolition waste is 1.24% of the total landfill volume. For the same diversion rate, about 2.45% of landfill space can be gained in a year by diverting C&D waste containing 90% of construction waste and 10% of demolition waste.
- The lift height that can be gained by diverting C&D waste from landfill of 20 acres area and 100 ft design height with side slope of 3H:1V was calculated. For C&D waste with 90% construction waste and 10% demolition waste, lift height that can be gained in a year by diverting

50%, 70% and 90% of C&D waste was about 0.67%, 0.94%, and 1.21%of the design height. On the other hand, lift height that can be gained in a year by diverting 50%, 70%, and 90% of C&D waste consisting 50% of construction and 50% of demolition waste was about 0.34%, 0.48%, and 0.61% of the design height. Therefore, it can be concluded that C&D waste having higher proportion of construction waste when diverted from landfill results in higher gain of lift height compared to that with higher proportion of demolition waste.

5.2 Recommendations for Future Studies

Based on the results obtained from the current study, following recommendations are made for future studies:

- C&D waste samples can be collected more frequently to monitor the variation in the physical composition and other properties of the C&D waste.
- The weight of collected C&D waste sample can be varied to observe the effect of the amount of sample collection on C&D waste properties.
- Economic assessment of the cost saved by diverting the C&D waste versus the cost incurred in recycling the diverted C&D waste can be done to determine the economic feasibility of C&D waste diversion.

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