# THE BEST MANAGEMENT PRACTICES FOR THE RECYCLING OF GYPSUM WASTE FROM DECONSTRUCTION TO MANUFACTURING

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Prepared for:
The Construction and Demolition Recycling Association (CDRA)
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## Executive Summary

Construction and demolition (C&D) debris is one of the largest waste streams in the United States with an estimated 600 million tons produced in 2018. According to the EPA, gypsum drywall accounts for 2.4% of the total C&D debris generated annually. The most recent data indicates a gypsum recycling rate of 17% annually. Most of the material is landfilled, and this results in hydrogen sulfide gas formation, a source of odor and potential health concerns. Several markets currently exist for recycling gypsum waste; the three considered in this specification are new drywall, agriculture, and cement production. Recycling gypsum waste ultimately saves landfill space, reduces nuisance odor, and saves energy. Therefore, the Construction and Demolition Recycling Association (CDRA) has developed a standard specification to provide deconstruction crews, recyclers, and manufacturers a guide for producing the highest quality recycled gypsum possible on an end market basis (www.cdrecycling.org).

The source of scrap drywall influences the level of processing required and the final recycled gypsum product. Therefore, the importance of deconstruction practices cannot be overstated. Proper deconstruction influences the quality and profitability of recycled gypsum and depends on an active dialogue between the deconstruction crews and recyclers to ensure the desired quality is achieved. Once the recycler has evaluated and accepted the gypsum waste based on their own internal standards, which can be informed by the recommended criteria present in the specification, multiple methods and technologies are available to process gypsum waste. Some factors will depend on desired product specification and the target market. During processing, the scrap drywall is reduced to a powder and the paper is separated from the gypsum. The physical and chemical properties of the recycled gypsum should be tested to ensure the product meets specification for various markets and applications. The chemical concentrations can be compared to regulatory risk thresholds or land application standards to ensure the product can be reused safely. These criteria will vary depending on the end market and should be a point of communication between recycler and manufacturer. The specification also includes how recycled gypsum might ideally be used in drywall production and cement manufacturing compared to natural gypsum. From an agriculture amendment standpoint, recycled gypsum can be directly land applied so long as it meets the necessary criteria. The standard specification created by CDRA includes all this information and more.

**Table of Contents**

**Important Note**

There is a lack of specific information in the current literature as to the optimum management practices for the deconstruction, processing, and manufacturing of gypsum waste on an end market by end market basis. As such, variations or additions to deconstruction and processing may be acceptable and/or required in the context of different end markets. This report (unless otherwise specified) is largely based on sources that primarily consider optimum gypsum waste management practices that promote closed-loop recycling and the production of high-quality recycled gypsum.

# 1. Introduction

## 1.1. Gypsum

Gypsum drywall is widely used in the construction sector for its favorable properties including non-combustibility, cost-effectiveness, sound regulation, and insulation. It is one of the few materials that can theoretically be indefinitely recycled; however, the majority of gypsum waste ends up in construction and demolition landfills. This report will attempt to generate a guide for gypsum recycling based on the best management practices defined from literature sources such as the Gypsum-to-Gypsum (GtoG) project and PAS 109 [1], [2]. These practices will extend from the deconstruction of gypsum as a waste material from new construction and demolition activities to the manufacture of new gypsum products in both a closed and open loop context.

### 1.1.1. Recycled Gypsum (RG)

RG is created from gypsum waste generated through manufacturing processes, construction, demolition, deconstruction, and renovation activities. For the purposes of this report RG is used to mean gypsum that is the result of the controlled processing of gypsum waste to separate the gypsum, paper lining, and any other contaminants. RG is usually in the form of a fine powder or small-aggregate type material.

#### *1.1.1.1. Open Loop Recycling*

Open-loop recycling is a recycling process that converts the manufactured goods into a useful material that can be used for new applications or in new products. Examples of this in the context of RG include use as an agricultural amendment and use as a set retardant in cement clinker.

#### *1.1.1.2. Closed Loop Recycling*

Closed-loop recycling is a recycling process through which a manufactured good is, upon disposal, recycled back into the same manufactured good or a similar product without significant degradation or waste.

## 1.2. Sources of Gypsum Waste

### 1.2.1. Demolition

Demolition sites are the largest source of gypsum waste; however, demolition drywall is not accepted at all gypsum recyclers because of wall coverings and contaminants [3]. These contaminants have the potential to inhibit the gypsum waste’s functionality in its intended end market, make the recycling of gypsum waste cost prohibitive or pose issues from a toxicological and environmental standpoint.

##### *1.2.1.1. Demolition vs. Deconstruction*

Demolition places the highest priority on the destruction of a structure and results in non-homogenous piles of materials. The recyclability and economic value of these materials are damaged when demolition is the primary method of building destruction or renovation. Deconstruction, on the other hand, serves to increase the recyclability of raw materials. Deconstruction results in numerous piles of homogenous building materials with minimal damage due to adequate time and care being taken in their recovery and sorting while still accomplishing the ultimate goal.

### 1.2.2. New Construction

New construction is the next largest source of gypsum waste. This material includes the unused drywall and dunnage from building construction sites. This material will have little to no contaminants because it has not been used in a building and the origins are known.

### 1.2.3. Manufacturing

Gypsum manufacturing waste is a small source of gypsum waste. This consists of any material rejected during the manufacturing of gypsum products. This material is usually reused onsite at the manufacturing facility.

## 1.3. Current Disposal Issues

Disposal of scrap drywall from both demolition and new construction using waste management methods can pose problems stemming from the chemical composition of gypsum. When gypsum is placed in a moist, anaerobic environment, such as a landfill, hydrogen sulfide gas is emitted. Hydrogen sulfide ($H_2S$) gas can be toxic at high concentrations (500-1000 ppm), but the main concern at many sites is the offensive odor [4]. Scrap drywall recycled at a mixed C&D recycling facility often becomes size reduced and accumulates in the C&D fines or residual. The gypsum content in C&D fines can range from 1% to over 25% of the total material [5]]. This prompted some states to develop reuse criteria and guidance that requires C&D processing facilities to sample and analyze fines prior to beneficial reuse [3]. Although $H_2S$ production is the biggest concern with respect to disposal, risk may also result from sulfate leaching from C&D fines and subsequent exceedances of allowable concentrations of sulfate in soil or water [6]. Another chemical associated with scrap drywall is boron [7]. Concentrations of boron have been observed near C&D landfills at concentrations of possible concern [7]. While this paper does not address worker safety, this must always be a top priority. It is recommended that any processing operation have a safety manual specific to the daily functions performed and refer to the United States Occupational Safety and Health Association (OSHA) for guidance.

# 2. Deconstruction

This section of the paper encompasses all deconstruction practices from the consideration and selection of a site that will undergo deconstruction, to transportation of gypsum waste to the recyclers to be processed.

## 2.1. Preparation

The following practices should all be conducted prior to the occurrence of any onsite deconstruction or demolition activities.

### 2.1.1. Coordination

Lack of coordination is a significant issue among agents in the construction sector [8]. As a result, regular meetings should be a priority to identify site specific problems, discuss procedures and schedules and coordinate requirements for specific recovery operations when considering the acquisition of gypsum waste from any new demolition/deconstruction site.

### 2.1.2. Waste Audit

The implementation of an effective pre-deconstruction waste audit, while not always mandatory, is an important part of any deconstruction operation. It allows the project manager to present relevant and adapted waste management guidelines to the deconstruction companies. Additionally, it aids in planning, reduces potential risks to workers, and allows estimates to be projected based-on economics in specific markets.

#### *2.1.2.1. General Recommendations for a Waste Audit*

It is advisable to complete an audit prior to any investment in tools, workers or any other relevant materials or services.

A reliable waste audit starts with a visual inspection, conducted by the person/entity/responsible party in charge of the audit. The initial goal is to identify different systems (drywall fixed to a wooden frame with insulation, gypsum ceiling tiles on a ceiling grid, drywall affixed to a metal frame etc.) and constitutive materials. This visit also aims to collect data related to waste fractions, amounts, locations, recovery rates, potential for recycling and the presence of any hazardous materials. It is recommended to include pictures in the audit report for ease of understanding. Additionally, the use of destructive techniques (for example breaking through a layer of drywall to identify the type of insulation) should be implemented whenever possible. This helps to avoid uncertainty on type and quantity of materials. However, this is not always possible, as is the case when the building still has occupants.

#### *2.1.2.2. Lead Containing Materials*

In the United States there are no specific requirements in the Code of Federal Regulations mandating the abatement of lead in C&D debris. Moreover, it is difficult for C&D waste to fail the EPA test method for determination of characteristic hazardous waste, SW-846 Test Method 1311: Toxicity Characteristic Leaching Procedure (TCLP), for lead leaching in the context of the sheer quantity of inert materials and the relatively small amounts of lead that can be present. Therefore, it is unlikely that C&D debris could be classified as a hazardous waste and require disposal in a Subtitle C hazardous waste landfill. As a result, the most cost-effective method would most likely be simply treating gypsum waste that is contaminated with lead as regular demolition waste to be landfilled in a C&D landfill. In the event that abatement is pursued, individuals and firms are required to follow federally regulated lead abatement procedures, as written in the *Code of Federal Regulations,* Part 745, Title 40, 2021 [9].

Similarly, Canada does not have a federal requirement associated with the removal of lead-based paint. However, the following guide outlines their recommendations for lead paint removal [10].

### 2.1.3. Asbestos

Prior to the execution of the waste audit, it is necessary to carry out the appropriate procedure regarding asbestos. In the United States the procedure for identifying and removing asbestos prior to the demolition or renovation of a building is described in the U.S. *Code of Federal Regulations* Part 61, Title 40, 1990 [11]. The facilities covered in this regulation are any institutional, commercial, public, industrial, or residential structure, installation, or building. Residential buildings with four or fewer dwelling units are excluded from the regulation. Before the demolition of a building, approval from the appropriate state agency is required, including a subsequent inspection to determine if asbestos is present and if so, how much [12]. If the amount of friable asbestos is greater than 1%, emission control requirements must be followed. The Regulated Asbestos-Containing Materials (RACM) must be disposed of following the regulations in 40 CFR, Part 61, Subpart M.

Canadian federal policy outlines their own procedure in the *Canada Occupational Health and Safety Regulations* where sections 10.26.1 through 10.26.11 outline the process for the identification, removal, decontamination, sampling and disposal of asbestos-containing materials and the locations in which they reside [13].

Workers must be made aware of the possibility of asbestos being present in pre-1990 gypsum waste. Most asbestos is found on materials applied to the wallboard, such as joint compound, drywall tape, etc… The primary concern with asbestos is airborne particles from handling drywall during deconstruction activities. Safety training and comprehensive screening procedures are effective tools to maintain worker safety when conducting a waste audit and processing gypsum drywall in recycling operations.

### 2.1.4. Audit Methodology

Audit methodology can be divided into different phases listed below [14].

- Collection of available documents associated with the project, including asbestos and lead assessments
- Visual inspection of the site
- Inventory of different structures and materials identified in each
- Recommendations for safety conscious procedures during deconstruction and waste management tasks
- Estimated quantity of each material
- Research from local markets to determine the preferred and alternate destination points for each waste stream
- Calculation of the recovery and elimination rates

#### *2.1.4.1. Detailed Reporting*

It is advisable to create an inventory of the materials or systems found for each building and each floor of the building, including the possible and recommended outlets wastes could be delivered to and necessary precautions to take during deconstruction. Here is a link to an example of what that table might look like (can be modified to be specific to drywall) placeholder for hyper link.

### 2.1.5. Site Waste Management Plan (SWMP)

A SWMP should be put into place, including detailed descriptions of waste management strategies and waste control applied for each waste stream at all stages of construction, deconstruction, or renovation. This is done to maximize recovery rates and correctly manage potential hazards. More specific information that a SWMP should contain includes but is not limited: to plans for reuse and recovery of forecasted wastes by specifying waste carriers, destinations, and recovery actions. The SWMP is a living document that should be updated throughout the course of the project to reflect actual management of identified waste types, as well as unforeseen materials, events, and operational changes as they occur.

#### *2.1.5.1. Effective Planning of a Gypsum Waste Capture Plan*

Effective planning and implementation of gypsum waste capture plan that are adapted to the construction sites characteristics allow for the most efficient transfer of materials from the site of deconstruction to roll-off boxes or other containment units. These systems should be designed to limit the manual handling of gypsum, reduce contamination and optimize operational efficiencies. Another good practice is placing containers adjacent to the footprint of the building and feeding waste directly into containers, as opposed to stockpiling it first.

#### *2.1.5.2. Containers and Roundtrips*

Another part of the SWMP should include an estimation of the number, size and type of containers needed. It is ideal to use covered open-top roll off boxes to limit the potential introduction of moisture and impurities. The number and size of containers should be based on the estimated volume of waste calculated from your waste audit. The frequency of waste collections should be planned alongside the container specifications to ensure that only full container loads are transported, and overfilling is prevented. These practices are conducive to economic, environmental and time saving benefits as gypsum waste storage and roundtrips to its final destination become more optimized.

### 2.1.6. Worker Assignment

The best method to ensure the waste management plan is adhered to is by designating at least one person responsible for supervision of waste management operations and regular inspection of storage areas [15]. Periodic checks on the use of gypsum waste roll-off boxes should be carried out. This includes, but is not limited to, covering the waste roll-off boxes at the end of the day to reduce the potential introduction of moisture and impurities.

#### *2.1.6.1. Worker Training*

Workers should be specifically trained in practices concerning dismantling of gypsum products, as well as sorting and storing gypsum waste. Deconstruction methods are more labor-intensive compared to demolition. However, deconstruction skills are easily learned with periodic training [15].

## 2.2. Execution

The following practices should be adhered to as deconstruction and demolition activities occur. As per ASTM C1264 each gypsum panel product or package shall have legibly marked thereon the following: the thickness, the name of the producer or supplier, the brand name, if any, and the ASTM specification for the product [16]. Boards that do not possess these markings are at risk for lead and asbestos, and other contaminants and should not be accepted.

### 2.2.1. Worker Appointment

Trained workers should be appointed to conduct gypsum product deconstruction. Workers dedicated to sorting operations have been found to successfully impact recycling operations by producing higher quality recyclable materials more quickly [15].

### 2.2.2. On-Site Segregation

On-site segregation refers to the process of sorting gypsum waste suitable for recycling at the source. High quality recovery is much more likely to occur if source segregation is carried out [15]. If the material is moved to a transfer station without segregation, the probability that it will meet the waste acceptance criteria (WAC) of the recycling facility is greatly reduced because of contamination introduced by mixing the materials. Additionally, the presence of gypsum in the waste stream can contaminate other recyclables.

### 2.2.3. Tools and Machinery

Exact deconstruction processes will likely vary from company to company. Some tools and machines are commonly used. Manual tools are used to lever up, unscrew, and cut or break parts of the system to isolate different materials. The following are a list of tools commonly used to accomplish this:

- Shovel
- Crowbar
- Saw
- Chisel
- Screwdriver
- Drill
- Pickaxe
- Sledgehammer

Some demolition companies prefer to use small hydraulic machines or compact excavators to deconstruct gypsum waste systems as it can often be faster. However, this has the added restrictions of weight limits and the fact that many rooms will not admit such machines due to space constraints.

Figure 1 Demo site for deconstruction

### 2.2.4. Deconstruction Techniques by Gypsum Waste-System

Deconstruction of any drywall system can generally follow the same procedure used to install the drywall system, but in the reverse order. Before beginning deconstruction of any drywall system, it is vital to turn off any electrical or plumbing systems that may run through it and determine whether the structure the drywall is attached to is load bearing. Although the drywall does not support weight, if a wall is determined to be load bearing the optimal method of deconstruction may change. Any joint compound and tape can be included in the same waste stream as the drywall.

#### *2.2.4.1. Deconstruction Techniques for Systems Fixed to a Frame*

Gypsum is often fixed to steel (commercial buildings) framing with screws or a wooden (residential buildings) framing by screws or nails. Deconstruction techniques will vary; however, they all involve the separation of drywall from the framing using manual tools.

When a system is attached to framing by screws they can be unscrewed and when attached by nails they can be removed with a crowbar. Another technique involves cutting the drywall away from the framing using a saw or splitting it away with the edge of a shovel. The drywall is then pulled away from the framing by hand and the screws and nails. Splitting the drywall away from the frame is not preferable when the structure is undergoing renovation as the residual drywall and hardware would still need to be removed.  Both techniques allow for the collection of drywall in large pieces which saves time in the segregation and loading of the waste.

The techniques described above are equivalent in terms of performance and will vary by worker habit and tool availability [17].  Techniques that consist of cutting and breaking the drywall will result in more pieces of board and could result in greater time investment in segregation [17]. Techniques that demand the breaking of drywall with sledgehammers or equivalent tools are not recommended as they generate many small pieces that require even more time to segregate and increase the risk of contamination by other materials and moisture [17].  Additionally, some drywall that would otherwise be eligible for recycling may be missed and remain on the floor [17].

**Example**: Deconstruction of a drywall partition nailed on wood framing with a crowbar [17]:

1. drywall cutting and breaking using a crowbar or a cutting chisel. Removal of the drywall by hand (the fasteners will remain in the framing)
2. removal of insulation by hand
3. removal of woodframing with tools and by hand

**Example**: Deconstruction of a partition with multiple layers of drywall secured to a steel frame

1. removal of joint compound and other materials that obscure the screws securing the firewall to the steel studs using a crowbar
2. unscrew the screws that secure the firewall to the framing
3. removal of the drywall by hand
4. removal of insulation by hand
5. removal of steel studs with tools and by hand

**Example**: Deconstruction of a drywall ceiling system secured to wood framing

1. removal of joint compound and other materials that obscure screws and/or other hardware securing the drywall to the framing using a crowbar
2. unscrew the screws that secure the drywall to the ceiling joists.  Have a fellow staff member or a drywall lift in place to ensure the drywall does not fall
3. removal of the drywall when each section has all the screws removed
4. removal of insulation by hand

#### *2.2.4.2. Deconstruction Techniques for Drywall on a Ceiling Grid*

Gypsum ceiling tiles that rest on a ceiling grid (also known as T-bar ceilings, suspended ceilings and drop ceilings) are generally not secured using any hardware and just rest on the grid. Therefore, the following procedures are advised:

1. using a secure scaffolding or individual platform a staff member removes the unsecured gypsum tiles. The staff member hands this off to a staff member on the ground.
2. the staff member then dismantles the ceiling grid piece by piece and hands the pieces off to a staff member on the ground as it is dismantled.

# 3. Recycling

This section of the report encompasses the receipt of gypsum waste material to the production of an RG (See section **1.1.1.** for definitions).

## 3.1. Location

Recycling plants or warehouses should consider the optimum location for their operation during siting and permitting of facilities. This step is crucial for minimizing GHG emissions and costs related to transportation [15]. It can also economically incentivize deconstruction companies to prioritize recycling, as opposed to landfilling. A suitable route should be designated that works to minimize social and environmental burdens (ecosystem disturbance, land value degradation, traffic burden etc.). A less centrally located facility may be preferable if it limits costs to deconstruction companies. Economic factors such as tipping fee, fuel prices and employee wages should be considered when selecting a location.

## 3.2. Quality Management System (QMS)

QMS's are an important tool to demonstrate compliance with RG quality criteria defined by the manufacturing company as well as organizing, directing, and recording actions carried out by the recycler. They should be recorded in a quality operating manual whose minimum scope should encompass the following:

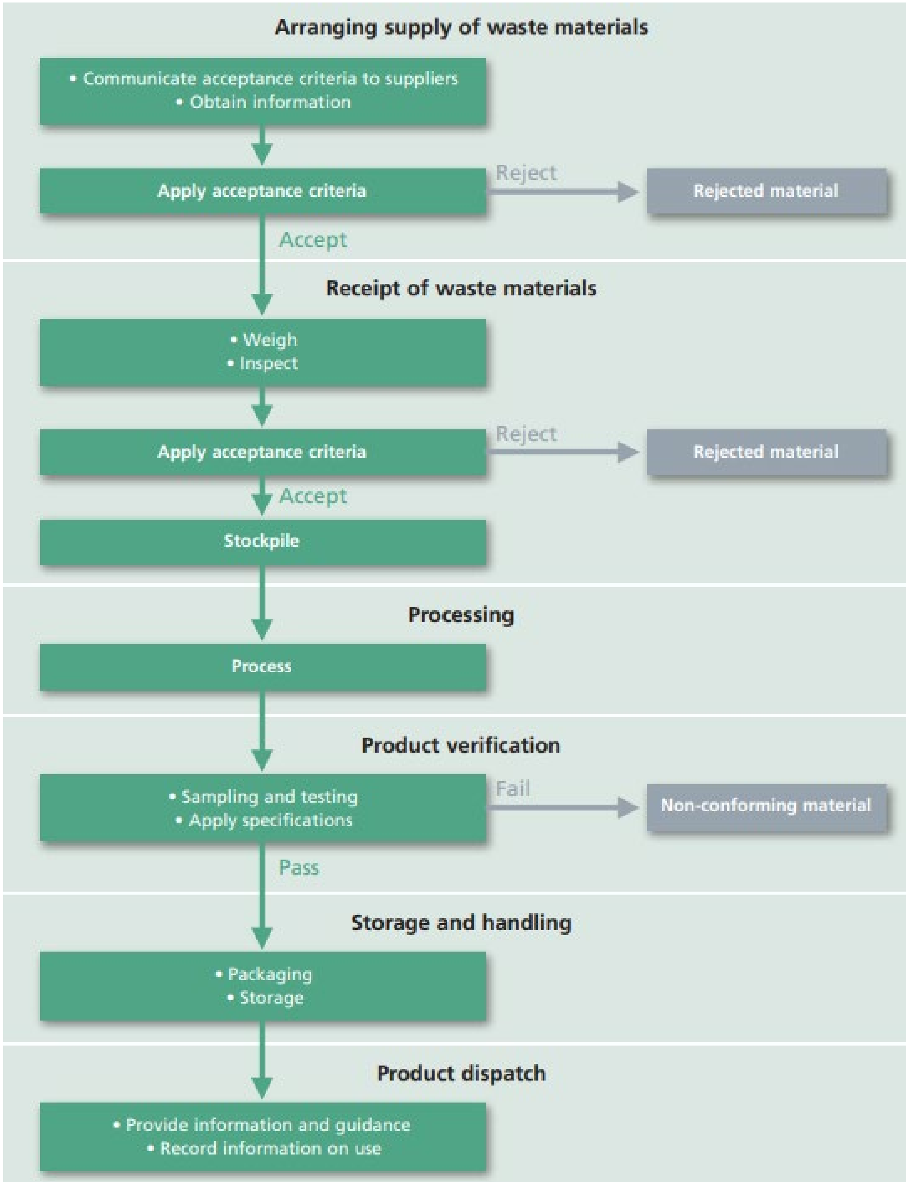


*Figure 2 Minimum scope of quality operations manual [2]*

### 3.2.1. Waste Acceptance Criteria (WAC)

Material related WAC criteria are developed and maintained to determine if specific gypsum waste is acceptable. Recyclers typically have their own WAC that will reflect the capabilities of their operation. However, the following are WAC agreed upon references, by the three recycling companies that participated in the GtoG project:

*Table 1 GtoG agreed upon WAC [18]*

| Material | Accepted | Accepted After Approval | Rejected |
|---|---|---|---|
| Gypsum Blocks | X | | |
| Gypsum ceilings, floors, walls, stucco | X | | |
| gypsum waste with nails and screws, wallpaper, glass tissue and other wall coverings | X | | |
| Plaster in bags | X | | |
| Cove Molding | X | | |
| Glass reinforced gypsum products (GRG) | X | | |
| Boards with tinfoil and polystyrene | | X | |
| Gypsum Fiber Board | | X | |
| Molds | | X | |
| Gypsum based ceiling tiles | | X | |
| Drywall with insulation | | X | |
| Hazardous Materials e.g. asbestos | | | X |
| Cement bound boards | | | X |

Other considerations for WAC that are not reflected in this table are a maximum range of impurities ranging between 2-3% and moisture content that is less than 10% by weight [18].

### 3.2.2. Impurities and Their Effects on Recycling

Some gypsum waste is not able to be recycled simply due to the presence of impurities that are difficult to separate. Although most of these elements should be sorted out in the process of unloading and before recycling takes place, tiny parts may remain the gypsum waste. The absence of a specific range of impurities and limited moisture content are the most common specifications for production of RG by recyclers [18]. Impurities, contaminants, and the effects of such are explained in this section.

#### *3.2.2.1. Moisture Content*

Moisture content above a certain threshold makes the separation of paper from gypsum material difficult. Additionally, the presence of moisture may increase the fuel needed to process materials and may even cause blockages in machinery. If a gypsum waste fraction has an unacceptable level of moisture, it can be mixed with a dryer fraction in order to balance the overall moisture content.

##### 3.2.2.2. Plastics, Foils, Stone, and Insulation Materials

These impurities do not typically pose a risk to machinery, but they decrease the overall quality of the RG output. Plastics, stone, and insulation can contaminate the RG powder and often end up in the paper output stream.

##### 3.2.2.3. Incidental Metal

Metals not sorted out prior to recycling process can block machines and lead to breakdowns. Some recycling machinery is designed to handle metals at input and magnets can be incorporated as part of the automated separation process.

##### 3.2.2.4. Wood

Big pieces of wood not removed at input can damage machinery and cause material to back up, preventing forward movement of the process. Once the gypsum waste is processed smaller wooden impurities mostly end up in the paper stream.

##### 3.2.2.5. Anhydrite

Calcium sulfate anhydrite, another contaminant, can mostly be found in blocks and molds and unlike gypsum it possesses no crystalline water and cannot be converted to active material that is capable of calcination. As a result, this material should be avoided to keep the quality of the RG high.

### 3.2.3. Waste Receiving

##### 3.2.3.1. Arranging Supply of Scrap Material

The acceptance criteria used for gypsum waste should be developed based on feedstock, processing capabilities, end markets and state regulations. Some states may only allow processing of new gypsum waste. The gypsum recycling facility should communicate the gypsum waste acceptance criteria and delivery requirements outlined in the operations manual. The procedure for inspecting incoming gypsum drywall and determining if it meets the acceptance criteria should be illustrated and include a written narrative for details on how employees are expected to process incoming materials. The operating manual should also include the procedure for handling hazardous substances and materials in accordance with local regulations, as well as state and federal level. There should be a record of the inspection of incoming material, the decision to accept or reject it, and documentation of delivery.

#### *3.2.3.2. Point of Origin*

The processing facility must determine the type of material they intend to process and the market(s) they will cater to. This will affect the type of drywall that should be accepted by the processor. The acceptance criteria can consist of classifying the material by type, source, and point of origin. The specific type will describe the physical characteristics of the drywall. Various types of drywalls are sold on the market including drywall with controlled density, enhanced strength, enhanced surface hardness, mat reinforcement, and reduced water absorption rate. The source of the drywall will provide insights into the contamination level of the drywall. Gypsum waste from drywall manufacturing or unused drywall from retailers will require less processing than demolition gypsum waste removed from buildings. The point of origin differentiates between drywall from a construction or demolition site and drywall originating from a materials recovery facility that processes C&D debris.

#### *3.2.3.3. Information Provided by Processor*

Information provided from the supplier/generator helps determine if the gypsum waste will be accepted by the processor. If the material does not meet the acceptance criteria,then the facility can determine if they would consider accepting the waste if certain criteria are met, for example, through removal of a specific contaminant.

#### *3.2.3.4. Information Provided by Waste Supplier/Generator*

The processor should record the following information from the generator: description of material, quantity in each load, number of loads, packaging of material, details of the point of origin, and date and time each load was delivered to the facility.

#### *3.2.3.5. Weight*

The weight of the total gypsum waste should be ascertained in order to determine what money is owed in terms of a tipping fee. This is typically accomplished by weighing the vehicle transporting the waste upon arrival and upon departure.

#### *3.2.3.6. Inspection/Screening*

Upon receipt of gypsum waste, WAC compliance should be determined by an initial visual inspection. A secondary inspection conducted once the material is accepted, allows for removal of inappropriate materials overlooked in the first inspection, to ensure the gypsum waste feed does not cause machine damage or catastrophic failure [15]. If rejected, the load shall be sent to a transfer station where it can either undergo additional sorting before being transported back to a recycler or be landfilled [15].

Figure 3 Gypsum waste in various forms

### *3.2.3.7. Sorting*

Effective sorting operations should be conducted prior to gypsum waste processing.  This should consist of a visual and manual sorting operation that can take place during the secondary inspection [15].  The level of impurities is typically limited to 2% to prevent the risk of machine failure and avoid low quality RG [15].

### *3.2.3.8. Storage and Stockpiling*

It is crucial for warehouses to possess adequate storage for gypsum waste and RG [19].  These warehouses should be designed and maintained to ensure damage and external contamination is prevented [19].  Gypsum waste that has met the WAC shall be put into a stockpile in an identifiable location where it cannot be contaminated, degraded, or introduced to moisture.  The operating manual should state what materials must be stockpiled separately for different processes or to produce different types of RG.  The walls and floors should be made of concrete, or another hard and stable material and the gypsum waste should be extracted from the middle of the bay in order to avoid scraping the sides and contaminating it.

### 3.2.4. Processing of Gypsum Waste

Different facilities operate different equipment and have different processes but are equally capable of producing RG. As a result, the processing recommendations are general in nature. The processes should produce desired grade or grades of gypsum according to a set of standard operating procedures (SOPs). Processes should also focus on the removal of contaminants in the gypsum waste (including the residual paper). It is advisable to remove the contaminants at the earliest possible stage as it becomes significantly more difficult after the gypsum waste has been size reduced. Moreover, early removal gives the greatest chance of producing a paper material that is suitable for recycling [2].


*Figure 4 Gypsum waste processing machinery from Scott Equipment Company*

#### *3.2.4.1. Pre-Processing of Gypsum Waste*

The recycling process should be arranged in a manner to ensure incoming material and outputs are segregated. Facility operators may use different methods for recycling gypsum drywall; however, the main components are separation, size reduction, and screening. Generally, after gypsum waste is accepted for processing, it is taken to a tipping floor where it can be sorted by type of drywall and intended processing. The gypsum waste is then loaded onto a sorting belt (conveyor). Magnets are typically used to remove ferrous metals up front. The material can then be manually sorted to remove contaminants that may damage processing equipment and decrease the value ofthe final product.

#### *3.2.4.2. Size Reduction*

The gypsum waste will be size-reduced to produce gypsum powder and paper. The paper is separated from the gypsum to create a higher quality product for their respective markets. Grinders, pulverizers, and rotating screens are common types of equipment used by gypsum recyclers to break up the material.

#### *3.2.4.3. Screening of Gypsum Waste*

Screens are used to separate size- reduced gypsum from the paper and any other miscellaneous items. The gypsum falls through the screen while paper and other larger pieces remain on the screen where they can be conveyed for separate storage or disposal.

Figure 5 Final RG product

#### *3.2.4.4. Particle Size*

The particle size of gypsum can be controlled by the size of screen chosen. The intended end market will dictate the size of gypsum particles produced as some markets prefer larger materials than others. The paper content will be a factor determined by the end market; however, a lower paper content is generally preferred by all markets. For example, paper content of recycled gypsum limits how much can be used to make new drywall because it affects the fire rating.

#### *3.2.4.5. Dust Production*

Gypsum processing will produce dust which can be mitigated by taking appropriate measures. This may involve misting water and ventilation systems in areas where gypsum processing actively occurs.

### 3.2.5. Residual Paper Removal and Recycling

The paper recovered from gypsum drywall processing can typically be recycled or reused. However, residual paper has the possibility of being contaminated by specialty coverings such as fiberglass, paint, moisture retardants and flame-resistant coverings that could make the material a characteristic hazardous waste or ineligible for recycling. Moreover, the paper removed in the recycling of gypsum waste may contain residual gypsum and starch as well as contaminants such as nails, adhesive tapes, pieces of wood, joints etc. These objects should be removed before the paper waste is considered for recycling.

#### *3.2.5.1. Contaminants of Concern*

The recycled paper should meet any and all applicable risk-based standards especially if application to the environment is to be considered. Materials historically used in construction that could contaminate residual paper and cause it to be considered a hazardous waste include but are not limited to:

- Lead – Heavy metal that may be found in lead paint applied to the paper facing in older homes
- Mercury – Heavy metal that is found in fluorescent bulbs and thermometers that could contaminate paper residue in deconstruction.
- Arsenic – Heavy metal sometimes used in the treatment of wood that could contaminate paper residue in deconstruction
- Oil-Based Paint – Could make paper facing a flammability characteristic hazardous waste
- Asbestos - Natural insulative fiber that saw large scale use. Can come in close contact with drywall.
- Polychlorinated Biphenyls (PCB's) – Toxic organic substance formerly used in ballast, paints, and caulks. Concern for contamination during deconstruction.
- Boron – Not a hazardous waste concern but is relevant to environmental application.
- Polybromidiphenyl ethers (PDBEs) – Direct application to paper facing as flame retardants (applied in the field and not in production). EPA established reference doses and residential soil, industrial soil and tap water screening levels have been developed [20]:

*Table 2 EPA screening levels for PDBE's in soil and tap water [17]*

| Chemical | Residential Soil (mg/kg) | Industrial Soil (mg/kg) | Tap Water (µg/L) |
|---|---|---|---|
| decaBDE-209 | 440 | 3,300 | 112 |
| octaBDE | 160 | 2,300 | 61 |
| tetraBDE-47 | 6.3 | 82 | 2.0 |
| hexBDE-153 | 13 | 160 | 4.0 |
| pentaBDE-99 | 6.3 | 82 | 2.0 |

One study by the Quebec Center of Expertise in Environmental Analysis noted that mercury concentration measured in gypsum paper residuals could not be explained by mercury naturally present in gypsum [21]. This suggested an alternative source of contamination (outside of production) that would disqualify beneficial use [21].

*Figure 6 Paper stream after separation from gypsum waste*

### 3.2.6. Quality Control

The processor should develop a quality control protocol that should be specified in the operating manual to outline procedures for effective management of all operations and associated quality management activities necessary to produce recycled gypsum with high market value. This protocol should be documented, implemented, and communicated to all personnel involved with quality management of the material.

#### *3.2.6.1. Sampling and Testing Procedure*

A procedure for sampling should be developed where samples are periodically collected to ascertain the quality and composition of the RG recycled gypsum. Parameters of concern are particle size distribution, gypsum content, physical contaminants, and chemical composition.

#### *3.2.6.2. Representative Sampling*

A representative sample should be obtained by collecting samples from the stockpile of gypsum or by taking regular samples from the process line before it reaches a stockpile. Samples can be collected from a stockpile by selecting roughly twenty areas in a stockpile to sample from. The top six inches should be removed from the area before samples are retrieved. The collected samples are then mixed to form a homogenous sample. The second method for sampling can be accomplished at hour increments throughout one working day. The samples are mixed and placed into a clean and sealed container to create a homogeneous sample representative of a full day of production. This mixed sample can then be tested for the parameters mentioned above.

#### *3.2.6.3. Frequency of Analysis*

The production of the recycled gypsum powder and paper should be visually inspected on a frequent basis to ensure the particle size distribution is within the correct range. This should be accompanied by periodic sampling of representative samples and followed by gradation testing and mass balance of residual paper content. The frequency of analysis will depend on the regulations within the state.

The frequency of testing needs to be agreed between the recycler and the manufacturer. In general, toxicological parameters are recommended to be tested monthly or quarterly, depending on volume of recycled powder that is supplied. Technical parameters are recommended to be tested either weekly or monthly. Some parameters may have to be tested daily, depending on location, e.g., moisture and chloride [22].

### 3.2.7. Material Handling, Packaging and Transport

The RG should be handled, stored, and transported in a method to prevent contamination. The procedure for each should be developed and recorded with a consideration for the method of dispatch, end market and delivery of the final material.

#### *3.2.7.1. Product Packaging*

The packaging used for the product should be waterproof to avoid damage during transport. If a large bag or other open packaging is used, the packaged product can be wrapped in polyethylene shrink wrap to protect it from water damage. The packaged products should be stacked and secured onto a pallet to prevent damage and water intrusion from beneath. The storage of the RG should follow procedures outlined in section *3.2.3.8.* The product should be packaged according to any specific standard(s) required. In the absence of such standards, the packaging should include the following information: material grade, quantity, instructions for storage, guidelines and conditions for use, and a batch code or similar identification.


*Figure 7 Gypsum packaging and labeling for agricultural use*

#### *3.2.7.2. Product Transport*

The contact information of the processor should be included along with any organization participating in the reselling of the product. This information can be printed on the packaging or on a separate document. Any product leaving the facility should be recorded including paper and processing residuals.

## 3.3. RG Quality Requirements

Manufacturers will likely possess their own quality criteria when considering the acceptance of RG for their product. Despite this, the following sections are designed as a guide to further inform the decision-making process for both the recycler and manufacturer. They include relevant legal and recommended criteria that both parties should be aware of when producing, accepting, and utilizing RG. Take note that, unless unique to processes that take place in recycling or manufacturing, the responsibility of meeting these requirements should be agreed upon between both parties.

### 3.3.1. Closed Loop and General Requirements

Drywall manufacturing typically follows a series of steps [19]:

- Calcination – Thermal processing of gypsum to change hydration state (produces stucco)
- Slurry production – Mixing of stucco with water and liquid additives to create a slurry that will eventually form the core of the drywall
- Board formation – Slurry is "sandwiched" between paper sheets to form continuous sheets of drywall
- Setting and Cutting – Transportation along a conveyer belt to allow for setting and bonding to paper facing before hardening enough to be cut as it approaches the end of the line
- Drying and Finishing – Entrance into drying kiln where excess free moisture is eliminated

#### *3.3.1.2. Legal Requirements for Use in Drywall*

Drywall manufactured or imported for use in the United States on or after July 22, 2015, must comply with the U.S. Code Title 15, Section 2056 [23]. This mandates a limitation on sulfur content detailed in ASTM C1396-14a [24]. Be advised that this document has been updated by the ASTM Subcommittee C11.01 on Specifications and Test Methods for Gypsum Products and these updates are not reflected in the current statute; however, requirements have not changed with subsequent editions of C1396.

#### *3.3.1.3. Recommendations for Closed Loop Recycling and General Use*

In order for plaster or drywall with RG to be considered acceptable in North America they must conform to ASTM C22, ASTM C28, ASTM C1396 and ASTM C1264 [16], [24]–[26]. Inclusion of RG in other forms of drywall such as those outlined in ASTM C1177, C1178 and C1658 may be feasible but it has not been verified.

Specific manufacturers and plants may have their own criteria; however, it is recommended that high quality RG intended for use in plaster or drywall adhere to the following technical and toxicological standards developed in the GtoG report:

*Table 3 Technical Parameters for RG [22].*

| Parameter | Unit | GtoG guidelines on RG quality criteria | Test Method |
|---|---|---|---|
| Particle Size | mm | 0-15 | ASTM D6913 |
| Free Moisture | %w/w | <10 | AOAC 965.08 |
| Purity | %w/w | >80 | ASTM C471M-17a |
| Total organic carbon (TOC) | %w/w | <1.5 | U.S. EPA 9060A |
| Magnesium salts, water sol. | %w/w | <0.1 | AAS or ICP OES |
| Sodium salts, water sol. | %w/w | <0.06 | AAS or ICP OES |
| Potassium salts, water sol. | %w/w | <0.05 | AAS or ICP OES |
| Soluble chloride | %w/w | 0.02 | Potentiometry, ion chromatography or titration or photometric determination |
| pH | | 6-9 | U.S. EPA 9045D |

*Table 4 Toxicological Parameters for RG [22]*

| Parameter | Unit | GtoG guidelines on RG quality criteria | Test Method |
|---|---|---|---|
| As | mg/kg | <4.0 | U.S. EPA 3050B,6010d |
| Be | mg/kg | <0.7 | U.S. EPA 3050B,6010d |
| Pb | mg/kg | <22.0 | U.S. EPA 3050B,6010d |
| Cd | mg/kg | <0.5 | U.S. EPA 3050B,6010d |
| Cr | mg/kg | <25.0 | U.S. EPA 3050B,6010d |
| Co | mg/kg | <4.0 | U.S. EPA 3050B,6010d |
| Cu | mg/kg | <14.0 | U.S. EPA 3050B,6010d |
| Mn | mg/kg | <200.0 | U.S. EPA 3050B,6010d |
| Ni | mg/kg | <13.0 | U.S. EPA 3050B,6010d |
| Hg | mg/kg | <1.3 | U.S. EPA 7471B |
| Se | mg/kg | <16.0 | U.S. EPA 3050B,6010d |
| Te | mg/kg | <0.3 | U.S. EPA 6010D |
| Tl | mg/kg | <0.4 | U.S. EPA 3050B,6010d |
| V | mg/kg | <26.0 | U.S. EPA 3050B,6010d |
| Zn | mg/kg | <50.0 | U.S. EPA 3050B,6010d |
| Asbestos | yes/no | no | EPA Method 600/R-93/116 |
| R index | <0.5 | <0.5 | RP 112 Document (EC) |

It is important to note that these are references values that do not represent the concentrations above which a human health risk occurs. They are based on the current sole scientific study of toxicity in gypsum and were agreed upon by the GtoG participants [22], [27].

#### *3.3.1.4. Particle Size*

Particle size control of gypsum is an agreed upon parameter between recycler and manufacturer that is crucial to achieve the exact stucco properties desired for specific drywall manufacturing.

It is a determinant factor for achieving uniform heat transfer in the calciner. Additionally, it strongly influences the water demand by influencing the viscosity of the stucco slurry [19]. The particle size of RG differs from that of natural gypsum (NG) and flue gas desulfurization (FGD) gypsum in that it is usually smaller and finer [19]. To minimize undesirable affects the particle size of gypsum should be compatible with conventional feedstock in use.

#### *3.3.1.5. Free Moisture*

Free moisture is the total water that is not chemically bonded to the gypsum drywall and its presence affects the feed/stucco mass ratio. Since the amount of dry feedstock of a given purity to produce one (1) ton of stucco is specific, the feed/stucco ratio increases when the feed is wetter [19]. Free moisture also increases the energy requirements of calcination (as more moisture necessitates higher fuel consumption [19]. RG (if properly stored and transferred) typically has lower moisture contents in comparison to natural and FGD gypsum [19]. This can reduce energy consumption. The amount of a specific feedstock that a gypsum plant can blend in its mixture is often determined by the thermal capacity of the drying system [28]. Therefore, the feasible maximum percentage of RG reincorporated, not the process, can be limited by high free moisture. Additionally, stucco with high free moisture has a greater tendency to stick and build up on conveying equipment and the presence of mold growth is an issue of concern in cases of high free moisture [19].

#### *3.3.1.6. Purity*

Purity is the most important quality index of gypsum as a raw material. Due to the endothermic nature of calcination, the higher the purity the higher the thermal energy demand. This is because the feedstock contains more chemically bound water that must be freed [19]. However, high purity material is preferable for product quality mainly because it lowers the weight of drywall [28]. RG typically has a lower purity than natural and FGD gypsum, which does result in lower energy consumption but also produces quality constraints for the final product.

#### *3.3.1.7. Residual Paper and Fiber Content (TOC)*

Residual paper is a major limiting factor in the reincorporation of RG into manufacturing processes. The paper flakes influence the consistency of feedstock and can form agglomerations in the calcining gypsum mass [19]. In calcination units heated indirectly paper pieces tend to stick to the walls of the vessels and form insulating layers that hinder heat transfer [19]. In the actual production of drywall, excess paper content can cause mixer blockages and increase water demand (which leads to increased energy demand in the drying process) [19]. They may also affect the fire rating and overall specifications of the drywall [19]. Not only the paper content, but also the size of the paper is a variable of concern in wallboard production as larger pieces have tendency to cause more equipment blockages.

Another limiting factor of RG maximum reincorporation rate is its cellulose fiber content [19]. Fiber is difficult to completely remove from RG and hinders efficient heat transfer in calcination.

TOC is typically used as a metric of both paper and fiber content [19].

#### *3.3.1.8. Water Soluble Salts*

Water soluble salts refers to chloride, magnesium, sodium, and potassium salts. The presence of these salts in the feedstock can affect the ability of paper to bond in drywall production [19]. During the drying process they migrate to the paper gypsum core interface and interrupt the bond [4]. The chloride concentration of the feedstock holds particular importance as it impacts the calcination rate of conversion [19]. Be aware that water soluble salts are common impurities in conventional NG. Therefore, this is not an issue specific to RG and infrastructure to manage water soluble salts is likely already in place. Nonetheless, water soluble salt content can still be an issue in RG and should be limited. Higher salts content in RG could also be linked to high paper content due to its ability to absorb water [19].

#### *3.3.1.9. Silicone Content*

Additives in drywall core are responsible for the presence of silicones in recycled gypsum as well as post-consumer modification (i.e., addition of ceramic tiles) [19]. In case water-resistant drywall is included in the recycling process the material may possess a relatively high silicone content [29]. Silicones are hydrophobic and can cause variability in water absorbance in the production of the fluid slurry [29]. This leads to the formation of blisters and blows in the core and higher thermal energy demand on the board dryer [27], [28]. Some drywalls have wax additives to create water resistance, but these are not a concern as they cannot withstand the heat of calcination.

X-Ray diffraction (XRD) is used to identify whether the $SiO2$ present is of amorphous or crystalline nature. ASTM C471M Standard Test Methods for Chemical Analysis of Gypsum and Gypsum Products – Section 10 describes a wet chemistry method to determine $SiO2$ and insoluble matter [4].

#### *3.3.1.10. Other Impurities*

When delivered to a manufacturing plant RG should be free of visible physical contamination and have low concentrations of chemical impurities to avoid compromising the quality of the finished product. Specification with limits for values of trace elements, mostly heavy metals, are necessary for RG to prevent human and environmental damage. Special attention should be paid to the absolute absence of asbestos, which was an unconditional criterion for acceptance of RG in the GtoG project [19].

#### *3.3.1.11. Feedstock pH*

The pH of RG is not considered an important parameter so long as it is not highly acidic [19]. In that case it may affect the quality of the final drywall product. A neutral or slightly alkaline pH to match that of NG is preferable.

### 3.3.2 Requirements for Agricultural Use

#### *3.3.2.1. Processing Specific to Agricultural Use*

In order to produce the highest quality recycled gypsum product, the recommendations presented should be adhered to for success. For gypsum waste intended for use as a soil amendment, processing may be more or less intensive depending on the soils they will be applied to. For example, the removal of residual paper and limitation of TOC that is imperative when RG is used is closed loop or used as an additive in cement clinker may not be as important or even necessary at all for use as an agricultural amendment. As a result, gypsum waste that is intended to be used as fertilizer or soil amendment may not need to have its paper residuals separated. However, paper content may inhibit proper flow during application in an agricultural setting. There are a variety of literature sources that recommend certain gypsum compositions to optimize specific soil properties [30]. However, these reports are highly individual, and it is advisable that the appropriate experts investigate land requirements on a case-by-case basis to determine the optimum physical and chemical characteristics of RG for their land.

#### *3.3.2.2. Legal Requirements for Agricultural Use*

Before RG can be beneficially reused via land application, the heavy metals, sulfates, and calcium concentrations should be compared with regulatory risk-based thresholds that address potential risk to humans and/or the environment via direct exposure or leaching into groundwater. Vendors should distribute RG with these thresholds in mind. Material that does not meet regulatory specifications can be reprocessed to lower concentrations of contaminants or disposed of at a landfill.

#### *3.3.2.3. Recommendations Specific to Agricultural Use*

While measured concentrations can and should be compared to clean soil and groundwater thresholds used for waste-derived materials, these thresholds typically assume the material will be applied as a soil fill. A more appropriate method to evaluate the land application potential of RG may be to compare the measured chemical concentrations to soil amendment standards. An example of standards for the application of gypsum as a soil amendment is provided by the UGWA in the Conservation Practice Standard Code 333 [31]. Note this is not a legally binding set of standards but has to do with eligibility for NCRS conservation program [32].

*Figure 8 Land application of RG*

## 3.3.3. Requirements for Use in Cement Clinker

### *3.3.3.1. Legal Requirements for Use in Cement Clinker*

Although it is unlikely, it is possible that some contaminants present in recycled gypsum could pose a risk to human health in the process of Portland cement manufacturing. Therefore, the National Emission Standards for Hazardous Air Pollutants from the Portland Cement Manufacturing Industry should be adhered to when relevant [33]. Moreover, the production of cement clinker with RG is still subject to the EPA Cement Manufacturing Effluent Guidelines and Standards that regulate direct and indirect discharge of pollutants as a result of cement manufacturing [34].

### *3.3.3.2. Recommendations Specific to Cement Clinker*

It has been demonstrated (on a limited basis) that RG can be used in cement clinker and produce acceptable mechanical properties [35], [36]. However, there is currently finite information as to the optimum quality of RG for specific use in cement clinker. The available literature suggests that the main difference between NG and RG is the presence of increased levels of hemihydrate [35], [36]. It has been shown to play a role in decreasing the setting times of Portland cement and should be appropriately controlled [35]. Outside of this parameter, it is recommended that recyclers pursue the same quality criteria articulated in the recommendations for RG to be used in drywall.

So far as the content of gypsum to be added to cement clinker is concerned; the amount of gypsum should account for 3% ~ 5% of the cement's mass [37]. If the content of gypsum exceeds this limit, it will lower the strength of cement and it can even lead to poor dimensional stability [37]. Additionally, excess gypsum may also accelerate the setting of cement as it can generate a coagulating agent itself [37]. If the content of gypsum is too low, the retardation effect will be minimal [37]. Normally, the appropriate amount of gypsum depends on the content of C3A in the cement, the SO3 in the gypsum, the fineness of the cement, and the content of SO3 in clinker [37]. However, in RG's case the percent distribution by mass of calcium sulfate species becomes another concern and currently lacks specific parameters.

# 4. Manufacturing

This section is intended to cover specific considerations when a manufacturer decides to incorporate RG in the manufacturing of their product.

## 4.1. Manufacturing Considerations for Drywall Production

RG is used in conjunction with FGD and NG to produce the stucco used in drywall manufacturing. The reason for this is that the non-standard quality of RG limits its use in drywall production to a maximum of 20-30% [19]. This was achieved without permanent investment of equipment and infrastructure [19]. It also necessitates recipe adjustments that demand a greater quantity of additives. Feeding system capacity limitations and recycled gypsum quality related issues, mainly residual paper content and to a lesser extent free moisture and purity, are reported by manufacturers as the main factors that limit the further increase of the re-incorporation rate during the trials [19]. Mixing undesirable RG with desirable fractions is common practice in order to improve overall quality [19].

### 4.1.1. Storage of RG

RG storage in a manufacturing setting specifically requires that sufficient storage space be allocated to achieve a certain level of homogeneity between the fluctuating characteristics of incoming loads. Separate storage for quarantined RG that is intended to be returned should be delineated.

### 4.1.2. Raw Material Feeding

It may be necessary for drywall manufacturers that feed raw materials to re-design their feeding systems. A higher percentage of RG in the feedstock will require speed adjustments or up-scaling of mechanical feeding equipment [19].

### 4.1.3. Processing Adjustments

The use of RG gypsum may call for adjustment in the following areas based on the variability of the RG feedstock and the capability of the manufacturing operation:

- Temperature Control
- Slurry Recipe
- Water Demand
- Use of Additives (Liquefiers, Dispersants, etc.)

Further information on what specific variables necessitate these adjustments can be found in ***3.2.8***.

#### *4.1.3.1 Equipment and Infrastructure*

It has been demonstrated that the incorporation of RG is possible without permanent investment in manufacturing equipment and infrastructure [19]. Lack of RG may be a restricting factor for the incorporation of this material. It is up to the specific manufacturer to determine if modifying or upscaling current equipment and infrastructure is desirable.

### 4.1.4. Setting Time

The setting behavior of the board's plaster core is influenced by the variability of the RG [19]. However, the slurry's setting time can be manipulated by the use of special additives as well as adjustment of the board line's speed [19]. The optimum solution is likely a combination of the two approaches.

## 4.2. Manufacturing Recommendations for Drywall Production

### 4.2.1. Production Trials

RG variations are currently addressed on a case-by-case basis [19]. Quality fluctuations have been overcome by adjusting the percentage of natural and/or FGD gypsum in their feed, modifying calcination and drying parameters, and using additives to reach the necessary stucco quality [19].

#### *4.2.1.1. RG Incorporation Limitations*

The following are general categories for the most common and restrictive factors that limited RG incorporation based on experiences of the five manufacturers that participated in the GtoG project:

- Physical limitations on storage space and management of recycled material including limited available space for the separate storage of accepted and off-spec material earmarked for return
- Overflows and restrictions due to limited capacity (volume and/or motor power and speed restrictions) of the available conveyor belts
- Issues with paper content and the size of residual paper pieces. Sieve blockages, bubbles or lumps in plaster, or lack of bonding between core and liners in drywalls
- Problems in the dosing units of stucco containing high percentage of RG due to a decrease in stucco density
- Problems drying drywall. Behavior of drywall with high content of RG caused boards to over dry
- Limited technical detection capability of non-visible contaminants in RG. This includes fibers (mainly asbestos), chemical contaminants and hazardous materials. This caused delays due to the long time needed for processing the results of analysis
    - There is a need for fast test methods where each loads quality can be ascertained

#### *4.2.1.2. Maximization of RG*

The following are process adaptations utilized to overcome the restrictions identified above, based on experiences of the five manufacturers that participated in the GtoG project:

- Installation of extra weighing units for more precise monitor of RG content
- Changes in equipment speed. Increasing conveyor belt speed to its maximum to achieve sufficient feeding rate of RG and decreasing of borderline speed to decrease stucco feed rate.

- Separation of the completion process step of stucco production with high content of RG (separate dose of calcination, separate silos used, emptying and re-filling of total stucco system etc.)
- Recipe adjustments with regards to chemical additives in the stucco slurry (adjustments in accelerator, foam and liquefier additives)

#### *4.2.1.3. Equipment Modifications*

following are equipment modifications deemed necessary if the maximization of RG reincorporation is to become routine practice, based on experiences of the five manufacturers that participated in the GtoG project:

- Upgrading conveyer belt capacity with enhanced motor power (faster and wider) for the feeding of RG
- Controls to vary recycled content when supplying different parts of the factory
- Enlargement of the complete pre-processing system for RG (i.e., milling, drying, sieving, storage) including the incorporation of a gas burner for drying the RG prior to blending that will allow more effective blending with conventional gypsum and fine grade milling of RG with very high levels of paper removal
- Inline moisture testing along the RG feeding belt prior to blending with conventional feedstock
- Enlargement of the complete transfer and dosage systems within calcination

#### *4.2.1.4. Reincorporation Issues with Plaster*

The bonding compounds utilized in the production of plaster require a very high-quality gypsum. As a result, RG quality parameters must align with those of a conventional feedstock as much as possible for it to be included. This mandates impurities like paper, glass fiber, silicon oil and wood fiber are fully removed [19].

#### *4.2.1.5. Reincorporation Issues with Drywall*

Since the quality of the feedstock mix will vary with an increase in RG content, the entire process (recycling system, calcination, storage, dosage, recipes, drying system) needs to be adjusted. This places great importance on a constant supply of high-quality RG that is compliant with supply chain specifications to guarantee process stability and board quality [19].

#### *4.2.1.6. Limitations and Considerations*

It is the opinion of the GtoG manufacturers that the current quality of RG makes it unsuitable for use in the manufacturing of more technical products where increased purity is required [38]. Trials were only performed on one type of board and the effect of RG reincorporation on other types of wallboards still needs to be assessed. Moreover, the studies trials were carried out in two rounds across five drywall manufacturers (for a total of ten production trials) for only a few hours per round making an assessment of the process impacts on a constant basis a necessity. It was suggested that manufacturers include potential enhancement of RG purity through chemical cleaning methods (although this may be cost-prohibitive) [38].

## 4.3. Manufacturing Considerations for Use in Cement Clinker

The setting behavior of cement is mainly attributed to the reaction of tricalcium aluminate with water, known as a flash set [35]. Gypsum is added to cement clinker during the grinding of Portland cement in a ball mill in order to prevent this reaction. As previously stated, it has been demonstrated that RG can act as a direct substitute for NG in the production of ordinary Portland cement [35], [36]. However, the initial composition of RG seems to contain greater quantities of hemihydrate; although this is subject to variability based on the source of the RG [35], [36].

Gypsum dehydration and formation of hemihydrate occur naturally within an industrial cement mill [36]. This conversion has a diverse effect on setting and compressive strength depending on the composition of the setting retarder [39]. Since the initial composition of the setting retarder (RG) differs from NG, the extent of dihydrate conversion and final hemihydrate content will differ and must be controlled appropriately. This can be accomplished through the regulation of clinker temperature and relative humidity within the mill [39]. By controlling these two parameters through the quantity of sprayed water in the mill optimum temperature and humidity for an ideal degree of dehydration can be determined. Currently there is a lack of information in the literature that articulates what degree of gypsum dehydration is optimal. However, one study found that optimum admixture demand to achieve required levels of workability, workability retention, and early hydration generally occurred with cements that had the least amount of dehydrated gypsum (hemihydrate) [40].

### 4.3.1 Reference Study

The following are the results of one study's chemical analysis of NG and RG (from slip casting molds) compositions to provide a reference for how the chemical compositions of NG and RG (which the study refers to as waste gypsum) can differ:

*Table 5 Gypsum proportions for dihydrate, hemihydrate and anhydrite [28]*

| Components | Natural Gypsum (%) | Waste Gypsum (%) |
|---|---|---|
| Dihydrate | 91.28 | 80.90 |
| Hemihydrate | 1.61 | 12.45 |
| Anhydrite | 4.32 | 4.34 |
| Other impurities | 2.79 | 2.30 |

*Table 6 Reference chemical composition of natural and waste gypsum [28]*

| Component | Chemical Analysis (wt%) | | |
|---|---|---|---|
| | Clinker | Natural Gypsum | Waste Gypsum |
| $SiO_2$ | 21.304 | 1.90 | 0.93 |
| CaO | 65.746 | 35 | 37 |
| $Al_2O_3$ | 6.107 | 0.63 | 0.16 |
| $Fe_2O_3$ | 3.829 | 0.28 | 0.17 |
| MgO | 1.626 | - | 0.97 |
| $K_2O$ | 0.838 | 0.13 | 0.03 |
| $SO_3$ | 0.74 | 41 | 42 |
| NiO | - | 0.02 | 0.02 |
| SrO | - | 0.09 | 0.13 |
| Free Lime | 0.782 | - | - |
| LOI | - | 20.4 | 18 |

The study then compares how various mechanical properties such as setting time, compressive strength, flexural strength, and surface area differed across samples with different amounts of natural (NG) and waste gypsum (WG):

*Table 7 Names and compositions of clinker samples used in the testing of various mechanical properties [28]*

| Symbol | CM97NG | CM96NG | CM95NG | CM97WG | CM96WG | CM95WG |
|---|---|---|---|---|---|---|
| CL (%) | 97 | 96 | 95 | 97 | 96 | 95 |
| NG (%) | 3 | 4 | 5 | - | - | - |
| WG (%) | - | - | - | 3 | 4 | 5 |

*Table 8 Comparison of compressive strength, flexural strength, and surface area of NG and WG clinker samples [28]*

| Sample | Compressive Strength (MPa) | | | Flexural Strength (MPa) | | | Surface Area ($cm^2/g$) |
|---|---|---|---|---|---|---|---|
| | 2 Days | 7 Days | 28 Days | 2 Days | 7 Days | 28 Days | |
| CM97NG | 16.05 ± 0.2 | 31.43 ± 0.5 | 49.2 ± 1.3 | 3.59 ± 0.1 | 5.78 ± 0.3 | 6.30 ± 0.3 | 3816 |
| CM96NG | 18.92 + 0.2 | 33.83 + 0.4 | 52.82 + 1.1 | 4.08 + 0.1 | 6.38 + 0.3 | 7.07 + 0.4 | 3637 |
| CM95NG | 21.82 + 0.4 | 36.05 + 1.2 | 50.7 + 0.8 | 4.39 + 0.1 | 6.62 + 0.4 | 7.81 + 0.1 | 3691 |
| Average | 18.93 | 33.77 | 50.91 | 4.02 | 6.26 | 7.06 | 3714.67 |
| CM97WG | 18.45 + 0.8 | 37.15 + 1.9 | 53.25 + 2 | 3.96 + 0.1 | 6.49 + 0.4 | 7.51 + 0.2 | 3785 |
| CM96WG | 18.95 I 0.1 | 32.13 + 0.6 | 51.75 + 1 | 4.17 + 0.1 | 6.37 + 0.1 | 7.16 + 0.1 | 3948 |
| CM95WG | 17.25 + 0.1 | 31.98 + 0.1 | 51.77 + 0.2 | 3.71 + 0.2 | 5.87 + 1.3 | 7.79 + 0.4 | 3785 |
| Average | 18.22 | 33.75 | 52.26 | 3.95 | 6.24 | 7.49 | 3839.33 |

*Table 9 Comparison of setting times for NG and WG clinker samples [28]*

| Sample | Water/Cement (%) | Initial Setting Time (minutes) | Final Setting Time (minutes) |
|---|---|---|---|
| CM97NG | 26.25 | 138 | 169 |
| CM96NG | 26.50 | 140 | 174 |
| CM95NG | 26.50 | 134 | 169 |
| Average | 26.42 | 137.33 | 170.67 |
| CM97WG | 26.25 | 98 | 125 |
| CM96WG | 26.25 | 125 | 164 |
| CM95WG | 26.00 | 126 | 153 |
| Average | 26.17 | 116.33 | 147.33 |

These results illustrate that the increased proportion of hemihydrate characteristic of RG seem to accelerate setting time but do not have a significant effect on cement strength. Further study is required to verify the validity of these results.

# 5. Conclusion

Gypsum is a material that can theoretically be indefinitely recycled.  This report is designed to aid deconstruction companies, recyclers, and manufacturers in the pursuit of this endeavor. Three theoretically viable end markets are considered: agricultural, drywall and cement clinker. Although this report pulls from all available sources, the literature for markets outside of closed loop recycling is limited and requires additional investigation.  Moreover, the body of work that outlines closed loop recycling into new drywall is finite in that it only examines a single drywall type.  The use of RG in specialty types (Type C, soundproof etc.) has yet to be evaluated.  The beneficial use of RG has been the most seriously pursued in Western Europe.  It is the hope of CDRA that this report will encourage a similar initiative in North America.

## References


[1] LIFE, "GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry." LIFE, 2016. [Online]. Available: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4191

[2] B.S.I., "PAS 109: Specification for the Production of Reprocessed Gypsum from Waste Drywall," *BSI*, 2013, [Online]. Available: https://standards.globalspec.com/std/1151358/BS%20PAS%20109

[3] T. Tolaymat, M. Krause, J. Smith, and T. Townsend, "The State of the Practice of Construction and Demolition Material Recovery," *US EPA*, 2017, [Online]. Available: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=338319

[4] K. Yang, Q. Xu, T. G. Townsend, P. Chadik, G. Bitton, and M. Booth, "Hydrogen Sulfide Generation in Simulated Construction and Demolition Debris Landfills: Impact of Waste Composition," *J. Air Waste Manag. Assoc.*, vol. 56, no. 8, pp. 1130–1138, Aug. 2006, doi: 10.1080/10473289.2006.10464544.

[5] S. E. Musson, Q. Xu, and T. G. Townsend, "Measuring the gypsum content of C&D debris fines," *Waste Manag.*, vol. 28, no. 11, pp. 2091–2096, Nov. 2008, doi: 10.1016/j.wasman.2007.09.012.

[6] Y.-C. Jang and T. Townsend, "Sulfate leaching from recovered construction and demolition debris fines," *Adv. Environ. Res.*, vol. 5, no. 3, pp. 203–217, Aug. 2001, doi: 10.1016/S1093-0191(00)00056-3.

[7] R. Xu *et al.*, "Boron as a contaminant at construction and demolition (C&D) debris landfills," *Waste Manag.*, vol. 109, pp. 85–93, May 2020, doi: 10.1016/j.wasman.2020.04.051.

[8] N. Calvo, L. Varela-Candamio, and I. Novo-Corti, "A Dynamic Model for Construction and Demolition (C&D) Waste Management in Spain: Driving Policies Based on Economic Incentives and Tax Penalties," *Sustainability*, vol. 6, no. 1, Art. no. 1, Jan. 2014, doi: 10.3390/su6010416.

[9] "Lead Based Paint Activities," *Code Fed. Regul.*, vol. Part 745, Title 40, 1995.

[10] H. Canada, "Lead-based paint," *Nov*, vol. 15, 2010, [Online]. Available: https://www.canada.ca/en/health-canada/services/home-safety/lead-based-paint.html

[11] "National Emission Standard for Asbestos," *Code Fed. Regul.*, vol. Part 61, Title 40, 1990.

[12] "Interim Method of the Determination of Asbestos in Bulk Insulation Samples. Code of Federal Regulations," *Append. E Subpart E Part*, vol. 763, Title 40, 1990.

[13] "Hazardous Substances Other than Hazardous Products," in *Canada Occupational Health and Safety Regulations, Part X, Division II*, 2022.

[14] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DB2, 2016, [Online]. Available: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4191

[15] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DA2, pp. 33–55, 2016.

[16] “Standard Specification for Sampling, Inspection, Rejection, Certification, Packaging, Marking, Shipping, Handling, and Storage of Gypsum Panel Products, ASTM C1264-19.” ASTM International, Oct. 08, 2019.

[17] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DB1, 2016, [Online]. Available: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4191

[18] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DB3, 2016, [Online]. Available: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4191

[19] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DB4, pp. 10–37, 2016.

[20] U.S. EPA, “Technical Fact Sheet - Polybrominated Diphenyl Ethers (PDBEs).” U.S. EPA, Nov. 2017. [Online]. Available: https://www.epa.gov/fedfac/technical-fact-sheet-polybrominated-diphenyl-ethers-pbdes-and-polybrominated-biphenyls-pbbs

[21] MoEFCC, “Assessing the danger potential of Gypsum paper residues, potentially valued as animal litter material,” *MoEFCC*, Sep. 2019, [Online]. Available: https://www.3rmcdq.qc.ca/client_file/upload/Table%20Gypse/Gypse201913092019.pdf

[22] L.I.F.E., “GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry,” *LIFE*, no. DC2, 2016, [Online]. Available: https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4191

[23] “United States Code,” in *Title 15: COMMERCE AND TRADE. CHAPTER 47: CONSUMER PRODUCT SAFETY*, 2020.

[24] “Standard Specification for Gypsum Board, ASTM C1396/C1396M-17,” *ASTM Int.*, Jan. 2022.

[25] “Standard Specification for Gypsum Plasters, ASTM C28/C28M-10,” *ASTM Int.*, Jul.

2020.
[26] "Standard Specification for Gypsum, ASTM C22." ASTM International, May 07, 2021.
[27] J. Beckert, *Comparison of natural gypsum and FGD gypsum: studies for a comparative assessment of the health impact of natural gypsum and FGD gypsum from coal-fired power plants with a view to their use in the manufacture of building materials*. VGB-Kraftwerkstechnik GmbH, Verlag Techn.-Wiss. Schr., 1990.
[28] P. J. Henkels and J. C. Gynor, "Characterizing synthetic gypsum for wallboard manufacture," *Prepr. Pap. Am. Chem. Soc. Div. Fuel Chem.*, vol. 41, no. 2, Art. no. CONF-960376-, Dec. 1996, Accessed: Aug. 10, 2022. [Online]. Available: https://www.osti.gov/biblio/430284-characterizing-synthetic-gypsum-wallboard-manufacture
[29] Henry, "Environmental, Health, & Safety Impact of Common Water Resistant Additive Technologies In Gypsum Wallboard Production." Henry, 2010. [Online]. Available: https://henry.com/fileadmin/pdf/literature/EHS_Global_Gypsum_Conference.pdf
[30] D. Kuttah and K. Sato, "Review on the effect of gypsum content on soil behavior," *Transp. Geotech.*, vol. 4, pp. 28–37, Sep. 2015, doi: 10.1016/j.trgeo.2015.06.003.
[31] "Conservation Practice Standard 333: Amending Soil Properties with Gypsum Products." National Resources Conservation Service; United States, Jan. 2020. [Online]. Available: https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcseprd1559465&ext=pdf
[32] C. S. Program, "Code of Federal Regulations, Part 1470," *Title*, vol. 7, 2021.
[33] "National Emission Standards for Hazardous Air Pollutants from the Portland Cement Manufacturing Industry," *Code Fed. Regul.*, vol. Part 63, Title 40, 2022.
[34] Code of Federal Regulations, "Cement Manufacturing Point Source Category," *Part*, vol. 411, Title 40, 2021.
[35] C. Chandara, K. A. M. Azizli, Z. A. Ahmad, and E. Sakai, "Use of waste gypsum to replace natural gypsum as set retarders in portland cement," *Waste Manag.*, vol. 29, no. 5, pp. 1675–1679, May 2009, doi: 10.1016/j.wasman.2008.11.014.
[36] N. Flores Medina, F. Hernández-Olivares, X. Arroyo, A. Aguilera, and F. Fernandez, "Characterization of a more sustainable cement produced with recycled drywall and plasterboards as set retarders," *Constr. Build. Mater.*, vol. 124, pp. 982–991, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.08.140.
[37] H. Zhang, Ed., "4 - Cement," in *Building Materials in Civil Engineering*, Woodhead Publishing, 2011, pp. 46–423. doi: 10.1533/9781845699567.46.
[38] L.I.F.E., "GtoG (Gypsum to Gypsum) - From Production to Recycling a circular economy for the European Gypsum Industry with the Demolition and Recycling Industry," *LIFE*, no. DB4, pp. 58–59, 2016.
[39] G. Tzouvalas, G. Rantis, and S. Tsimas, "Alternative calcium-sulfate-bearing materials as cement retarders: Part II. FGD gypsum," *Cem. Concr. Res.*, vol. 34, no. 11, pp. 2119–

2125, Nov. 2004, doi: 10.1016/j.cemconres.2004.03.021.

[40] S. Dean, S. Farrington, and B. Christensen, “Hydration Behavior of Portland Cements with Different Hemihydrate/Gypsum Ratios in the Presence of Common Chemical Admixtures,” *J. Astm Int.*, vol. 2, Feb. 2005, doi: 10.1520/JAI12478.