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# Design and Assessment of a Dual Stage Crusher for Gypsum Recovery from Plasterboard Residue Recycling

Alexander Hamilton S. Atienza*, Riahleen M. Ramos, Dean Jarius V. Tuiza, Medard Francis S. Yapsangco

Mapua Institute of Technology at Laguna, Mapua Malayan Colleges Laguna, Pulo-Diezmo Road, Cabuyao, 4025 Laguna, Philippines
ahsatienza@mcl.edu.ph

Plasterboards, agricultural additives, and partial concrete substitutes all use gypsum as an essential raw material. Although gypsum is widely used in many sectors in the Philippines, there are currently no technologies available for its recovery. The eventual generation of waste resulting from using gypsum boards calls for the urgent development of effective recycling and disposal methods. This study aims to develop an efficient gypsum-extracting machine for plasterboard residue recycling. The machine consists of two stages of roll crushers, comprising smooth and toothed roller crushers. The system recovered 16.65 kg of crushed gypsum plaster out of 18 kg of clean plasterboard waste, resulting in a recovery rate of 92.50 %. Losses of no more than 7.5 % were also verified the percentage of mass per trial. It was found that there is a significant effect of the type of feed ($p=0.000$) and incorporation of the first stage of rollers ($p=0.002$) on the feed rate. The distribution of the particle size for the crushed plaster was also clustered and analyzed, considering the type of feed and the condition of the first stage of crushing. The results also show that the particles of the crushed gypsum plaster greater than 3 mm have the highest mass average percentage of 37.63 %, while particle sizes close to 1.4 mm have the least value with 4.82 %.

## 1. Introduction

In this world of modernization, various industrialized products have emerged and are being widely used in all aspects of life. Incorporated with numerous life innovations is the eventual generation of waste, starting from the production of materials to be used, manufacturing, and distribution of products. In construction and demolition waste (CDW), demolition activities significantly lead to waste generation, as described in a study by Ittyeipe et al. (2023), which mentioned that the average demolition waste generated was 1,065.515 kg/m2. Gypsum was originally employed as a construction material because of its great features, its ability to quickly harden and take shape, and its exceptional behavior against changes in humidity (Del Río-Merino et al., 2022). Furthermore, Hansen and Sadeghian (2020) state that gypsum mixed with fly ash can serve as a partial alternative for concrete. Moreover, gypsum is utilized in agriculture to reduce naturally occurring hazardous aluminum levels and as a source of calcium and sulfur (Vicensi et al., 2019). Gypsum board waste is complex to reuse or recycle due to impurities from renovation and demolition (Bumanis et al., 2022).
Gypsum is a flexible material utilized for walls in homes, offices, or other buildings (Hansen and Sadeghian, 2020). It can be used as concrete's practical alternate binder (Petropavlovskaya et al., 2021). Walls made of gypsum board are often used in construction and act as barrier elements to offer passive fire protection (Norsk et al., 2022) and are highly capable of absorbing sound (Júnior et al., 2021). Moreover, gypsum from Flue Gas Desulfurization (FGD) is a beneficial source of calcium (Ca) and sulfur (S) for nourishing crops, and its inclusion may enhance the decomposed material's agronomic qualities (Koralegedara et al., 2019). It is an industry extensively established in technologically advanced countries such as the US, Western Europe, Japan, and Canada. The gypsum industry makes up 1 % of the CDW as they are being discarded in landfills that leads to the yield of hydrogen sulfide, which can result in environmental issues, as stated by Bumanis et al. (2022). Gypsum waste is not allowed to be disposed of in a waste facility because doing so could cause hydrogen

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sulfide ($H_2S$), a potentially harmful gas, to dissipate (Hamid et al., 2021). It is the product of the biological reduction of sulfate from disposed gypsum boards (Xu et al., 2011). It is essential to provide means for managing the gypsum board waste. The demand for a secure and reliable disposal process results from environmental awareness (Rodzi et al., 2019). Gypsum board waste is produced in millions of tons each year, and it can still be partially recycled and utilised as a cement substitute in concrete (Takbiri and Sadeghian, 2024). This waste harms the environment in three primary ways: by promoting disposal consumption, depleting natural resources, and creating hydrogen sulfide gas when dumped in a saturated environment. Gypsum waste cannot be dumped in disposal facilities since it can result in the emergence of the potentially toxic gas. Gypsum debris obtained from ceiling plasterboard used during commercial and institutional refurbishments is being recycled and calcined to obtain gypsum paste (Antunes et al., 2019). The study of Erbs et al. (2018) focused on the abstraction of gypsum from plasterboard and compared the recycled gypsum obtained from the process with commercially ready gypsum products based on their mechanical and physical properties. Initially, they prepared the subject, gypsum boards, before putting them in a manual cylinder for mass pressing to achieve a grounded powder. Gypsum can be recycled via crushing to ensure breakdown to smaller and manageable pieces (Fedoskina et al., 2024). Crushing is an efficient approach used for recycling gypsum from plaster since it gives effective separation from other materials (Erbs et al., 2021). Currently, there is lack of literature regarding the recycling of gypsum boards in the Philippines. Given the problems in the waste disposal of gypsum boards in facilities managing CDWs, the concept of extraction from gypsum board scraps has been formed to introduce recycling and to amend the significance of gypsum importation. The feasibility of combining smooth and toothed roller crusher mechanisms for gypsum extraction was considered in this study. Having dual stage crushing is essential to make particles size more consistent (Van Dam, 2008). This novel solution also seeks the determination of a significant percentage of the mass of gypsum plaster that can be obtained from clean plasterboard wastes, the particle size distribution of the crushed gypsum plaster considering type of feed and smooth roll condition, and its profitability as related to the beneficiary and other facilities or institutions interested in the waste recycling of plasterboard residues.

## 2. Methodology

This study identified key issues and areas that need improvement, enabled tailored solutions to be effectively implemented, and met the specific needs of the beneficiary. Overall, this study was accomplished through literature evaluations, correlation of principles, designing, experimentation, and statistical analysis to develop an extracting machine that would aid waste recycling in the construction and demolition industries.

### 2.1 Literature evaluations and correlation of principles

The study analyzed relevant literature related to crusher designs that can be utilized for gypsum recycling. It also employed machine design principles in the finalization of the design.

### 2.2 Material Selection

The gypsum board crusher was made of durable materials, including steel, alloys, and wear-resistant parts, to handle waste gypsum board in an effective, secure, and sustainable manner. The weighted-properties approach has been employed in this study that focused on quantitative techniques for material selection (Farag, 2015). A typical kind of crusher in mining and other industries is the roller crusher. The material is smoothly gripped and drawn into the crushing gap between the rollers. In this design, the roll crushers were made smooth, for the first stage of crushing, and made toothed, for the second stage. Tool Steel 4140 was the best-suited material that should be considered as the material for the toothed roll crusher. The frame is a structural element that provides mechanical systems with stability and support. It also acts as a base for the mounting of other machine components. Based on the ranking, steel was the best-suited material that should be considered as the material for the frame. The hopper aims to keep the material being processed or delivered, providing direct feeding into downstream devices or equipment. Stainless steel 304 was found to be the best material for the hopper based on the results. A chute is a short tunnel or passage with steep sides that is used for transporting components from one surface to another. Stainless steel 304 was also determined to be the potential material for the chute.

### 2.3 2.3 Crusher Design

The technical and actual design of the machine, as seen in Figures 1a and 1b, was centered on the two-stage roll crushers, with the first stage being smooth, and the second stage being toothed. The study considered the physical properties of the gypsum board components, such as its face and back. The first stage of crushing was composed of a pair of cylindrical, smooth rollers. Its operation was connected to the operation of the toothed rolls by incorporating meshing gears. After passing these stages, the particles were directed to the chute until the container was filled with crushed gypsum plaster. The crusher was powered by a gear motor and used sprockets and chains to transmit mechanical power to the crushers. The mechanical power transmission system starts from the gear motor to the chains and sprockets to the meshing gears until the first stage of crusher. Following the mechanical transmission to the crusher, the rotational speed of the second-stage crusher was utilized by the first stage of crushing with gears on the other side of the machine.

(a) (b)

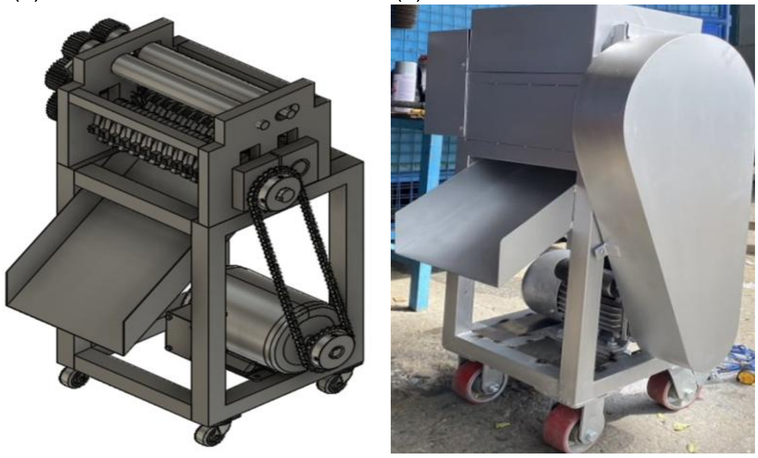

*Figure 1: Crusher Design (a) Drawing (b) Actual Design*

The crusher setting and specifications were calculated and presented from the first stage of crushing to the second stage, utilizing the rotation speed calculated. The first stage was composed of smooth rolls with varying distances that depended on the meshing capacity of the gears attached to these. Given smooth rolls having 50 mm diameter and 290 mm width, the following formulas were utilized. The reduction ratio R is the radius r of the roller and to the gap a between rolls in Eq(1). The angle of nip θ in Eq(2) is formed by the tangents to the roll surfaces at their contact points with the particle, and the compressive force exerted by the rolls. It can be computed in terms of R, r and a. The coefficient of friction μ between steel and particle ranges roughly 0.2 - 0.3 for nip angles not exceeding 30 °(Wills and Finch, 2016). This coefficient as shown in Eq(3) can be calculated with the aid of the visual representation analysis on the forces acting on a particle, assumed to be spherical, in crushing rolls, assumed to be of smooth surface. Due to the motion involved, the coefficient of friction between a particle and moving rolls is given by Eq(4) where V is the peripheral velocity. The theoretical capacity of rolls Q in terms of the ribbon material that would pass the space between rolls was given in Eq(5) from Gupta and Yan (2016). It is in terms of roll diameter $D_R$, width of roll $W_R$, Speed N, distance between roll s and bulk SG of the mineral $\rho_B$.

$$R = \frac{r}{a} \tag{1}$$

$$\theta = 2\cos^{-1}\left(\frac{R+a}{R+r}\right) \tag{2}$$

$$\mu = \tan\frac{\theta}{2} \tag{3}$$

$$\mu_k = \left[\frac{1+1.12V}{1+6V}\right]\mu \tag{4}$$

$$Q = 60\pi \cdot D_R \cdot W_R \cdot N \cdot s \cdot \rho_B \tag{5}$$

### 2.4 Experimental procedure

The experiments for the gypsum extraction have been conducted in triplicates with varying first stage roller conditions and type of feeds. The feed rate was quantified as 1 kg of gypsum over the time taken as it passed through the gypsum extracting machine. The first stage rollers condition can be classified according to opening distance of 9 mm, 10 mm and 15.5 mm, in which the last distance pertains to no first stage rollers. The feed type can be low or high feed. The parameter monitored during the duration of the experiments will be the feed time, feed rate and percentage of gypsum mass extracted. After which sieving will proceed to classify according to particle sizes in which A is less than 3 mm), B is around 3 mm, C is 1.4 mm and D is 0.8 mm. Using statistical analysis, the significant effects of the first stage roller conditions and feed type to the feed rate, mass of gypsum extracted, and particle size have been analyzed using two-way ANOVA

## 3. Results and Discussion

To properly design the crusher, the following parameters have been calculated and can be seen in Table 1. As observed, the nip angle close to 30° has a desired coefficient of friction ranges from 0.2 to 0.3 (Wills and Finch, 2016). The increase in gap between rolls enhances the roll capacity.

*Table 1: Design Calculations for Rolls Given a Variable Gap Between Rolls*

| Rolls | a (mm) | R | θ (°) | μ | μK | Q (kg/h) |
|---|---|---|---|---|---|---|
| Smooth | 9 | 1.28 | 32.79 | 0.29 | 0.06 | 162.72 |
| Smooth | 10 | 1.15 | 25.36 | 0.22 | 0.04 | 180.83 |
| Toothed | 1 | 10.00 | 46.89 | 0.43 | 0.08 | 23.26 |

Low feed, for every setting on the 1st stage of rolls, took the longest time for gypsum board scraps to be crushed. It was on the high feed where a higher rate of crushing could be observed. The absence of the first stage of rolls resulted in a low-feed operation with an average duration of 221.82 s. Furthermore, under conditions of high input in the feed, the average duration required to crush the gypsum was 91.09 s. There are large differences in terms of feed rate between the conditions of the 1st stage of rolls (9 mm and 10 mm opening) and no 1st stage of rolls. The percentage mass of gypsum board can be obtained by getting the quotient of total mass of gypsum plaster obtained after crushing and the total mass of plasterboard residue input. Given the uniform input of 1 kg of plasterboard, the minimum percentage of mass obtained from high feeding on the operation with a 10 mm opening at the first stage of crushing is 85.80 %. On the other hand, the maximum percentage of mass is 96.40 % acquired from low feeding during the operation of the 15.5 mm opening without the first stage of crushing. Low feed has a higher percentage than high feed for each variation in the first stage of rolls. Based on the condition of the first stage rolls, the application of no initial roll crushing with a 15.5 mm opening has the highest percentage, with an average of 93.20 %. Using the percentage mass of gypsum in each trial, it was determined that up to 15 % of the input plasterboard waste was lost throughout the crushing process. Overall, the machine was 92.52% efficient in crushing all plasterboard residue utilized in this study, crushing 16.65 kg of gypsum plaster from 18 kg of plasterboard residue. Mass loss can be contributed to changes in porosity (Zhu et al., 2018) and microstructures (Li et al., 2016) during crushing. The particle classifications A, B, C, and D have been analyzed. High feed at 10 mm opening has shown in Figure 2 the highest mass of Particle A with 0.438 kg. On the other hand, the highest mass of Particle D, consisting of, has been produced from high feeding at 9 mm opening resulting in 0.440 kg of cleanly crushed gypsum. It is observed that with a 15.5 mm opening and without the operation of the first stage of roll crushers, the resulting mass was more uniform comparing to the 10 mm gap used in the study of Fedoskina et al. (2024). It was observed that size A had the largest amount, with an average of 37.63 %, followed by size D with an average of 35.97 %. An average of 14.10 % of the crushed gypsum was of size B, while C had the smallest amount of gypsum plaster, with an average of 4.82 %. This data was based on the machine's output from inputting a total of 18 kg of plasterboard residue. Using two-way ANOVA, the researchers sought to understand the significant relevance of each input variable used to the output variables gathered from the experiment. Input variables include the variation in the feed type and the variation in the condition of the 1st stage of rolls. On the other hand, the output variables include the feed rate, the percentage of mass for each trial, and the mass of each particle size. A p value of 0.000 for the relevance of the feed type and 0.002 for the relevance of the 1st stage of rolls in which these values proved that the feed type and the condition of the 1st stage of rolls are significantly affecting the feed rate, but the interaction between the two showed no relevance to the output variables. The mass of the crushed gypsum and particle size were not significantly affected by feed type, the condition of the 1st stage of rolls, and the interaction between the two with p values greater than 0.05.

The recycled gypsum particle sizes obtained from the study can be used in different applications. For particle size at 0.8 mm can be utilized as material for concrete production (Ganjian et al., 2011) while size at 1.4 mm can used for road foundation applications (Ganjian et al., 2011). The 3mm size particles can be partially replaced by cement (Takbiri and Sadeghian, 2024) and particle size greater than 3 mm can be used for precasting and ornaments (De Moraes Rossetto et al., 2016). Most of these particle sizes can also be used for composting and soil amendment (Ntombela et al., 2019).

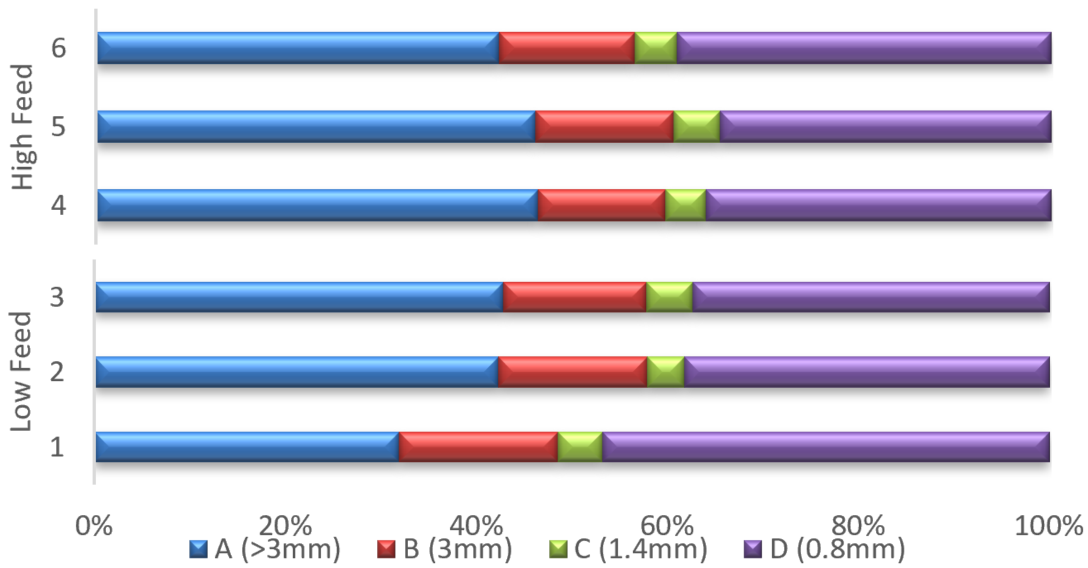


*Figure 2: Particle Size Distribution of Crushed Gypsum at 10 mm First Stage Crusher Opening*

## 4. Conclusion

The machine was tested on the gypsum extraction side and identify the percentage mass of gypsum plaster under different conditions of its opening and feed rate. 9 mm, 10 mm, and 15.5 mm openings were the setup of the 1st stage roll crusher (smooth). At different openings, the feed rate varied from low to high. Given the uniform input of 1 kg of plasterboard, the minimum percentage of mass is 85.80 % obtained from high feeding on the operation with a 10 mm opening at the 1st stage of crushing. On the other hand, the maximum percentage of mass is 96.40 % acquired from low feeding during the operation of the 15.5 mm opening without the 1st stage of crushing. Even though there are differences in the width opening at the 1st stage level of crushing, the recorded and computed percentages of mass of gypsum plaster were almost equal. After crushing, not more than 7.5 % of the total gypsum plasterboard weight was lost. Another aim is to establish the distribution of the particle size of the crushed gypsum plaster, considering the type of feed and the condition of the first crushing stage. The particle sizes where a large amount of the total crushed gypsum was observed were greater than 3 mm and 0.8 mm. The smallest amount gathered came from particle size of gypsum plaster measured 1.4 mm. This study has shown the capability of extracting gypsum for recycling purposes, minimizing waste and aid in sustainable production.

### Nomenclature

a – gap between rolls, m
$D_R$ – roll diameter, m
N – speed, rpm
Q – roll capacity, kg/h
r – roller radius, m
R– reduction ratio, -
V – peripheral velocity, m/s
$W_R$ – width of the roll, m
$\rho_B$ – bulk SG in the mineral, kg/m3
$\theta$ – angle of nip, º
μ– coefficient of friction, -
$\mu_K$– coefficient of friction between particles and moving rolls, -


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