

Cooper Union

Beneficial Use Potential of Gypsum Drywall in NYC

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Selected Material

The material selected for this project is gypsum drywall, which is composed of a hardened gypsum core bonded between two layers of paper. The core material originates from finely crushed gypsum rock, which becomes gypsum powder. The gypsum powder is combined with water and additives to create a slurry, which hardens to form the solid core of the drywall board [10].

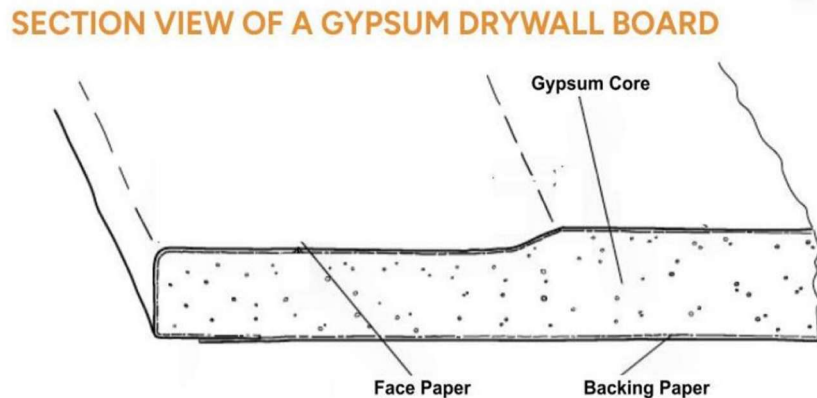


Figure 1: Section View Of A Gypsum Drywall Board [10]

How Gypsum Drywall Is Used in NYC

In New York City's vertical high-rise buildings, gypsum drywall is a standard fireproofing material installed behind finished surfaces. It plays an important role in ensuring fire safety, as it creates fire-resistant rooms and hallways [20]. Additionally, gypsum drywall lines elevator shafts and staircases, as these enclosed spaces could threaten occupants escaping a fire [10]. Furthermore, a NYS building code from the year 2020 asserts that gypsum drywall can be used horizontally in buildings' ceilings to act as diaphragms, which are crucial elements of wind resistance, this is still within the vertical building context [22]. It is worth stating that gypsum drywall has limited true horizontal infrastructure use as it is not typically used within roads or bridges.

Why Beneficial Use Pathways Must Be Identified

Gypsum drywall is primarily disposed of in landfills that foster under anaerobic, or low-oxygen, conditions. When contained in anaerobic landfills, its organic paper facing decomposes, releasing methane gas. Methane is harmful to the environment because it is a greenhouse gas that contributes to global warming. Furthermore, anaerobic conditions allow sulfate-reducing bacteria to convert the sulfate in gypsum into hydrogen sulfide (H_2S), which is both toxic and odorous [22][24]. In addition to being released into the atmosphere, hydrogen sulfide can also leach into groundwater over time, creating an environmental hazard [18].

How Gypsum Drywall Enters The Waste Stream

Primarily, gypsum drywall enters the waste stream through construction and demolition. During construction, drywall must be cut to fit specific dimensions. Gypsum drywall cutting generates scraps that are typically discarded into landfills. Moreover, during the demolition of buildings, existing drywall is removed. As this form of gypsum drywall is often damaged or no longer meets performance standards, it is also sent to landfills. These construction and demolition activities represent the primary sources of gypsum drywall waste [22].

Annual Quantity of Gypsum Waste

The annual quantity of gypsum drywall generated in NYC's C&D waste stream can be estimated using figures and statistics from reliable sources concerning construction and demolition in NYC. The Department of Design and Construction (DDC) reports that NYC generates 13,500 tons of mixed construction and demolition debris every day [2]. Furthermore, an article concerning gypsum wallboard recycling published by the Association of Wall and Ceiling Industry (AWCI) states that an estimated 10% to 15% of the gypsum board necessary for a new building ends up as scrap [3]. The information on behalf of the DDC and AWCI allows a low and high estimate of the annual tons of gypsum drywall waste to be calculated. The low estimate takes the daily NYC C&D mixed debris tonnage and multiplies it by the product of 0.10 and 260 working days, a value that assumes a 5-day work week. An annual quantity of 351,000 tons of gypsum drywall debris is yielded for the low estimate. The high estimate takes the daily NYC C&D mixed debris tonnage and multiplies it by the product of 0.15 and 312 working days, which assumes a 6-day work week. An annual quantity of 631,800 tons of gypsum drywall debris is yielded for the high estimate.

The estimated numeric range for the annual quantity of gypsum drywall generated in NYC's C&D waste stream spans from 351,000 tons to 607,500 tons. The method used to find the numeric range is given by the following formula.

$$(\text{Daily NYC C\&D mixed debris tonnage}) \times (\text{Gypsum Drywall Fraction}) \times (\text{Number of Working Days})$$

Once the appropriate values are put into the formula, the following is received.

$$\text{Low Estimate: } (13,500 \text{ tons/day}) \times (0.10) \times (260 \text{ days}) = 351,000 \text{ tons/yr}$$

$$\text{High Estimate: } (13,500 \text{ tons/day}) \times (0.15) \times (312 \text{ days}) = 631,800 \text{ tons/yr}$$

The major assumption of these estimates is the assumption that every week of the year is a full 5 or 6-day work week. Realistically, this is not the case due to holidays and idiosyncrasies in construction schedules. The major uncertainty associated with the method above is that we do not exactly know what NYC counts as mixed debris. If the NYC DDC considers a quantity of excavated soil and rocks as mixed debris, the dry wall percentages from prior, 10% to 15%, could be skewed.

The Chemical, Physical, and Morphological Characteristics Of Gypsum Drywall

Gypsum drywall has a chemical composition primarily consisting of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) [11]. Moreover, approximately 21% of its weight is chemically combined water, which provides significant fire resistance [6].

Regarding its physical properties, gypsum drywall has low strength and mild porosity. The strength of a sheet depends on the quantity of physical additives mixed into the gypsum core slurry. The most common additive is cellulose fiber, which increases the drywall's stiffness and permeability [6].

Morphologically, gypsum drywall is composed of interlocking crystals that form a micro-porous structure, making it susceptible to abrasion and moisture damage [6].

Gypsum Drywall's Condition When Recovered

When demolished, gypsum drywall is commonly recovered in broken pieces or as powder due to the covalent bonds within the interlocking crystal structure, which snap under external forces as opposed to bending [10]. The two primary typical recovered forms of gypsum drywall are clean new scrap and demolition gypsum. Clean new scrap is characterized by having minimal paper and a uniform composition, while demolition gypsum is characterized by containing joint compound, paint, or fasteners [21].

Relevant ASTM Standards

Several ASTM standards exist to ensure and encourage proper recycling [7]. For example, ASTM Standard C1881 establishes that recovered drywall waste must be uncontaminated and suitable for recycling [10]. This standard is relevant because recovered gypsum fragments can be broken down into a powder, and this powder is commonly used to form a new gypsum core during the drywall recycling process [22].

Gypsum Drywall's Environmental Concerns

The production of new gypsum drywall is energy-intensive, with the largest portion of energy required in manufacturing the board itself. Since recycling gypsum drywall needs significantly less energy, recycling presents a viable method for reducing the material's overall carbon footprint [10].

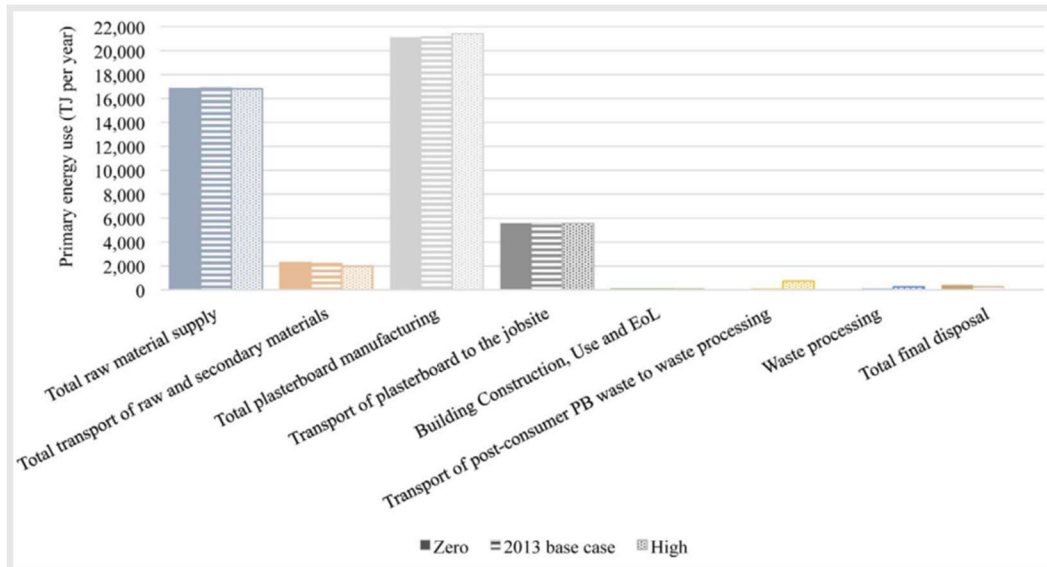


Figure 2. Primary energy use in TJ per year within a drywall board's life cycle. [10]

Properties With Reuse Options Table

Properties With Reuse Options		
Properties	Importance	Reuse Options Affected
Paper Fiber Contamination	Residual facing paper cannot remain on a gypsum drywall that undergoes the recycling processes. Facing paper residue can hinder the calcination process [25].	The closed-loop recycling of gypsum waste is affected by paper contamination, as the purity of the recycled gypsum product is lowered [25] [23].
Moisture Content	Gypsum drywall must maintain a low water content, as elevated moisture levels increase its mass and promote microbial growth [4].	High levels of moisture in recycled gypsum drywall disrupts moisture control in ceramic brick bodies, resulting in an increased risk of drying defects such as cracking and warping [8]. Gypsums incorporation into ceramic blocks is affected here.
Sulfate Content	Variations in sulfate content impact gypsum's compatibility as a supplementary	Excess sulfate will result in delayed ettringite formation for gypsum drywall that has been crushed into a fine powder and mixed with fly ash, meaning that the fly ash co-

	cementitious material [26].	utilization option will be affected [26].
Particle Size	The size of the particles that make up a board of drywall's gypsum core impacts reactivity, blending uniformity, and the amount of energy needed for processing [3].	Particle size impacts the closed-loop recycling of gypsum waste and co-utilization with fly ash in concrete; fine particles are ideal for both applications, as coarse particles require continued milling [3].
Solubility	The solubility of gypsum governs the rate at which sulfate is released [19].	The re-use option that is affected would be gypsum's application in geotechnical soil stabilization, since potential leaching can occur [19].

Closed-Loop Recycling of Gypsum Waste

Closed-loop recycling of gypsum waste is a cyclical process using mechanical and thermal methods to restore the binding properties of discarded gypsum plasterboard and commercial gypsum for manufacturing new construction materials, such as coating plasters or new wallboard. The process is based on the reversible dehydration and hydration reactions of calcium sulfate, with the primary objectives of diverting gypsum from landfills, preserving natural reserves, and establishing a circular production system [13].

Achieving these goals requires rigorous preprocessing and quality assurance of the closed-loop recycling of gypsum plasterboard. The sequence involves the collection and sorting of waste plasterboard and commercial gypsum, followed by crushing and grinding (often using manual or electro-mechanical cylinders) to detach the gypsum core from its paper backing. The material is then milled into a fine powder within a ball mill and subsequently calcined in a controlled oven at 180°C for 24 hours. This calcination step chemically converts calcium sulfate dihydrate back into the reactive hemihydrate form. The final stage involves hydrating the recycled gypsum powder with water to create new building components [13]. This entire process is based on the reversible dehydration and hydration reactions of calcium sulfate [13]. Quality testing follows technical standards such as the Brazilian ABNT NBR 13207:1994, which establishes minimums for key parameters. Critical tests for recycled gypsum include particle-size analysis, setting-time tests (initial set >10 minutes, final set >45 minutes for coating plaster), and compressive strength evaluations (≥ 8.40 MPa) [13]. The material must also meet standards for surface hardness (≥ 30 N/mm²) and bulk density (≥ 700 kg/m³) [13].

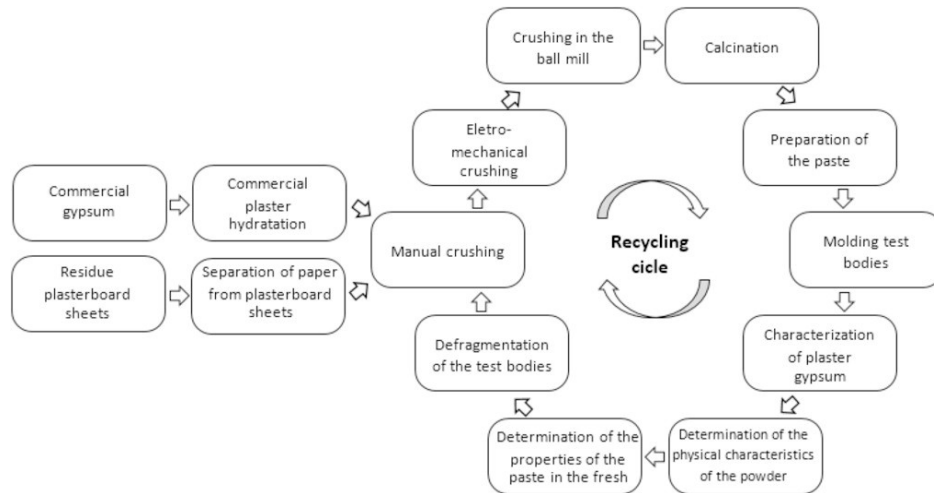


Figure 3: Cyclical Procedure of Gypsum Waste Recycling [13]

The advantages of multi-cycle gypsum recycling are significant. It lowers carbon emissions and conserves natural resources by replacing virgin gypsum, thereby reducing the environmental impacts of quarrying and transportation [13]. Gypsum can be recycled up to three times without significant degradation of mechanical properties, with compressive strength and hardness consistently meeting Brazilian standards for coating plasters throughout these cycles [13]. Research demonstrates that through the third cycle, recycled gypsum from plasterboard and commercial sources maintains an axial compressive strength of at least 8.40 MPa and surface hardness exceeding 30 N mm⁻² [13]. Economically, the process reduces waste disposal expenses and supports markets for products containing recycled materials [13].

Nevertheless, several technical constraints limit its widespread adoption. The number of viable recycling cycles is limited, as mechanical properties deteriorate after the third cycle, with materials from the fourth and fifth cycles failing to meet the required Brazilian compressive strength standards [13]. Residual paper fibers compromise material purity and long-term performance [13]. A major technical challenge is achieving the required bulk density (minimum 700 kg m⁻³). Recycled gypsum often fails this requirement due to its more porous, less compact crystalline structure [13]. This structure results from the formation of shorter orthorhombic crystals, which offer less interlocking and lower packing efficiency compared to the elongated crystals of virgin gypsum [13]. The material also exhibits increased sensitivity to the water/gypsum ratio, which influences density and strength [13]. For example, using a constant water/gypsum ratio of 0.7 leads to a more fluid recycled gypsum paste that can trap excess water and air, increase porosity, and decrease strength in subsequent recycling cycles [13]. In NYC, dense urban construction sites typically lack space for the separate collection and protected staging needed to keep gypsum clean and dry, which is essential for this pathway [14]. Furthermore, this engineering-intensive pathway is not explicitly covered under NYSDEC's current predetermined Beneficial Use Determinations (BUDs), requiring case-by-case approval and creating regulatory uncertainty and added cost [13], [16]. The lack of local pilot projects or a developed end-market in NYC further discourages implementation [14].

Co-utilization with Fly Ash in Concrete

An alternative management strategy involves using recycled gypsum powder from waste drywall alongside fly ash to partially replace Portland cement in concrete mixtures. This approach substitutes a portion of cement with recycled gypsum powder and fly ash (often up to 20% recycled gypsum powder and 50% fly ash by weight of the total cementitious content), requiring the addition of a high-range water reducer (superplasticizer) to maintain concrete workability [9]. The specific aims are to lower the carbon footprint of cement production, divert both drywall and fly ash from landfills, and expand the application of recycled gypsum powder beyond its usual role as a set-time regulator in cement manufacturing [9].

Successful implementation requires careful preparation, material qualification, and performance testing against specific standards and targets. The recycled gypsum powder must be sieved through a No. 100 sieve (0.149 mm opening) to remove paper fiber contaminants [9]. To ensure batch consistency, the hygroscopic powder must be oven-dried and stored in sealed containers [9]. For concrete application, the high sulfate content ($\text{SO}_3 \sim 44.65\%$ in the source material) must be compared with the typical ASTM C150 limit of 3.5% SO_3 for cement [9]. Performance testing is focused on the concrete compressive strength targets (matching or exceeding 35 MPa at 90 days for mixes with 50% fly ash) and workability, which requires superplasticizer dosage adjustments (0.6-4.1 L/m³) to maintain consistency as gypsum content increases from 5% to 20% cement replacement [9].

The benefits of this co-utilization are substantial. It reduces carbon emissions, diverts two major waste streams, and supports the circular economy [9]. Chemically, the sulfate ions (SO_4^{2-}) supplied by the recycled gypsum powder activate the alumina (Al_2O_3) present in fly ash, facilitating the formation of additional strength-contributing products like ettringite and calcium silicate hydrate (C-S-H). Consequently, mixtures containing 50% fly ash and up to 20% recycled gypsum powder can achieve long-term compressive strengths (approximately 35 MPa at 90 days) comparable to those of concrete without it [9]. Economically, it decreases cement consumption and lowers waste disposal costs [9].

Several key limitations exist, however. The concrete gains strength slowly due to the pozzolanic nature of fly ash, making it unsuitable for projects requiring rapid formwork removal or high early strength [9]. When used alone, recycled gypsum powder weakens concrete, and high contents (15-20%) can cause a rapid false set, leading to early stiffening during mixing, posing risks for field placement [9]. Additionally, recycled gypsum powder also increases water demand, requiring greater amounts of superplasticizer to maintain workability [9]. Significant regulatory barriers exist in NYC, as recycled gypsum increases the sulfur trioxide (SO_3) content, potentially exceeding the ASTM C150 limit of 3.5% for Portland cement and preventing certification under current standards [9]. Furthermore, this advanced reuse pathway is not covered under existing NYSDEC predetermined Beneficial Use Determinations (BUDs), requiring case-by-case approval and creating regulatory uncertainty [11], [16]. NYC-specific logistical constraints, such as limited space for source separation and protected storage on dense urban construction sites to prevent contamination and moisture exposure, further challenge the consistent material quality required for this application [9], [14].

Application in Geotechnical Soil Stabilization

Gypsum waste can also be utilized as an additive for stabilizing weak soils in geotechnical engineering. In this application, recycled gypsum powder (produced from crushed and heat-treated waste plasterboard) is mixed with soil along with a small quantity of a cement-based solidifying agent. Research indicates a minimum of 2.5% Portland cement by soil weight is sufficient to counteract gypsum solubility and ensure durability [1]. The mixture is compacted at its optimum moisture content and maximum dry density to produce a stronger, more durable material [1]. The objectives are to divert gypsum waste from landfills and to enhance the load-bearing capacity of soils for use in embankments, roadbeds, and similar infrastructure projects [1].

Effective implementation relies on proper preprocessing and testing. Plasterboard waste must be processed through crushing, pulverization, and screening to remove contaminants like paper fibers [1]. For soil stabilization, laboratory testing includes Standard Proctor compaction tests to determine optimal moisture content and maximum dry density. Quality control focuses on achieving sufficient unconfined compressive strength (UCS) and durability against environmental cycles. Specifically, samples should be subjected to 12 freeze-thaw cycles (freezing at -23°C and thawing at 22°C) and 12 wet-dry cycles per ASTM D560-03. Post-cycling, the material must meet durability thresholds. For sandy soil (AASHTO A-2-4), the allowable soil loss is less than 14%, and volumetric change should be minimal (under 1.5%) [1]. Furthermore, a minimum cement content of 2.5% is often required to prevent gypsum solubility and ensure long-term integrity under these cyclic conditions.

This method offers substantial benefits. It creates a high-volume application for gypsum waste, reduces disposal costs, and significantly improves soil strength. Experimental results show that soil strength improves with recycled gypsum content, as unconfined compressive strength increased from 14.42 kPa (0% gypsum) to 25.43 kPa, 81.99 kPa, and 331.18 kPa at 5%, 10%, and 20% recycled gypsum, respectively [1]. When stabilized with at least 2.5% cement, the soil-gypsum composite (containing up to 20% recycled gypsum) demonstrates strong resistance to environmental cycling. After being subjected to 12 freeze-thaw cycles, the composite exhibits minimal volume change (typically under 1.5%) and experiences low mass loss. This performance meets durability requirements for applications like road sub-bases, where the tested soil loss remained below the 14% threshold after 12 cycles [1]. The study confirms that without a solidification agent like cement, soil-gypsum mixtures are not durable, but with 2.5% cement, the composite gains sufficient rigidity to resist cyclic environmental damage effectively.

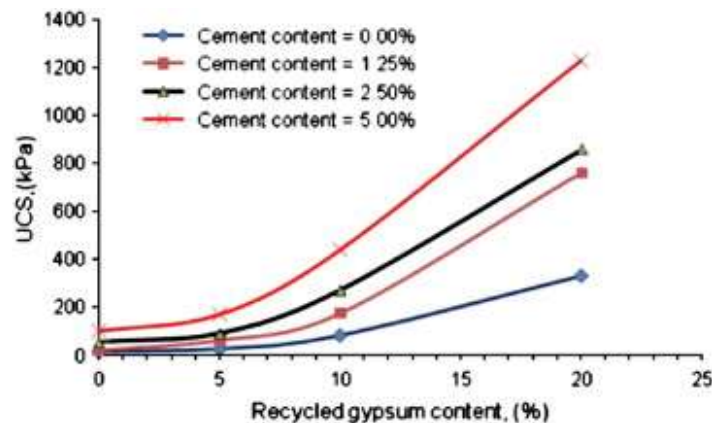


Figure 4: Effect of Recycled Gypsum Content on Compressive Strength at Different Cement Contents [1]

Several limitations exist, however. Gypsum is highly water-soluble; for example, soil stabilized with only gypsum deteriorates rapidly under freeze-thaw or moisture exposure, often failing within the first few cycles [1]. While Portland cement addition prevents this, it introduces additional cost, complexity, and carbon emissions [1]. There is also a risk of sulfate leaching into groundwater, requiring environmental monitoring [1]. Furthermore, performance is highly dependent on the mix design. While strength generally increases with higher gypsum content (from 5% to 20%), durability against environmental cycles is only achieved with sufficient cement content [1]. NYC regulations classify gypsum board within construction and demolition waste streams, but they do not mandate specific high-value reuse pathways [14], [15]. NYSDEC's Part 360 Beneficial Use Determination (BUD) historically approves only low-complexity uses like agricultural soil amendments or animal bedding, while advanced engineering applications, such as soil stabilization, are not covered under current predetermined BUDs and require case-by-case approval, creating regulatory uncertainty [11], [16]. Furthermore, practical implementation in NYC is hindered by dense urban jobsites that lack space for clean, source-separated storage and moisture sensitivity that degrades material quality [9], [11], [14].

Use as an Adsorbent for Fluoride Removal from Water

Waste gypsum board can be utilized as a highly effective adsorbent for removing fluoride from contaminated water. Composed mainly of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), dissolved calcium ions from the waste gypsum board react with fluoride in water to form insoluble calcium fluoride (fluorite, CaF_2), which precipitates out of the solution [11]. This approach aims to provide a low-cost, efficient water-treatment option while diverting waste gypsum board from landfills [11].

A key advantage is the minimal pre-processing required for water treatment applications. The process involves only the removal of paper or vinyl backing, followed by crushing and sieving to a uniform particle size (typically 0.425-0.850 mm) [11]. Unlike many calcium-based adsorbents, waste gypsum board does not require thermal activation or chemical treatment, as calcination does not enhance its fluoride adsorption capacity due to the stable crystalline structure of CaSO_4 . For performance validation, analytical techniques like BET (confirming mesoporous features with pores <30 nm), XRD, and XPS are employed to verify the primary removal mechanism of the reaction of dissolved Ca^{2+} with fluoride to form insoluble CaF_2 . For environmental handling, Toxicity Characteristic Leaching Procedure (TCLP) tests confirm that the spent material (F-WGB) is non-hazardous for disposal, with leached heavy metals such as Cd, Cr, and Pb concentrations well below U.S. EPA regulatory limits (e.g., <1.0 mg/L for Cd, <5.0 mg/L for Cr and Pb) [11].

The adsorption performance is notable. Waste gypsum board has a high maximum fluoride-removal capacity of 285.90 mg/g (305.40 mg/g according to the Langmuir model), outperforming many commercial and waste-derived adsorbents. It effectively treats both groundwater and wastewater, removing 94% of fluoride from groundwater (50 mg/L) using 0.33 g/L and >95% from artificial wastewater (500 mg/L) using 3.33 g/L, meeting effluent targets [11]. It remains effective in alkaline conditions up to pH 11 due to its pH-buffering capacity [11].

The process has a low carbon footprint and is inexpensive, utilizing an unmodified waste material [11]. The fluoride is permanently sequestered in a stable mineral phase (CaF_2). This chemical immobilization process follows a predictable rate, and TCLP results confirm the spent adsorbent is safe for disposal [11].

Several limitations hinder real-world application. Competing anions, particularly phosphate (PO_4^{3-}) — which forms strong inner-sphere complexes — can reduce fluoride removal by up to 73% at a concentration of 10 mM [11]. Waste gypsum board functions as a single-use adsorbent with poor regeneration performance (only 74.3% capacity recovery after one cycle), thus necessitating a continuous waste supply [11]. The reaction is endothermic and non-spontaneous at lower temperatures ($\Delta G^0 > 0$ at 15-25°C), leading to reduced treatment efficiency in colder climates; however, it becomes spontaneous only at elevated temperatures (35°C) [11]. From a regulatory and logistical standpoint, this pathway is not listed as an approved beneficial use under current NYSDEC Part 360 BUD precedents, requiring case-specific approval [11], [16]. NYC infrastructure constraints, including limited space for source separation and protected storage on dense construction sites, challenge the collection of clean, contamination-free gypsum needed for reliable performance [9], [14]. The technology also remains at laboratory scale, with unresolved challenges for NYC implementation such as full-scale reactor design, potential filter clogging, and flow management [11].

Incorporation into Ceramic Blocks

Gypsum waste can be utilized in the manufacture of unfired ceramic blocks as a partial clay substitute. An optimal mixture, identified in research as Formulation 10, consists of 35% plastic clay, 35% non-plastic clay, 20% gypsum waste, and 10% Portland cement, with water added before molding and curing under controlled conditions ($30 \pm 2^\circ\text{C}$; $83 \pm 3\%$ humidity) for 18 days without firing [12]. The objective is to divert gypsum from landfills while reducing consumption of virgin clay and natural gypsum [12].

Material preprocessing and testing are essential steps to evaluate the technical and environmental viability of recycling gypsum waste into ceramic blocks. All materials dry overnight at 110°C and sieved through a 0.45 mm mesh to ensure particle uniformity [12]. Technical performance is assessed by its uniaxial compressive strength compared against the 1 MPa minimum required by Brazilian standard NBR 7171 [12]. Environmental screening can be conducted using a minimal battery of ecotoxicological tests on a standardized leachate (NBR 10005). Specifically, the leachate should exhibit no acute toxicity to fish (*Danio rerio*) and algae (*Scenedesmus subspicatus*) at the EC50/LC50 level (the median Effective Concentration required to induce a 50% effect), while only weak toxicity is allowed toward bacteria (*Vibrio fischeri*) and daphnids (*Daphnia magna*), with EC20 values ideally above approximately 69-75% leachate concentration [12].

The benefits are significant. Using 20% gypsum waste reduces landfill disposal and conserves raw materials [12]. The optimal mix exceeds structural strength requirements, and cement hydration contributes to immobilizing potentially toxic elements within a stable matrix, primarily through the formation of ettringite [$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$] during solidification [12]. This formulation achieves a mean uniaxial compressive strength of 2.66 MPa, substantially above the 1 MPa minimum required by Brazilian standard NBR 7171 [12]. Ecotoxicity testing

indicated generally low toxicity, with leachate being weakly toxic to daphnids (EC20 = 69.0%) and bacteria (EC20 = 75.0%), while exhibiting no toxicity to algae and fish at the EC50 level [12].

Several limitations must be considered, however. Adequate compressive strength is contingent on Portland cement addition, as mixes without cement exhibit poor structural performance (strength below 1 MPa) [12]. The sulfur content in gypsum presents potential long-term environmental risks, necessitating ongoing leachate monitoring [12]. Varying responses among test organisms necessitate ecotoxicological screening for safety assurance; consequently, the study recommends a battery focusing on the more sensitive bacteria and daphnid tests [12]. Finally, single-step leaching tests may underestimate long-term leaching behavior, suggesting that time-dependent or scenario-based leaching protocols are needed for accurate environmental assessment [12]. For NYC, significant constraints exist. The requirement for clean, source-separated, and dry gypsum feedstock conflicts with typical dense urban construction sites that lack space for careful staging and protection from moisture and contamination [2, 3]. Most critically, this engineered, high-value reuse pathway is not covered under existing NYSDEC Part 360 predetermined Beneficial Use Determinations (BUDs), which have historically approved only low-tech uses [11], [16]. Implementing this pathway would require a case-specific BUD, creating regulatory uncertainty and increased costs [11].

NYC and New York State Policies:

1. NYC Rules and Specifications for Gypsum Drywall Management

Gypsum drywall is explicitly addressed within New York City’s construction and demolition (C&D) waste management framework, primarily through material classification, tracking, and operational requirements rather than prescriptive reuse mandates. NYC regulations classify gypsum board and drywall as distinct materials within C&D waste streams and require documentation and record-keeping during construction and demolition activities [14], [15]. These requirements emphasize source separation, contamination control, and traceability as mechanisms to reduce landfill disposal and support recycling.

The NYC Comparative Waste Management Plan specifications identify gypsum and drywall as recyclable materials commonly handled by C&D processing facilities [15]. While the specifications do not mandate specific recycling technologies, they impose operational conditions, such as maintaining material cleanliness, preventing contamination, and documenting material handling, that directly affect recycling feasibility. For gypsum drywall, these requirements are particularly significant because closed-loop recycling into new wallboard is only technically viable when the majority of the paper backing and surface contaminants are removed, yielding clean gypsum suitable for reprocessing [14]. Contamination from joint compounds, adhesives, coatings, and mixed paper fibers remains a primary technical barrier to high-value recycling. As a result, NYC’s emphasis on source separation and cleanliness functions as an indirect but critical enabler of higher-value gypsum recycling pathways, even in the absence of explicit reuse mandates.

	Masonry	Wood	Metals	Soils	Roofing	Drywall
Composition of C&D Debris by Weight	35% ¹³	15%	6%	27%	5%	2%
Source / High Generator	Infrastructure	Residential/nonresidential buildings	Nonresidential buildings	Infrastructure and new building construction	Residential/nonresidential buildings	Residential/nonresidential buildings
Applicability to NYCEDC Project Type	Construction and deconstruction of existing infrastructure, including roadways, sidewalks, buildings, parks, open space, waterfronts, parking lots	Construction, deconstruction, and renovation of building and interiors	Construction and deconstruction/renovation of building and interiors including copper piping, aluminum duct work, steel beams, and rebar	Construction and deconstruction of existing infrastructure, including roadways, sidewalks, buildings, parks, public areas, boardwalks, parking lots	Construction and deconstruction/renovation of building and interiors	Construction and deconstruction/renovation of building and interiors
Existing Markets and Circularity Potential	Emerging solutions to reducing emissions in cement production through use of supplementary cementing materials such as ground glass pozzolan	Clean yard debris for landscape mulch/some nontreated wood used as wood chip fuel	Reused as ferrous and non-ferrous scrap metal	Reuse onsite for topsoil and plants as well as onsite fill or use in New York City’s Clean Soil Bank	Asphalt shingle scrap can be used in pavement, sidewalks, driveways, road and ground cover, and many other products ¹⁴	Gypsum can be recycled into new drywall if most of the paper is removed
Reuse & Remanufacturing Opportunities	Ubanite for patios ¹⁵ /walkways ¹⁴ Masonry can be cleaned and reused as concrete in structural components	Reclaimed wood for flooring, walls, and furniture or regreded for load-bearing applications ¹⁶	Steel construction components are highly reusable and can be inspected, refabricated, and primed to the requirements of the new project ¹⁷	Geotechnically and environmentally impacted soils can be reused in many onsite applications	High potential for reuse in roadway projects ¹⁸	Certain drywall manufacturers can accomplish close loop recycle drywall

Table 1: Material Composition of New York State Construction & Demolition Waste Stream

2. New York State Regulatory Framework: NYSDEC Part 360 and Beneficial Use Determinations

At the state level, the New York State Department of Environmental Conservation (NYSDEC) regulates gypsum drywall under the Part 360 solid waste management framework. A key regulatory mechanism within this framework is the Beneficial Use Determination (BUD) process, which allows certain materials to be classified as no longer solid waste when specific

conditions are met [17]. This process governs whether recovered gypsum drywall may be reused outside of traditional disposal pathways.

However, existing predetermined and historical BUD approvals related to gypsum have largely focused on low-technology applications, including agricultural soil amendments, animal bedding, absorbents, and land application [17]. Engineering-intensive reuse and recycling pathways, such as incorporation into concrete, soil stabilization, ceramic manufacturing, or closed-loop wallboard production, are not explicitly covered under current predetermined BUD approvals. As a result, these pathways require case-by-case regulatory approval or processing at permitted facilities, increasing regulatory uncertainty and transaction costs for advanced gypsum recycling initiatives.

In addition to reuse classification, NYSDEC also restricts disposal options for gypsum drywall. Large-scale incineration of gypsum-containing waste is prohibited due to the risk of sulfur dioxide emissions during combustion, which pose environmental and public health concerns [17]. This restriction further limits disposal pathways and increases reliance on landfill disposal or low-value reuse when approved recycling options are not readily available.

No Longer Considered Solid Waste When Meeting Requirements for Use - 360.12 (c)(3)		
Ground granulated blast-furnace slag	Cement kiln feedstock or concrete aggregate	360.12(c)(3)(i)
Unadulterated wood ash	Soil amendment	360.12(c)(3)(ii)
Industrial waste	Manufacturing feedstock (historical use)	360.12(c)(3)(iii)
Fats, oil, grease, and rendered animal parts	Feedstock for non-fuel products	360.12(c)(3)(iv)
Coal combustion fly ash	Ingredient in concrete products, block, flowable fill	360.12(c)(3)(v)
Flue-gas desulfurization or other gas-scrubbing byproducts	Substitutes for gypsum and calcium chloride (except for land application)	360.12(c)(3)(vi)

Table 2 NYCRR 360.12 No Longer Considered Solid Waste When Meeting Requirements for Use

3. Approved and Unapproved Gypsum Reuse Pathways Under Current Policy

Under the current NYC and New York State regulatory landscape, approved gypsum drywall reuse pathways remain limited in scope and skewed toward low-technology applications. Based on official NYSDEC Part 360 case-specific Beneficial Use Determinations (BUDs), regulatory approvals for gypsum drywall and board reuse have historically focused on agricultural, land application, and waste management uses rather than engineered material recycling. Past and current approvals include the reuse of waste gypsum as animal bedding, soil fertilizer or amendment, general absorbent material, and direct land application [16]. These pathways typically require minimal processing and are well aligned with existing BUD precedents.

In contrast, higher-value engineering and materials-recovery pathways face significantly greater regulatory barriers. Although previous BUD approvals (now inactive) have permitted the

use of waste gypsum as a general manufacturing feedstock, as an ingredient in cement, and for closed-loop recycling into new gypsum wallboard, these approvals are no longer broadly applicable under the current predetermined BUD framework [16]. Moreover, highly technical reuse pathways, such as co-utilization with fly ash in concrete, advanced geotechnical soil stabilization using tailored cement blends, fluoride adsorption in water treatment, and incorporation into ceramic blocks, are not listed as approved or having received BUD authorization within existing New York State regulatory records [16].

This regulatory gap highlights a disconnect between technical feasibility and regulatory implementation. While complex, high-value gypsum reuse pathways are technically viable and supported by engineering research, NYSDEC approvals have largely prioritized simpler, direct-use applications that pose fewer regulatory and enforcement challenges. As a result, even when NYC’s source-separation and material cleanliness requirements create conditions favorable for high-quality gypsum recovery, the absence of clear regulatory authorization for advanced reuse pathways limits their practical deployment. This structural mismatch contributes to the continued predominance of low-value reuse and disposal options for gypsum drywall in New York State.

Gypsum Reuse Option	Part 360 / BUD Status	Conditions and Limitations
Animal bedding	Predetermined / approved	Limited to specific handling and contamination controls; non-engineered use
Agricultural soil amendment	Predetermined / approved	Application rates and land-use controls required; low processing intensity
General absorbent material	Predetermined / approved	Non-structural use; minimal processing requirements
Direct land application	Predetermined / approved	Subject to environmental safeguards; lowest-value reuse pathway
Manufacturing feedstock (general)	Case-specific (inactive approvals)	Previously approved on a case-by-case basis; not covered under current predetermined BUDs
Cement ingredient	Case-specific (inactive approvals)	Prior approvals existed; currently not included under predetermined BUD framework
Closed-loop gypsum wallboard recycling	Case-specific (inactive approvals)	Historically approved in limited cases; not broadly authorized today
Co-utilization with fly ash in concrete	Not listed / no documented approval	Not included in predetermined or case-specific BUDs
Engineered soil stabilization	Not listed / no documented approval	Requires precise material control; no documented BUD authorization
Ceramic manufacturing	Not listed / no documented approval	High-temperature processing; absent from BUD records
Fluoride removal from water	Not listed / no documented approval	Requires environmental testing and case-specific approval under Part 360

Table 3 Part 360 / BUD Status Table by Gypsum Reuse Options

Pilot projects or beneficial-use efforts in NYC (signals for market direction)

Currently, there are no publicly documented pilot projects in NYC specifically focused on high-value recycling or closed-loop recycling of gypsum drywall. Although NYCEDC’s Circular Design and Construction Guidelines promote circularity across City-supported projects and identify flagship developments intended to demonstrate circular practices, these efforts do

not include gypsum-specific reuse initiatives [14]. As a result, gypsum drywall reuse in NYC remains largely theoretical despite extensive technical research demonstrating feasible reuse pathways.

Infrastructure, storage, and permitting constraints affecting feasibility for gypsum drywall

Infrastructure and logistical constraints in NYC strongly influence which gypsum drywall beneficial use pathways are realistically achievable. Dense urban construction sites typically lack sufficient space for the separate collection, protection, and staging of drywall waste. This constraint has direct implications for high-value reuse options reviewed in this study. Closed-loop recycling into new gypsum products, co-utilization in cementitious systems, and incorporation into ceramic or engineered construction materials all require clean, source-separated gypsum with minimal paper fibers, coatings, adhesives, and moisture contamination [9]. Even limited commingling with mixed debris can render recovered gypsum unsuitable for these applications, effectively downgrading it to disposal or low-complexity reuse.

Moisture exposure presents an additional challenge. Several of the beneficial use pathways evaluated, particularly closed-loop recycling and cementitious co-utilization, require controlled gypsum chemistry and particle morphology [17]. Unprotected storage on-site or during transport can lead to premature hydration, agglomeration, or degradation of recycled gypsum powder, reducing its suitability for reuse and increasing preprocessing requirements.

Permitting and regulatory constraints further shape feasibility. Because post-consumer gypsum drywall is not broadly covered under predetermined NYSDEC Part 360 Beneficial Use Determinations, advanced reuse pathways such as closed-loop wallboard recycling, concrete admixture use, or engineered soil stabilization typically require case-specific BUDs or acceptance by permitted facilities [17]. This introduces additional testing, documentation, and approval requirements that disproportionately affect higher-value, technically complex reuse strategies compared to lower-value applications such as land application or absorbent use. As a result, even when laboratory and pilot-scale research demonstrate strong performance, regulatory friction can prevent these pathways from being implemented in NYC practice.

Potential Incentives, Barriers, and Open Questions for Implementation

Current incentives for gypsum drywall reuse in NYC are largely **indirect** and primarily support diversion rather than material upgrading. NYC agency waste management specifications and NYCEDC circular construction initiatives encourage source separation, contamination control, and documentation, which are essential enabling conditions for beneficial uses such as closed-loop recycling and cementitious applications [14]. When rigorously implemented, these measures can improve feedstock quality and make higher-value reuse technically possible. However, they stop short of actively promoting or prioritizing specific gypsum reuse pathways.

Significant barriers remain for the beneficial uses evaluated in this review. Contamination risks, limited jobsite space, moisture sensitivity, and inconsistent feedstock quality present challenges for closed-loop recycling and advanced material applications. Regulatory uncertainty under Part 360 further discourages adoption of engineered reuse options, particularly those requiring precise material performance and quality control [17]. Furthermore, the lack of a well-

developed local end market for recycled gypsum products in NYC means that contractors and processors lack the economic incentive to pursue high-value recycling instead of disposal or low-grade uses.

Several open questions remain critical for advancing gypsum drywall reuse in NYC. This includes how NYC agencies can standardize testing protocols, documentation requirements, and procurement specifications to reduce uncertainty regarding recycled gypsum materials. This accounts for whether design for disassembly and internal systems planning can substantially improve drywall recycling quality, and how regulatory processes can evolve to better accommodate technically proven gypsum recycling strategies demonstrated in academic and pilot-scale studies. Moreover, for fluoride removal from the water method, environmental testing is required by the NYSDEC Part 360 BUD [17]. Addressing these questions would be essential to closing the gap between the proven material science potential of gypsum drywall and its limited real-world reuse in NYC.

Claim	Source	Scope
NYC C&D rules emphasize source separation, tracking, and contamination control but do not mandate gypsum-specific reuse	NYCEDC Circular Design & Construction Guidelines	NYC
Gypsum/drywall classified as recyclable material requiring documentation and cleanliness	NYC DSNY Comparative Waste Management Plan Specs	NYC
Predetermined BUD approvals for gypsum focus on low-tech applications; advanced uses require case-specific approval	NYSDEC Part 360 BUD Guidance	NYS
Incineration of gypsum drywall restricted due to sulfur dioxide emissions	NYSDEC Part 360	NYS
No documented NYC pilot projects for closed-loop gypsum recycling	NYCEDC Circular Guidelines review	NYC

Table 4 NYC Feasibility Discussion Table

Continued Use of Gypsum Drywall in NYC Construction

Gypsum board is still widely used in new construction in NYC and is not being phased out. The provisions related to gypsum board and gypsum systems specified in the NYC building code demonstrate the continued importance of gypsum board as a standard interior building material. However, the large volume of gypsum drywall waste generated and the lack of pilot projects or regulatory frameworks for gypsum recycling reveal a significant gap between materials science research and practical application within NYC's circular economy construction framework.

Option-by-Option Feasibility Assessment in NYC

1. Low-Technology Reuse: Animal Bedding, Soil Amendment, Absorbent Use, Land Application

These routes are the most feasible option under the current circumstances and regulatory framework in NYC. It is feasible to collect materials from construction sites with minimal separation requirements and transport them to local end users outside the city via existing construction and waste transfer facilities. The primary issue is not technical feasibility, but rather

limited value creation. While this application tolerates contamination and moisture, it does not encourage strict recycling or separation. As a result, they do little to drive improvements in on-site material handling or gypsum quality despite being regulatory approved [11], [16].

2. Closed-Loop Gypsum Wallboard Recycling

Closed-loop recycling into new gypsum boards would be least feasible on dense NYC construction sites due to limited space for protected, source-separated storage. In practice, this pathway would require segregation at the jobsite followed by transport to a specialized regional processor with controlled storage and preprocessing capacity. The dominant issues are contamination from paper backing and joint compounds, moisture exposure during handling, and the lack of an active predetermined BUD approval for this pathway, which introduces permitting uncertainty and discourages investment [14], [11], [16].

3. Cementitious Use (Cement Ingredient or Concrete Co-Utilization)

Use of gypsum drywall as a cement ingredient or in concrete systems would most realistically occur at off-site, regional cement or concrete processing facilities rather than within NYC. Clean gypsum feedstock would need to be produced either through on-site segregation with strict contamination control or at a transfer station equipped for drywall separation. The primary issues are feedstock consistency, moisture sensitivity, and regulatory status, as these applications are not included in current predetermined BUD approvals and therefore require case-specific authorization [11], [16].

4. Engineered Soil Stabilization

Advanced soil stabilization applications using gypsum-based blends would likely occur at large infrastructure or geotechnical processing facilities outside NYC rather than at urban jobsites. While technically feasible, these applications require precise control of gypsum chemistry and particle size, making them incompatible with mixed or poorly protected C&D waste streams. The dominant barriers are inconsistent with feedstock quality and the absence of explicit BUD approval, which increases regulatory risk relative to simpler reuse options [11], [16].

5. Ceramic Products and High-Temperature Manufacturing

Incorporation of gypsum drywall into ceramic blocks or related products would necessarily occur at specialized manufacturing facilities outside NYC due to space, energy, and emissions constraints. Although moisture contamination is less critical for high-temperature processing, these pathways are absent from documented BUD approvals and therefore face significant regulatory uncertainty. The primary bottlenecks are permitting requirements and the lack of a demonstrated regional end market for recycled gypsum-based ceramic products [16].

6. Environmental Treatment Applications (e.g., Fluoride Removal from Water)

Gypsum-based applications for water treatment would occur exclusively at controlled industrial or environmental facilities, not construction sites or transfer stations. These pathways require extensive environmental testing, performance validation, and case-specific BUD approval under Part 360. Regulatory burden and uncertainty, rather than technical feasibility, represent the principal barriers to implementation in NYC practice [11], [16].

Conclusions

This study evaluated the feasibility of gypsum drywall reuse in New York City by integrating material property analysis with NYC and New York State regulatory frameworks and on-the-ground feasibility constraints. While numerous technically viable reuse pathways for gypsum drywall exist in the literature, regulatory approvals, infrastructure limitations, and feedstock quality constraints significantly narrow the set of options that are realistically implementable in NYC.

Based on current policy, infrastructure, and material performance requirements, the most viable gypsum drywall reuse strategies in NYC are low-technology, off-site applications supported by existing NYSDEC Beneficial Use Determinations. These include land application, agricultural soil amendment, absorbent use, and animal bedding. These pathways are compatible with NYC construction site constraints because they tolerate higher levels of contamination and moisture, require minimal preprocessing, and rely on established regional end markets. Although these uses provide limited material value recovery, they remain the most immediately implementable under existing regulatory conditions.

Among higher-value options, closed-loop recycling into new gypsum wallboard represents the most technically aligned strategy with the material properties of recovered gypsum, particularly when purity, particle size, and sulfate chemistry are preserved. However, this pathway is only conditionally viable in NYC, as it requires rigorous on-site source separation, protected storage, and access to specialized regional processing facilities. Without a predetermined BUD approval and local pilot-scale infrastructure, closed-loop recycling remains feasible in theory but difficult to implement in practice.

Cementitious and engineered material applications (cement ingredient, concrete co-utilization, or soil stabilization) demonstrate strong performance in material-property evaluations but are currently the least viable in NYC. These pathways require precise control over gypsum chemistry, moisture content, and contamination levels that are difficult to achieve within NYC's dense construction environment and are not explicitly authorized under existing regulatory approvals.

The primary challenges limiting gypsum drywall reuse in NYC are structural rather than technical. Space constraints at urban construction sites restrict the ability to segregate and protect drywall waste. Moisture sensitivity and contamination from paper backing, joint compounds, and surface coatings further degrade feedstock quality, undermining high-value reuse pathways that depend on controlled material properties. Regulatory friction under the NYSDEC Part 360 framework, particularly the absence of predetermined BUD approvals for advanced reuse options, introduces permitting uncertainty that discourages investment in higher-value recycling strategies.

These challenges collectively explain the disconnect observed between the favorable material properties of gypsum, such as its cementitious compatibility, sulfate chemistry, and adsorption capacity, and the limited scope of real-world reuse in NYC. The material-property table indicates that gypsum drywall is technically suitable for multiple engineered applications; however, current systems consistently downgrade the material due to handling and regulatory constraints.

Several critical information gaps must be addressed to enable large-scale gypsum drywall reuse in NYC. First, a reliable estimate of annual post-consumer gypsum drywall tonnage generated within NYC is needed to assess market scale and infrastructure requirements. Second, empirical data on contamination levels in NYC drywall waste streams, particularly paper content, joint compound residues, and moisture exposure, would clarify which reuse pathways are realistically achievable.

Third, information on existing local and regional processor capacity, including drywall-specific separation or preprocessing capabilities, is necessary to evaluate logistical feasibility. Fourth, standardized performance specifications and procurement of language for recycled gypsum products would reduce uncertainty for designers, contractors, and regulators. Finally, a clearer regulatory pathway, either through expanded predetermined BUD approvals or a streamlined case-specific process, is essential to translate technically proven gypsum reuse strategies into practice.

In conclusion, while gypsum drywall exhibits strong material potential for high-value reuse, current conditions in NYC and NYS favor low-technology applications. Closing the gap between material science potential and implementation will require coordinated advances in data availability, regulatory clarity, infrastructure development, and procurement policy.

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