CSCE 2022 Annual Conference
Whistler, British Columbia
May 25th – 28th, 2022

Applications of Recycled Gypsum from Waste Drywalls in Construction Industry: A Review

Jafari, Alireza [1,3] and Sadeghian, Pedram [2]
[1] Ph.D. Student, Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada
[2] Associate Professor and Canada Research Chair in Sustainable Infrastructure, Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada, Email: Pedram.Sadeghian@dal.ca
[3] Alireza.Jafari@dal.ca

Abstract: Reusing and recycling construction and demolition waste materials is one of the main approaches to reduce the environmental impacts of the construction industry. Waste gypsum drywalls from ever-growing renovation projects and scrap drywalls from new constructions have become a major issue for municipalities. Several researchers have studied the potential use of recycled gypsum from waste drywall as a second-raw construction material, especially for concrete construction. However, there is no comprehensive review study on the topic while it can identify research gaps and provide a direction for future studies. With this background, this review paper focuses on the applications of recycled gypsum drywall (RGD) in the construction industry and its environmental and economic benefits. Additionally, this paper proposes the best mixtures for the concrete containing RGD through the literature review. The cementitious composite of this mixture can be used in other introduced applications. To this end, applications of RGD in the construction industry were classified into seven groups, including supplementary materials in concrete materials, soil stabilization, ceramic industry, recycled aggregates, cement production, plaster, as well as blocks and walls, and new achievements in each group were discussed. Then, the most eco-friendly concrete mixture with acceptable mechanical strength was proposed, assisting researchers in future studies. The results illustrate that reusing recycled gypsum can significantly reduce the carbon dioxide emissions of the concrete and provide economic benefits. A combination of ordinary Portland cement, recycled gypsum, fly ash or perlite, and slag was proposed as the most appropriate cementitious concrete composite.

Keywords: Recycled gypsum drywall, Construction industry, Cementitious composites, Environmental impact, Economic benefits, Recycling

1 Introduction

Todays, Reusing and recycling waste materials is well-known as one of the strategies to not only decrease the cost of produced materials but reduce the environmental impacts of industries and materials. Given these benefits and the critical situation of global climate-changing, which results from releasing a vast amount of greenhouse gases, many researchers have established their studies on reusing and recycling waste materials in industries.

One of the primary sources of waste materials that contributes to approximately 27 percent of total solid waste materials in Canada results from the construction industry (Yeheyis et al., 2012). Meanwhile, many construction and demolition waste materials can be recycled and reused in the construction industry, significantly reducing the demand for landfill space and virgin and raw materials. Additionally, using recycled construction and demolition waste materials can noticeably decrease the carbon dioxide (CO_2) emission of the construction industry, which is valuable. This reduction is also accentuated due to the 65 percent of the contribution of CO_2 in greenhouse gases effects and the critical situation of global climate-changing (Hansen and Sadeghian, 2020; Naik, 2008).

Gypsum is one of the most common construction materials that have been used for hundreds of years due to its suitable characteristics. Currently, the majority of gypsum in the construction industry is used in manufacturing gypsum drywalls because of its heat and sound insulation characteristics, which increases the utilization of the walls in the construction industry. Regarding this increasing demand, drywall waste has also been raised to the extent that the gypsum drywalls contribute to about 9 percent of total construction and demolition waste in Canada, typically disposed of in the landfills (Oh, 2019). Disposing of the gypsum drywall, however, has some environmental impacts not only on the landfill space but on the underground water sources since the gypsum can react with the rain and leachate and produce toxic liquids (Oh, 2019; Oliveira et al., 2019). On the other hand, previous studies indicated that gypsum has a close recycling loop and can be completely recycled at least three times (Basile et al., 2020; Boccarusso et al., 2020). Therefore, studying the applications of recycled gypsum drywall (RGD) is necessary for protecting the planet.

Despite the above advantages of RGD, its utilization has been limited in the construction industry due to the sparse number of studies on its applications and benefits. Therefore, providing a review paper on the applications of RGD can indicate the research gaps and provide a direction for future studies.

Given this fact, the present paper aims to provide a comprehensive review of the applications of RGD in the construction industry to not only indicate its applications as well as environmental and economic benefits but also introduce the most appropriate mix for the cementitious composites containing RGD. To this end, earlier studies were classified into seven groups based on their proposed applications in the construction industry. Then, a brief comprehensive review of the applications was represented. Next, the environmental and economic benefits of using RGD were determined, and the most appropriate mix for the cementitious composites containing RGD was introduced. Finally, the research gaps were identified based on the literature, and several research directions were proposed for future studies.

2 Methodology

This study focuses on the English published papers between 2019 and 2021, which have one or any combination of recycled gypsum, gypsum, drywall, and wallboard words and are related to the applications in the construction industry on google scholar. The period includes studies that not only covered the past applications of RGD but introduced new applications of RGD in the construction industry, while the earlier studies than 2019 mainly focused on the applications of RGD as a soil amendment for agricultural purposes, animal bedding, and water treatment.

3 Paper Structure

The first section briefly introduces RGD’s characteristics and recyclability. The second section indicates applications of recycled gypsum that have been studied during the determined years. The third section is allocated to the environmental benefits of using RGD in introduced applications, while the economic benefits of this utilization are discussed in the fourth section. The most appropriate mix component for creating the most environmentally friendly cementitious composites is proposed through literature in the next section. Finally, the main research directions and gaps are identified based on the reviewed papers.

4 Recycled Gypsum Drywall

RGD is powder or aggregate forms of gypsum drywalls that are currently considered as construction waste materials. The powder form can be treated thermally at a temperature between 125℃ and 180℃ for around 24 hours to increase its reactivity which is called the calcination process (Weimann et al., 2021). However, according to the literature (Weimann et al., 2021), thermal treatment can improve the reactions of the RGD, some researchers such as (Hansen and Sadeghian, 2020) showed that RGD powder can be used as a supplementary material without any heat treatment, which can improve the sustainability index of recycled gypsum drywall. These powders were typically used as supplementary cementitious materials or filler in soil stabilization (Janbaz et al., 2021; Thul et al., 2019), manufacturing drywalls (Grasielly et al., 2019), concrete materials (Chernyshova et al., 2020; Hansen and Sadeghian, 2020; Nguyen et al., 2019a), plaster (Li et al., 2019; Papailiopoulou, 2018), and blocks (Iqbal et al., 2020), cement production (Almeida et al., 2020), and ceramic industry (Cipriano et al., 2020). On the other hand, the aggregate form has been generally employed as recycled aggregate in concrete and composite materials (Diotti et al., 2020).

5 Applications

This section aims to briefly introduce the studied applications of RGD in the literature. The applications of RGD can be clustered as supplementary materials in concrete materials, soil stabilization, ceramic industry, recycled aggregate, cement production, plaster, and blocks and walls.

5.1 Supplementary Materials in Concrete Materials

Supplementary cementitious materials are the materials that are used as a partial replacement for ordinary Portland cement (OPC) and contribute to the hardening and strengthening reactions of the concrete through hydraulic and pozzolanic activity. These materials are also named as the partial alternatives of OPC since OPC is responsible for around 5-7 percent of carbon dioxide emissions of the construction industry and consumes a vast amount of energy while its production is also required a vast amount of raw materials that can deteriorate the environment (Hendriks et al., 1999; Toufigh and Jafari, 2021).

RGD is one of the supplementary cementitious materials that has been studied in the literature. Although, utilizing the combination of RGD and OPC can significantly reduce the strength of concrete (Hansen and Sadeghian, 2020); recent studies approved that adding fly ash (Hansen and Sadeghian, 2020), mine waste such as perlite (Chernyshova et al., 2020), and slag (Nguyen et al., 2019a) can significantly enhance the compressive strength of concrete while substantially reducing the OPC demand and its harmful environmental impacts. The recent studies also indicated that the RGD acts as an activator for alkali materials such as fly ash and slag and improves their participation in the concrete strengthening reactions (Hansen and Sadeghian, 2020; Hong et al., 2020; Nguyen et al., 2019a). Additionally, (Hong et al., 2020) also presented that employing RGD can improve the waterproof characteristics of concrete. In addition to the strength of concrete, an earlier study demonstrated that using the combination of OPC, RGD, and fly ash can significantly improve the water-resistance and reduce the drying shrinkage of cementitious mortars and concrete (Jiang et al., 2018). Additionally, (Timpano, 2019) denoted the potential of RGD in 3D printed composite materials, which shows the efficiency of RGD as supplementary cementitious materials. Table 1 briefly shows the previous studies on using RGD as supplementary cementitious materials.

Although recent studies indicated the potential of RDG as supplementary materials, one of the main adverse effects of utilizing RGD is its effect on setting time reduction. Due to this adverse effect, some researchers, such as (Nguyen et al., 2019b), examined the effect of retarders on the setting time and compressive strength of concrete containing RGD and slag. Their results represented that the citric acid retarder can significantly improve the compressive strength of the concrete while increasing the setting time of the fresh mix. However, they proposed an appropriate retarder; the effect of other retarders and superplasticizers on the properties of concrete containing RGD is still unknown. Additionally, the impact of adding RGD to concrete on its durability characteristics is undetermined.

Table 1: Recent studies on using RGD as supplementary cementitious materials

Study	Materials					Objectives of study			
	OPC	RGD	Fly ash	Slag	Others	S	WR	D	Others
Hansen and Sadeghian (2020)	√	√	√	-	-	√	-	-	-
Hansen (2020)	√	√	√	-	-	√	-	√	-
Chernyshova et al. (2020)	√	√	-	-	Mine waste	√	-	-	-
Hong et al. (2020)	√	√	-	√	-	√	-	-	Electrical resistivity
Lu et al. 2020)	√	√	√	-	-	√	√	-	-
Nguyen et al. (2019a)	-	√	-	√	-	√	-	-	Bending beam (fracture)
Mukhametrakhimov et al. (2019)	√	√	-	-	Metakaolin	√	-	-	-
Nguyen et al. (2019b)	-	√	-	√	-	√	-	-	Effect of retarder

S: Strength, WR: Water resistance, D: Durability

5.2 Soil Stabilization

Traditionally, gypsum was used for soil stabilization because of its appropriate characteristics and price. Recently, using RGD for soil stabilization has been frequently studied so that the topic is mentioned in a large number of published papers on applications of RGD. The majority of the articles are studied stabilizing expansive and clayey soils with a composite containing RGD for the structural foundation, backfills, and road base and subbase(Imteaz et al., 2020; Kamara et al., 2019; Krishnaiah et al., 2020). In addition to using the RGD powder, some researchers utilized the aggregate form of RGD in their studies on soil stabilization. Their results illustrate that the RGD aggregates can be used in road subbase and pipeline bedding (Imteaz et al., 2020). Table 2 demonstrates the recently published papers on using RGD for soil stabilization and their research goal.

According to Table 2, most of the research on stabilizing soils by using RGD only examined the unconfined compressive strength of their mixes, while one of the main points of reusing the RGD in the construction industry is the penetration of the leachate to groundwater and soil pollution. Therefore, although replacing OPC with RGD has some environmental benefits regarding CO_2 emission reduction, other environmental impacts of this replacement should be studied in the future. Additionally, there are spare numbers of studies on the durability of stabilized soil by recycled gypsum and the effect of the water on the mechanical and durability properties of the stabilized soil, which can be studied in future studies.

Table 2: Recent studies on soil stabilization and their objectives

Study	Materials				Objectives
	RGD	Soil	OPC	Others	
Krishnaiah et al. (2020)	√	√	-	-	Strength of Expansive clay soil
Kamara et al. (2021)	√	√	√	Slag, Quarry Waste dust, and asphalt filler	Strength, high-pressure flow, and freeze/thaw
Tan and Adajar (2020)	√	√	-	Rice Husk Ash	Strength, Expansion index, and Atterberg's limits
Imteaz et al. (2020)	√*	√	-	-	Suitability of RGD in aggregate form for non-load bearing embankment

* RGD used in aggregate form

Table 2: Recent studies on soil stabilization and their objectives (cont.)

Study	Materials				Objectives
	RGD	Soil	OPC	Others	
Maqsood et al. (2020)	√	√	-	-	Strength, unconfined creep, and cyclic loading properties
Allah et al. (2020)	√	√	-	-	Strength of unbounded paving materials
Janbaz et al. (2021)	√	√	√	-	Unconfined compressive strength
Cheng et al. (2020)	√	√	√	Fly ash, quicklime, and skeleton soil	Unconfined compressive strength
AL-Adili et al. (2019)	√	√	-	-	Unconfined compressive strength
Apriyanti et al. (2019)	√	√	-	-	Shear and unconfined compressive strength
Rustam et al. (2019)	√	√	-	-	Shear and unconfined compressive strength
Thul et al. (2019)	√	√	-	Tin Tailing	Strength, Atterberg's limit, and Free swell index
Bure and Kamara (2020); Kamara et al. (2019)	√	√	-	Reclaimed asphalt filler, Medium hydrated tailing, slag, By-pass dust	unconfined compressive strength

* RGD used in aggregate form

5.3 Ceramic Industry

Utilizing RGD is another application of RGD that has been studied in the reviewed papers. However, there is only one published article on this application among the reviewed papers, which examined the effect of temperature on the ceramic composites containing RGD (Cipriano et al., 2020). The encouraged readers referred to the past reviewed paper on this topic (Almeida et al., 2020).

5.4 Recycled Aggregates

One of the applications proposed as potential applications of RGD is using them as recycled aggregate, which can reduce the required energy for their grinding while slowing down the depletion of aggregates sources (Tazi et al., 2021). Unfortunately, there is no study on using the RGD as recycled aggregate in concrete. Therefore, it can be a topic for future studies that reduce the environmental impacts of disposing of gypsum and reduce the demand for aggregates and deterioration of the environment due to the extractions.

5.5 Cement Production

In addition to studies on using RGD as supplementary cementitious material, some researchers focused on utilizing RGD in cement production (Khudyakova et al., 2019). Although these studies have been quite limited in recent years, their results show the potential of RGD as a replacement for natural gypsum in cement clinker (Khudyakova et al., 2019). According to the study, replacing natural gypsum with RGD not only reduces the environmental impacts of extracting gypsum but also results in a composite with higher compressive strength. This outcome is completely aligned with the proposed close recycling loop of RGD in earlier studies (Basile et al., 2020).

5.6 Plaster

Utilizing the RGD as a partial or complete replacement of commercial gypsum in manufacturing plaster has been studied in recent articles. The reviewed papers focus on not only the mechanical properties of plaster containing RGD (Li et al., 2019) but the workability (M.A. Pedreño-Rojas et al., 2020), sound absorption (Oliveira et al., 2020), and thermal properties (Pedreño-Rojas et al., 2019) of the plaster as well. Additionally, an earlier study evaluates the effect of the heating process on the RGD plaster, which can show the effect of the thermal treatment on the RGD properties (Pedreño-Rojas et al., 2019). According to the articles, the plaster containing RGD plaster has the same mechanical, workability, and sound absorption as the commercial gypsum plaster. (Pedreño-Rojas et al., 2019) also demonstrated that the plaster with entirely replaced RGD can achieve the appropriate performance. Table 3 summarizes the reviewed articles on the partially and entirely RGD replaced plasters.

Table 3: Reviewed paper on using RGD in plaster

Study	Type of replacement		Results
	Partially	Entirely	
Manuel Alejandro Pedreño-Rojas et al. (2020)	-	√	The RGD plaster achieved higher strength and thermal conductivity than the commercial gypsum plaster.
M.A. Pedreño-Rojas et al. (2020)	√	√	There is no difference between the microstructure of heated and unheated RGD. Their results also demonstrated that the RGD plaster could achieve sufficient mechanical strengths and thermal conductivity compared to reference plaster.
Cristina et al. (2019)	-	√	Heating treatment up to 150℃ efficiently increases the reactivity of the RGD by returning its microstructure to the commercial gypsum. Their tests also demonstrated that the RGD plaster obtained a higher setting time and compressive strength.
Oliveira et al. (2020)	-	√	The sound absorption of RGD plaster is as same as the commercial plaster.
Pedreño-Rojas et al. (2019)	-	√	Commercial gypsum can be completely replaced with the unheated RGD in the plaster based on the mechanical properties and thermal conductivity.
Bartolomei et al. (2019)	√	-	Employing RGD can improve thermal stability and reduce the flammability of the composite.

5.7 Blocks and Walls

The final studied application of the RGD in the literature is employing RGD in the manufacturing blocks, bricks, and drywalls (Arumugam and Shaik, 2021; Assis and Neto, 2019; Chiang et al., 2018). According to (Chiang et al., 2018), the RGD can be efficiently used as a mineral foaming agent in manufacturing lightweight bricks, which improves the mechanical properties and thermal conductivity of the bricks. Additionally, using RGD is an efficient method to reduce the CO_2 emission of bricks (Chiang et al., 2018). A recent study also represented that the walls manufactured by RGD have superior mechanical performance compared to the conventional ones (Assis and Neto, 2019). (Iqbal et al., 2020) also used the RGD for producing unfired mud blocks based on the fire resistance and inflammability of the RGD. In the end, (Arumugam and Shaik, 2021) reported that the gypsum could activate the fly ash in the mud bricks and, therefore, act as a cementitious material in brick manufacturing.

6 Environment Benefits

This section examines the environmental benefits of using RGD as a supplementary cementitious material. One of the main environmental factors that have been widely studied in the environmental evaluations of concrete materials is CO_2 emission since this gas is responsible for around 65 percent of greenhouse gases' effects (Naik, 2008). Another factor that can be considered as an environmental benefit of employing RGD is the reduction of landfill pollution due to decreasing the amount of RGD by reusing the waste as secondary raw materials. The RGD contains nanometal particles that can pollute the landfill's soil and underground and surface water while reacting with rainwater and producing leachate (Oh, 2019; Oliveira et al., 2019). In addition, the reaction between RGD and rainwater releases hydrogen sulfide gas which is toxic, flammable, and dangerous for public health (Oh, 2019).

However, other parameters such as underground and surface water pollution are also important; this section mainly focuses on the effect of using RGD in the CO_2 emission of concrete. Additionally, due to the variability of the CO_2 emission of transportation which is affected by the type of transporting vehicle and distance, this study only focused on the CO_2 emission of the materials. The data on the CO_2 emission of the materials and the mix design contents were also achieved through literature. The main property for mix design selection is the compressive strength of hardened concrete equal to 35 MPa since this characteristic is one of the essential features of concrete.

Tables 4 and 5 show the estimated CO_2 emissions of materials and the mix designs used to calculate the CO_2 emissions of concrete mixtures. Additionally, since the previous article denoted that the RGD can be used as supplementary cementitious material without thermal treatment, this study ignores the CO_2 emission from heating the RGD (Hansen and Sadeghian, 2020). Table 6 indicates the estimated CO_2 emission due to the mix design components based on the mentioned data in Tables 4 and 5. Figure 1 also illustrates the estimated CO_2 emissions.

Table 4: CO_2 emissions of mix design components

Material	OPC	Fly ash	RGD	Slag	Fine aggregates	Coarse aggregates
CO_2 emissions (kg/kg)	0.82[1]	0.027[1]	0.034[2]	0.143[1]	0.0139[1]	0.0459[1]

[1]: Source (Islam et al., 2015)
[2]: Source (Weimann et al., 2021)

Table 5: The weight of Mix design components with the specified compressive strength of 35 MPa

Materials	Weight of materials (kg/m^3)				
	OPC	Fly ash	RGD	Fine aggregate	Coarse aggregate
Mix design 1[1]	435	-	-	672	1093
Mix design 2[2]	138.32	197.6	59.28	574.6	1184.3

[1]: ACI method (211.1-91)
[2]: (Hansen and Sadeghian, 2020)

Table 6: Estimated CO_2 emission of the mix designs

Materials	CO_2 emission (kg)

	OPC	Fly ash	RGD	Fine aggregate	Coarse aggregate	Total
Mix design 1	356.7	-	-	9.34	50.17	416.21
Mix design 2	113.42	6.72	1.6	7.99	54.36	184.09

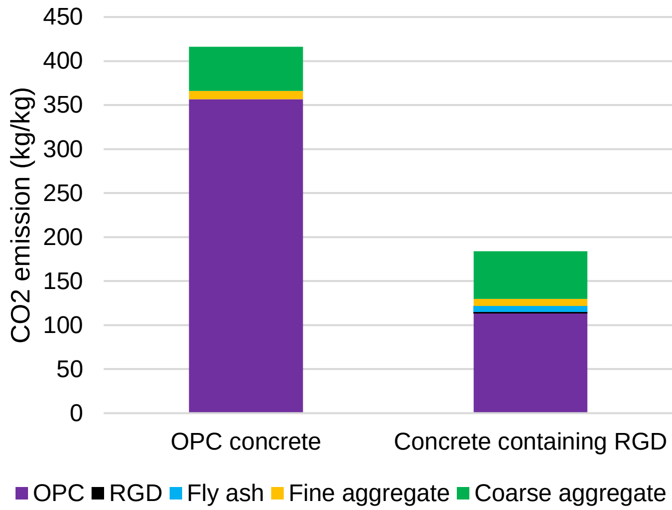

Figure 1: Estimated CO_2 emission of the mix designs

According to Table 6, using a combination of RGD, OPC, and fly ash can reduce the CO_2 emission of the concrete with the compressive strength of 35MPa up to 55.7 percent. It is worth mentioning that replacing OPC with slag can also reduce the CO_2 emission of concrete more than the estimated amount; however, due to the lack of examined mix design with the combination of slag, OPC, RGD, and fly ash, this article could not estimate the reduction.

7 Economic Benefits

This section aims to introduce and evaluate the economic benefits of utilizing RGD based on the cost of materials. According to the last section, due to the variety of transporting types and distances, the cost of carrying materials was ignored in this section. Tables 7 and 8 show the price of each material and the cost of mix designs determined in Table 5. The sources of unit prices were also mentioned in Table 7. Figure 2 also demonstrates the estimated cost of two mix designs schematically.

Table 7: Unit price of concrete mix design components

Material	OPC	RGD	Fly ash	Fine aggregate	Coarse aggregate
Unit price (CAD/kg)	0.24[1]	0.25[2]	0.21[1]	0.021[1]	0.013[1]

[1]Ocean contractors: https://www.oceancontractors.ca
[2] Source: www.usagypsum.com

Table 8: Estimated cost of mix design

Material	Cost of materials (CAD)					
	OPC	RGD	Fly ash	Fine aggregate	Coarse aggregate	Total
Mix design 1	104.4	-	-	14.11	14.21	132.72
Mix design 2	33.2	14.82	41.5	12.07	15.4	117

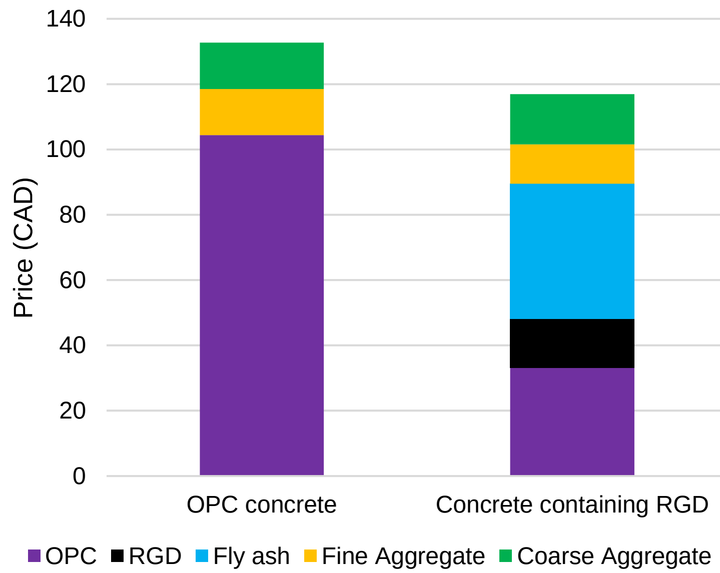

Figure 2: Estimated cost of mix designs

According to the estimated cost, 35MPa-compressive strength concrete containing RGD, OPC, and fly ash is around 11.8 percent cheaper than pure OPC concrete. Additionally, it is anticipated that the estimated cost will decrease by partially replacing OPC with slag since the slag is a waste of steel production and is cheaper than OPC.

8 Discussion on The Most Appropriate Mixture

This section aims to discover the most appropriate mix for the composite containing gypsum. Based on the literature, the strength of gypsum products in contact with water reduces between 50 to 60 percent due to the dissolving of the contacts of the crystalline intergrowth, separation of structural elements due to the wedging action of water films, and recrystallization process (Ahmed et al., 2011; Carvalho et al., 2008; Kondratieva et al., 2017; Singh and Middendorf, 2007). Given this strength reduction, (Carvalho et al., 2008) proposed a gypsum-ordinary Portland cement composite to reduce the effect of water on the strength reduction of the gypsum composite. Accordingly, many researchers studied the gypsum composites containing slag (Nguyen et al., 2019a), ordinary Portland cement (Hansen and Sadeghian, 2020), fly ash (Hansen and Sadeghian, 2020), pozzolana (Mukhametrakhimov et al., 2019), and mine waste (Chernyshova et al., 2020) to improve the strength of concrete containing gypsum.

According to (Chernyshova et al., 2020), adding the perlite mine waste with a specific surface area of 600 m^2/kg can improve the compressive strength of gypsum composite, while the best chemical additive to the mixture is S-3. It is worth mentioning that the chemical composition of the perlite is approximately similar to the fly ash. On the other hand, some researchers like (Hansen and Sadeghian, 2020) used the combination of ordinary Portland cement, fly ash, and RGD to manufacture the concrete specimens. Their findings illustrate that RGD can act as an activator for fly ash while the combination of gypsum and fly ash can reduce up to 50 percent of ordinary Portland cement demand, which significantly reduces the carbon dioxide emission of the concrete industry. Additionally, recent studies approved that adding gypsum to the slag composite can improve the hydration reactions of slag while the dosage of gypsum is lower than 30 percent (Nguyen et al., 2019a).

Based on the above mentioned and the similarity between the chemical composition of slag and ordinary Portland cement, it is anticipated that the combination of recycled gypsum drywall, ordinary Portland cement, fly ash or perlite, and slag can result in concrete that can meet the concrete structural requirement while the percent of RGD is limited to 30 percent of cementitious materials in the mixture.

9 Main Insights and Research Directions

This section discusses valuable insights based on the literature review and provides research directions for future studies. It includes understanding the most promising research lines that can better contribute to dealing with the open and difficult research challenges of using RGD in the construction industry. The main insights and research directions of the literature review are:

- The majority of studies examined the mechanical strengths of mixtures containing RGD. However, these factors are the critical parameters for constructions; the durability parameters are also significant since they are used to evaluate the lifetime of buildings. Therefore, examining the durability parameters of the mixtures such as concrete containing RGD and the cement or plaster and other materials which use RGD should be examined in future studies.
- Despite the studies on the effect of RGD on the mechanical strength of construction materials containing RGD, the effect of RGD on the microstructure of the construction materials such as concrete was not fully determined. Thus, evaluating and surveying the effect of RGD on the chemical reactions and microstructures of the construction materials can be considered as one of the research fields in using RGD as the second-raw construction materials.
- Soil stabilization is one of the main applications of RGD. However, with regard to the reaction of RGD with the rainwater, the environmental impacts of soil stabilization with RGD should be conclusively examined in the future.
- One of the applications of RGD that has rarely been studied in the literature is using RGD as recycled aggregates which can significantly reduce the demand for extracting the natural aggregates. Given the fact that the source of natural aggregates will be depleted by 2050, examining the effect of RGD as recycled aggregate can provide a new source of aggregates for concrete manufacturers.
- However, the previous studies indicate the applicability of RGD in the construction industry; the RGD cost can significantly limit its usage. Therefore, however, this research direction is not related to the utilization of RGD in the construction industry at first glance; investigating new approaches to produce the RGD powder to minimize the cost of RGD can significantly expand its applications in not only the construction industry but also other industries.

10 Conclusions

This paper reviewed the applications of recycled gypsum drywall (RGD) in the construction industry through the literature published between 2019 and 2021. Then, the environmental and economic benefits of using RGD as a supplementary cementitious material were determined, and the most appropriate mixture was proposed based on the reviewed articles. The main conclusions of this study are:

- RGD can be fully recycled based on the literature and used as supplementary cementitious material and aggregate in the construction industry.
- RGD can be used as supplementary cementitious material whether it is thermally treated or not.
- Utilizing the RGD as supplementary cementitious materials can reduce the CO_2 emission of the concrete by at least 55.7 percent.
- Employing the RGD as supplementary cementitious materials can decrease the cost of concrete by at least 11.8 percent.

- The combination of RGD, OPC, fly ash or perlite, and slag as cementitious materials can result in economically eco-friendly concrete.
- Perlite mine waste can be used as a replacement for fly ash to reduce the cost of concrete containing RGD.
- Several insights and research directions were proposed for future studies.

References

Ahmed, A., Keizo Ugai, Kamei, T., 2011. Investigation of recycled gypsum in conjunction with waste plastic trays for ground improvement. Construction and Building Materials 25, 208–217. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2010.06.036

AL-Adili, A., Salim, N., Al-Soudany, K.Y., 2019. Response of Soft Soil Mixing with Recycled Gypsum (Plasterboard) as Stabilized Agent for Soil underneath oil tank as a case study Response of Soft Soil Mixing with Recycled Gypsum (Plasterboard) as Stabilized Agent for Soil underneath oil tank as a ca. IOP Conference Series Materials Science and Engineering. https://doi.org/10.1088/1757-899X/579/1/012048

Allah, R.A.F., Al-Busaltan, S., Shaban, A.M., 2020. Determining field bearing resistance of subgrade soils using physical characteristics. IOP Conference Series: Materials Science and Engineering 745. https://doi.org/10.1088/1757-899X/745/1/012143

Almeida, K.S. De, Soares, R.A.L., Matos, J.M.E. de, 2020. Effect of gypsum and granite residues on products from the red ceramic industry: Literature review. Revista Materia 25. https://doi.org/10.1590/s1517-707620200001.0893

Apriyanti, Y., Fahriani, F., Fauzan, H., 2019. Use of Gypsum Waste and Tin Tailings as Stabilization Materials for Clay to Improve Quality of Subgrade Use of Gypsum Waste and Tin Tailings as Stabilization Materials for Clay to Improve Quality of Subgrade. IOP Conference Series: Earth and Environmental Science 1–6. https://doi.org/10.1088/1755-1315/353/1/012042

Arumugam, C., Shaik, S., 2021. Transforming waste disposals into building materials to investigate energy savings and carbon emission mitigation potential. Environmental Science and Pollution Research 28, 15259–15273. https://doi.org/10.1007/s11356-020-11693-0

Assis, F. De, Neto, M., 2019. Recycled gypsum block: development and performance. https://doi.org/10.1590/s1678-86212019000200307

Bartolomei, S.S., Augusta, E., Moura, B. de, Wiebeck, H., 2019. Recycled Expanded Polystyrene by Biodegradable Solvent — Preparation and Characterization. Springer International Publishing, pp. 757–763. https://doi.org/10.1007/978-3-030-05749-7

Basile, M., Conti, S., Arfò, S., Matarazzo, A., Cirino, E., 2020. GYPSUM AS SECOND RAW MATERIAL TO BE USED ENDLESS TIMES IN GREEN BUILDING, in: 24th International Trade Fair of Material & Energy Recovery and Sustainable Development. pp. 69–77.

Boccarusso, L., Durante, M., Iucolano, F., Langella, A., Minutolo, F.M.C., Mocerino, D., 2020. Recyclability process of standard and foamed gypsum. Procedia Manufacturing 47, 743–748. https://doi.org/10.1016/j.promfg.2020.04.227

Bure, K., Kamara, B., 2020. Making Road Base and Foundation from Secondary Waste Minerals and Recycled Aggregates By.

Carvalho, M.A., Calil, C., Savastano Jr, H., Tubino, R.M.C., Carvalho, M.T., 2008. Microstructure and Mechanical Properties of Gypsum Composites Reinforced with Recycled Cellulose Pulp. Materials Research 11, 391–397. https://doi.org/https://doi.org/10.1590/S1516-14392008000400002

Cheng, X., Li, B., Chen, G., Gao, S., 2020. Solidification/Stabilization of Textile Sludge as Subgrade: Usage of Binders and Skeleton Material. Advances in Civil Engineering 2020. https://doi.org/10.1155/2020/8873098

Chernyshova, N., Lesovik, V., Fediuk, R., Timokhin, R., 2020. Enhancement of fresh properties and performances of the eco-friendly gypsum-cement composite (EGCC). Construction and Building Materials 260, 120462. https://doi.org/10.1016/j.conbuildmat.2020.120462

Chiang, K., Yen, H., Lu, C., 2018. Recycled gypsum board acted as a mineral swelling agent for improving thermal conductivity characteristics in manufacturing of green lightweight building brick.

Cipriano, P.B., Galdino, T., Sá, C., Ferraz, A., 2020. Study of phases formed during sintering at different temperatures in ceramic composites containing gypsum waste. https://doi.org/10.21203/rs.3.rs-21149/v1

Cristina, H., Cordon, F., Carvalho, F., Furlan, F., 2019. Comparison of physical and mechanical properties of civil construction plaster and recycled waste gypsum from São Paulo , Brazil. Journal of Building Engineering 22, 504–512. https://doi.org/10.1016/j.jobe.2019.01.010

Diotti, A., Galvin, A.P., Piccinali, A., Plizzari, G., Sorlini, S., 2020. Chemical and leaching behavior of construction and demolition wastes and recycled aggregates. Sustainability (Switzerland) 12, 1–12. https://doi.org/10.3390/su122410326

Grasielly, D., Assis, F. De, Neto, M., 2019. Recycled gypsum block: development and performance 45–58.

Hansen, S., Sadeghian, P., 2020. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. Journal of Cleaner Production 274, 122785. https://doi.org/10.1016/j.jclepro.2020.122785

Hansen, S.K.A., 2020. GYPSUM POWDER RECYCLED FROM WASTE DRYWALLS AS A PARTIAL CEMENT REPLACEMENT IN CONCRETE.

Hendriks, C.A., Worrell, E., Price, L., Martin, N., Ozawa Meida, L., de Jager, D., Riemer, P., 1999. Emission reduction of greenhouse gases from the cement industry, in: Greenhouse Gas Control Technologies 4. Elsevier, pp. 939–944. https://doi.org/10.1016/B978-008043018-8/50150-8

Hong, S.H., Yuan, T.F., Choi, J.S., Yoon, Y.S., 2020. Effects of steelmaking slag and moisture on electrical properties of concrete. Materials 13, 1–14. https://doi.org/10.3390/ma13122675

Imteaz, M.A., Arulrajah, A., Maghool, F., 2020. Environmental and geotechnical suitability of recycling waste materials from plasterboard manufacturing. Waste Management and Research 38, 383–391. https://doi.org/10.1177/0734242X19881213

Iqbal, K., Hussain, S., Farooq, A., 2020. Influence of Waste Gypsum on the Microstructural Characteristics and Strength Behavior of Unfired Mud Block. Arabian Journal for Science and Engineering 45, 8551–8560. https://doi.org/10.1007/s13369-020-04749-3

Islam, A., Alengaram, U.J., Jumaat, M.Z., Bashar, I.I., Kabir, S.M.A., 2015. Engineering properties and carbon footprint of ground granulated blast-furnace slag-palm oil fuel ash-based structural geopolymer concrete. Construction and Building Materials 101, 503–521. https://doi.org/10.1016/j.conbuildmat.2015.10.026

Janbaz, M., Iacobucci, L., Francisco, K., Miskewitz, R., Kitazume, M., Maher, A., 2021. Effect of gypsum and cement content on unconfined compressive strength of soft sediment. International Journal of Geotechnical Engineering 15, 373–378. https://doi.org/10.1080/19386362.2019.1573474

Jiang, C., Wang, Y., Huang, S., Tao, G., 2018. Properties and microstructure of cementing material made with waste silty clay soil. European Journal of Environmental and Civil Engineering 8189, 1–12. https://doi.org/10.1080/19648189.2018.1426499

Kamara, K.B., Ganjian, E., Khorami, M., 2021. The effect of quarry waste dust and reclaimed asphalt filler in hydraulically bound mixtures containing plasterboard gypsum and GGBS. Journal of Cleaner Production 279. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.123584

Kamara, K.B.B., Ganjian, E., Khorami, M., 2019. Optimisation of secondary waste gypsum for mechanical stability in road (base) and foundation, in: Fifth International Conference on Sustainable Construction Materials and Technologies. https://doi.org/10.18552/2019/IDSCMT5100

Khudyakova, T.M., Kolesnikov, A.S., Zhakipbaev, B.E., Kenzhibaeva, G.S., Kutzhanova, A.N., Iztleuov, G.M., Zhanikulov, N.N., Kolesnikova, O.G., Mynbaeva, E., 2019. Optimization of Raw Material Mixes in Studying Mixed Cements and Their Physicomechnical Properties. Refractories and Industrial Ceramics 60, 76–81. https://doi.org/10.1007/s11148-019-00312-2

Kondratieva, N., Barre, M., Goutenoire, F., Sanytsky, M., 2017. Study of modified gypsum binder. Construction and Building Materials 149, 535–542. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.05.140

Krishnaiah, E., Kiran, D.N., Kumar, G.K., 2020. Amelioration of Expansive Clay Using Recycled Bassanite, in: Problematic Soils and Geoenvironmental Concerns. https://doi.org/10.1007/978-981-15-6237-2_12

Li, Z., Xu, K., Peng, J., Wang, J., Ma, X., Niu, J., 2019. Study on hydration and mechanical property of quicklime blended recycled plaster materials. Construction and Building Materials 202, 440–448. https://doi.org/10.1016/j.conbuildmat.2019.01.036

Lu, W., Ma, B., Su, Y., He, X., Jin, Z., Qi, H., 2020. Low-Energy Consumption Preparation of Fine Waterproof Cementitious Material with High-Volume Phosphogypsum. Journal of Materials in Civil Engineering 32. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003423

Maqsood, Z., Koseki, J., Miyashita, Y., Xie, J., Kyokawa, H., 2020. Experimental study on the mechanical behaviour of bounded geomaterials under creep and cyclic loading considering effects of instantaneous strain rates. Engineering Geology 276, 105774. https://doi.org/10.1016/j.enggeo.2020.105774

Mukhametrakhimov, R.K., Galautdinov, A., Gilmanshin, I., 2019. Modified gypsum-cement-pozzolanic composites reinforced withpolypropylene fibers. IOP Conference Series: Materials Science and Engineering. https://doi.org/10.1088/1757-899X/570/1/012068

Naik, T.R., 2008. Sustainability of Concrete Construction. Practice Periodical on Structural Design and Construction 13, 98–103. https://doi.org/10.1061/(ASCE)1084-0680(2008)13:2(98)

Nguyen, H., Kinnunen, P., Carvelli, V., Mastali, M., Illikainen, M., 2019a. Strain hardening polypropylene fiber reinforced composite from hydrated ladle slag and gypsum. Composites Part B: Engineering 158, 328–338. https://doi.org/10.1016/j.compositesb.2018.09.056

Nguyen, H., Kinnunen, P., Gijbels, K., Carvelli, V., Sreenivasan, H., 2019b. Ettringite-based binder from ladle slag and gypsum -The effect of citric acid on fresh and hardened state properties Cement and Concrete Research Ettringite-based binder from ladle slag and gypsum – The effect of citric acid on fresh and hardened state pr. Cement and Concrete Research 123, 105800. https://doi.org/10.1016/j.cemconres.2019.105800

Oh, H., 2019. Opportunities for Promoting the Recycling of Gypsum Board from Construction , Renovation , and Demolition in Manitoba.

Oliveira, K.A. De, Barbosa, J.C., Christoforo, A.L., Molina, J.C., 2020. Sound Absorption of Recycled Gypsum Matrix Composites with Residual Cellulosic Pulp and Expanded Polystyrene. https://doi.org/10.15376/biores.14.2.4806-4813

Oliveira, M., Izquierdo, M., Querol, X., Lieberman, R.N., Binoy, K., Silva, L.F.O., 2019. Nanoparticles from Construction Wastes: A Problem to Health and the Environment. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2019.02.096

Papailiopoulou, N., 2018. Techno-economic impact assessment of recycled gypsum usage in plasterboard manufacturing.

Pedreño-Rojas, M.A., de Brito, J., Flores-Colen, I., Pereira, M.F.C., Rubio-de-Hita, P., 2020. Influence of gypsum wastes on the workability of plasters: Heating process and microstructural analysis. Journal of Building Engineering 29, 101143. https://doi.org/10.1016/j.jobe.2019.101143

Pedreño-Rojas, M.A., Flores-Colen, I., De Brito, J., Rodríguez-Liñán, C., 2019. Influence of the heating process on the use of gypsum wastes in plasters: Mechanical, thermal and environmental analysis. Journal of Cleaner Production 215, 444–457. https://doi.org/10.1016/j.jclepro.2019.01.053

Pedreño-Rojas, Manuel Alejandro, Rodríguez-Liñán, C., Flores-Colen, I., de Brito, J., 2020. Use of polycarbonate waste as aggregate in recycled gypsum plasters. Materials 13. https://doi.org/10.3390/ma13143042

Rustam, R.K., Resti, A., Purwanto, H., Firdaus, M., 2019. The effect of gypsum plafond waste on shear strength of soft clay soil. IOP Conference Series: Materials Science and Engineering PAPER. https://doi.org/10.1088/1757-899X/620/1/012039

Singh, N., Middendorf, B., 2007. Calcium Sulphate Hemihydrate Hydration Leading to Gypsum Crystallization. Progress in Crystal Growth and Characterization of Materials 53, 57–77. https://doi.org/10.1016/j.pcrysgrow.2007.01.002

Tan, J.F., Adajar, M.A.Q., 2020. RECYCLED GYPSUM AND RICE HUSK ASH AS ADDITIVES IN THE RECYCLED GYPSUM AND RICE HUSK ASH AS ADDITIVES IN THE STABILIZATION OF EXPANSIVE SOIL. International Journal of GEOMATE 18, 197–202. https://doi.org/10.21660/2020.70.9201

Tazi, N., Idir, R., Ben Fraj, A., 2021. Towards achieving circularity in residential building materials: Potential stock, locks and opportunities. Journal of Cleaner Production 281, 124489. https://doi.org/10.1016/j.jclepro.2020.124489

Thul, P., Raut, T., Yadav, K., Inamdar, M.M., 2019. Stabilization of Black Cotton Soil by using Waste Gypsum. International Journal of Research in Engineering, Science and Management 2, 2–4.

Timpano, C.S., 2019. A review on Manufacturing , Machining , and recycling of 3D printed composite materials . A review on Manufacturing , Machining , and recycling of 3D printed composite materials . c, 0–6. https://doi.org/10.1088/1757-899X/653/1/012024

Toufigh, V., Jafari, A., 2021. Developing a comprehensive prediction model for compressive strength of fly ash-based geopolymer concrete (FAGC). Construction and Building Materials 277, 122241. https://doi.org/10.1016/j.conbuildmat.2021.122241

Weimann, K., Adam, C., Buchert, M., Sutter, J., 2021. Environmental evaluation of gypsum plasterboard recycling. Minerals 11, 1–13. https://doi.org/10.3390/min11020101

Yeheyis, M., Hewage, K., Alam, M.S., Eskicioglu, C., Sadiq, R., 2012. An overview of construction and demolition waste management in Canada : A lifecycle analysis approach to sustainability An overview of construction and demolition waste management in Canada : a lifecycle analysis approach to sustainability. https://doi.org/10.1007/s10098-012-0481-6